Handbook of Paper and Board

Edited by
Herbert Holik

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Preface

"Paper is out"... and "paper flood increases"...
Is paper now dead or alive?

Paper is reality in our life. This book informs on the technical, economic and social importance of paper and board. The authors give a concise description of the fascinating art and technology of paper making, providing laymen, students, politicians and others with most recent information and on the state-of-the-art technology. It shows the relevance of paper and board today as well as the historical background and economic aspects. The chapter on raw materials for paper and board manufacture contains an overview and summary of what is described in Volume 1 on fibrous material, followed by more detailed description of pigments as fillers and for coating. Paper chemistry has found an adequate scope covering this important area by basics and practical application. The process of stock preparation first describes the unit processes which are then combined to systems for primary and secondary fiber preparation. Water circuits with loop designs and circuit closure follow. The chapter on paper and board manufacture covers the different sections in the paper machine as well as fabrics, rolls and roll covers, and describes the different types of machines producing the various paper and board grades. The high technical standard of the control, information and analysing systems in the paper industry is described in the chapter of control systems. Coating is dealt with in a separate chapter covering color formulation and preparation as well as the actual coating application. Paper finishing gives an insight in what happens at roll slitting and handling. The chapter on environmental aspects includes waste water treatment as well as handling, utilization and disposal of solid waste. The following chapters describe the main paper and board grades and their properties, followed by testing of paper and board. The paper and book preservation chapter points at an area of burning interest of mankind. The appendix includes latest papers on state-of-the-art as well as earlier ones giving basics in certain areas.

This wide knowledge field of paper and board – the big elephant – could only be eaten by cutting it into smaller pieces. This was successfully done by the readiness of more than 20 authors, all professionals with detailed knowledge in their areas, to contribute to this project. The variety of their points of view are certainly one of

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the advantages of this book. My thanks go to my colleagues for their cooperation, to the individual companies for providing the pictures, to BASF, OMYA and Voith for enabling the handbook to be printed in colors and to Ullmann for the support during the preparation of this book.

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1
Introduction

1.1
Paper and Board Today

Herbert Holik

The history of paper is also the history of human culture and civilization. The Egyptians, Greeks and Romans wrote on "papyrus", a paper-like material. Today's kind of paper was first developed and used in China. Paper was the most important carrier of information in the past. It was only with increasing paper production that the transfer of knowledge, education and information to a larger portion of society became possible. With paper emperors were able to administrate large empires more easily. In former times paper was a valuable product, and paper making an art – an art that was often kept secret because of the outstanding advantages of the product.

Today paper has changed from a rare artisan material to a commodity product, with a high practical value in communication, in educational, artistic, hygienic, sanitary, and technical applications. Nobody can imagine a world without paper. A large variety of paper grades are produced to suit the special requirements of each application: Graphic paper grades, packaging papers and board, hygienic papers, and speciality paper grades. Paper can be impregnated, coated, laminated, creped, molded etc. Paper products embellish our homes, and sanitary products made of paper ease our daily life. An easier life is also more likely with a sufficient number of banknotes in the briefcase. Packaging papers and board grades support supermarket logistics and product presentations. Computer print-outs and other graphic papers such as newspapers, magazines and books accompany us through our life. Even today in our digital world paper is a reliable means of long-time documentation and data preservation.

The worldwide consumption of paper is increasing steadily over the years. The paper consumption in individual countries is related to their gross national product and hence the further increase in paper and board consumption will be different in different countries depending on whether economic saturation, as e.g. in the United States and Central Europe, or fast increasing demand, as in China, is prevailing. The ratio of the worldwide consumption of the different paper and board grades has changed in the past and will change in the future according to

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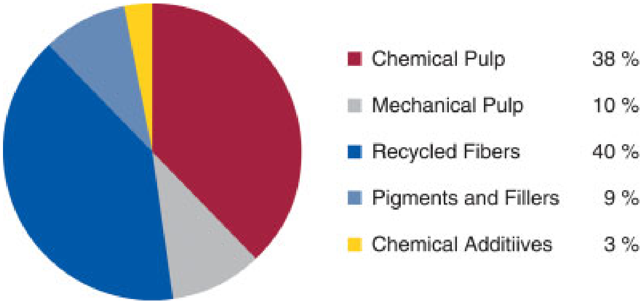

Fig. 1.1 Components used in paper and board production worldwide (by mass ratio).

technical and social evolution and developments in the individual countries and in the world as a whole.

The components used in paper and board production worldwide are given in Fig. 1.1. Today recovered paper has become the main resource for paper and board production, followed by chemical pulp, mechanical pulp, pigments and fillers, and chemical additives. Paper is mainly based on fibers from cultured woods, and is a renewable and recyclable raw material. The special characteristic of this fiber material is that the paper strength results from the hydrogen bonding between the individual fibers. In certain cases it is enhanced by the addition of starch or wet strength additives. The hydrogen bonds are loosened by rewetting the paper which allows easy recycling.

Increased paper recycling and sustained foresting help to preserve the wood resources of the earth. The paper industry has steadily improved its standards in complying with environmental demands as related to water consumption and water effluents, energy consumption, and primary (and secondary) fiber consumption. These standards have to be maintained and even improved in the future because of further increasing paper and board consumption and limited resources. The paper and board market is global, and so is the paper industry where an evident consolidation has occurred over the last decades: In 1980 the 150 biggest companies contributed about 45% to the overall production, in 2000 this figure was about 70% in a market which had nearly doubled from about 170 million tons/year to about 320 million tons/year. It seems that this concentration process has not yet come to an end.

Papermaking has changed from an “art”, where all specific processes were kept secret, to an industry with high-tech production facilities and with a scientific approach. Great challenges are e.g. the huge production quantities per unit and the high quality demands placed on the paper and board properties and their uniformity. Only high quality products – at low price – satisfy the expectations of the customer and end user.

Since paper is a commodity, low cost production is mandatory. As the fiber raw material is the main cost factor in paper production recovered paper has become the main fiber stock material worldwide and its proportion will increase further. Several grades, such as newsprint and many packaging and board grades, can be entirely based on recycled fibers. Today recovered fibers must be used in paper grades similar to the recovered paper grade, downgrading of recovered paper (high quality fibers for lower quality paper products) is no longer economic.

In former times, with mainly virgin fibers consumption, a paper mill was located close to the wood (and the water and energy resources). This is still true for regions of Portugal, Spain and Brazil with Eucalypt plantations used mainly for copy or similar paper grades. One result of the increased use of recovered paper is that certain new “green field” paper mills are established today in the vicinity of highly populated areas to have easier access to recovered paper resources and to be closer to the market.

The capital demand for a new mill is of the order of magnitude of 500 million €. In the last thirty years the investment costs (inflation-adjusted) related to the specific annual production (t/a) have been approximately halved. This drop is mainly due to increased machine speeds and machine widths as well as to improved runnability. On the other hand the investment costs related to annual turnover have remained constant or even increased.

1.2
Overview of the Manufacturing Process for Paper and Board

Papermaking today includes, in principle, the same process steps as applied for centuries: preparation of the fiber material, sheet or web forming, pressing, drying, sizing and smoothing. However, in the last two centuries much of the detail has changed. Each process step has undergone – and still undergoes today – intensive research and development work to meet economic and ecological requirements. All links in the chain between fiber and end user contribute to this progress. The chain does not only include the paper producing industry itself and its suppliers such as the machine and chemical industry, but also the paper industry’s customers and related industries, e. g. printing-houses, printing ink and printing machine suppliers and the manufacturers of corrugated board.

R&D focus has been on economic and environmental aspects such as

- reduction in consumption of raw material, energy and water as well as noise reduction
- high machine runnability and long lifetime of machinery and its components
- improvement of paper and board quality with respect to improvement of converting quality

which has led to results of high practical value such as

- better understanding and consequent control of the whole process in a narrow band
- reduction in fiber consumption by reducing basis weight at the same quality level and practical value

- increased ratio of recycled fibers in graphic paper production, with up to 100% for newsprint and a growing ratio in high grades such as supercalendered (SC) and light weight coated (LWC) papers
- fillers and coatings replacing part of the expensive fiber material and improving quality
- new coating and calendering technologies
- higher safety in Yankee dryer and suction press roll operation
- new methods of material design for fighting wear of machine components
- minimum number of personnel involved in the paper and board production process.

R&D work is supported by modern tools and sciences e. g.

- process analysis using advanced measuring and analysis techniques
- process simulation and advanced control techniques
- morphological characterization of fibers for papermaking
- chemistry developing functional and process chemicals
- finite element method (FEM) and computational fluid dynamics (CFD)
- visualization techniques in the micro- or nano-ranges, video documentation and analysis
- material sciences including plasma ions implantation into the base material at low temperatures.

The papermaking process (Fig. 1.2) starts with the delivery of the raw material of the stock components. These are

- fibers such as
  - virgin pulps (chemical or mechanical) which are usually supplied in bales or, in special cases, as a suspension when both pulp and paper are manufactured at the same location (integrated processing)
  - recovered paper in bales or as loose material
- fillers and pigments
- chemical additives
- coating colors when coated paper is produced.

All these components have to be adequately prepared for optimum use in the papermaking process steps. The additives may be delivered ready for use or may have to be finally prepared according to the requirements in the mill. Fiber stock preparation includes several unit operations depending on the furnish and the purpose. Stock preparation of virgin fiber pulp needs less machinery and energy than the preparation of recovered paper which, however, is the cheaper raw material. Fiber stock preparation ends at the paper machine chest. Here stock of high consistency is preferred to minimize carry-over of chemicals and contaminants.

Stock preparation is followed by the approach flow system connecting stock preparation with the paper machine. Its main tasks are

- to dose exactly and mix uniformly all the different components of the final suspension to be delivered to the paper machine

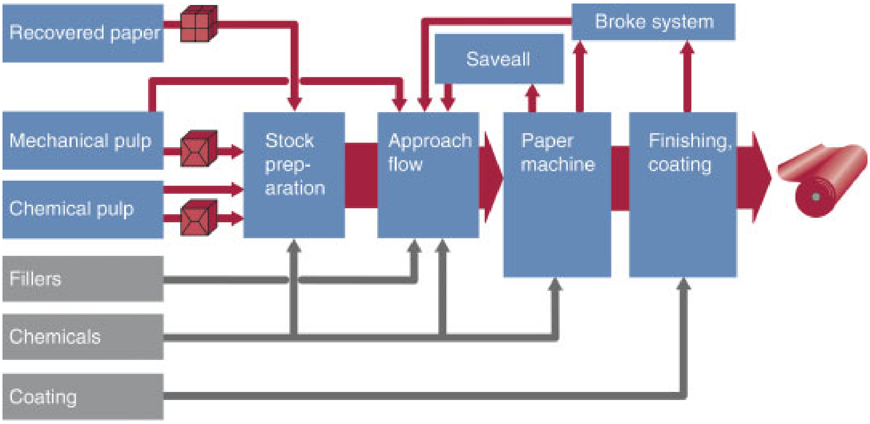

Fig. 1.2 Overview of the paper making process.

- to supply a continuous suspension flow of constant consistency, quality and flow rate at constant pressure to the headbox of the paper machine.

The approach flow system ends at the distributor of the headbox.

The task of the paper machine is to produce paper or board of the quality required by the end user – or by the intermediate process steps such as converting or printing. The paper and board properties have to be uniform in machine direction (MD) as well as in cross machine direction (CD). Further, the paper machine has to make the best use of the quality potential of the entering stock. The paper machine includes

- the headbox distributing the suspension across the machine width onto the wire
- the wire section where the suspension is formed into an endless web by dewatering
- the press section pressing water out of the web by mechanical means
- the dryer section where the residual water is evaporated
- often a sizing unit where starch, or pigments are transferred onto the web
- sometimes a coating section where coating color is applied to the web
- the calender to finally smooth the paper or board surface.

The paper manufacturing process ends with the paper web being reeled at the reeler at full width.

By tradition and technical feasibility, coating and supercalendering for surface quality improvement have been off-line processes. Today both are increasingly integrated into the paper machine. The final activities in paper and board production are slitting of the full width reels into smaller rolls at the winder followed by packaging the rolls for shipment.

Table 1.1 Different naming of consistency ranges in the various unit operations in paper making.

Unit operation	**Actual consistency**		
	LC (%) (low consistency)	**MC (%) (medium consistency)**	**HC (%) (high consistency)**
Repulping	< 6	< 12	12–28
Screening	< 1.5	< 4.5	–
Centrifugal cleaning	< 1.5	< 2.5	2.5–6
Bleaching	–	10–15	25–35
Refining	3–6	10–13	28–35
Web forming (headbox)	< 2.0	–	> 2.5

Paper broken during the manufacturing process has to be recycled and fibers are recovered from the white water of the paper machine in a saveall. White water is fed back from the paper machine to the approach flow system and stock preparation. Fresh water is supplied to the paper machine.

Along the paper production line stock consistency varies according to the requirements of the unit operations. Unfortunately the terms low, medium and high consistency relate to different consistency numbers depending on the actual unit operation (Table 1.1). It is also important to note whether the number gives the overall consistency including fibers and fillers or just fibers.

1.3
Historical Background and General Aspects [1]
Peter F. Tschudin

1.3.1
Introduction

Paper is defined internationally as a thin layer of mostly cellulosic plant fibers, produced on a screen by dewatering a slurry of fibers in water [2]. The slurry is called *pulp*. Despite recent developments (proteinic or synthetic fibers, chemical additives, coating, etc.) the “cellulosic plant fiber” will be the main, not exclusive, component of paper, and water will be used in preparing the pulp and in forming the paper web also in the future.

1.3.2
Precursors of Paper

1.3.2.1 Tapa (Bark-cloth)

Bark-cloth, made since prehistoric times, is found widely along the Equator belt in nearly all cultures, used mainly for decorating and clothing [3]. It is produced by beating or pressing the inner bark (*liber*, bast) of trees and shrubs like paper mulberry, lime-tree, fig or daphne, and is known by the generic term "tapa", derived from the Polynesian language. Tapa is a felt-like material, similar to thick woven paper, showing in most cases traces of the beating mallets. Technically speaking, it is a kind of non-woven paper.

There are three different techniques to be observed in tapa-making. The most sophisticated method consists of three steps. In the first, small strips of bast are cut and cooked for several hours in suds of wood ash. This cooking is very similar to the basic operation of our alkaline pulping. Then the strips are rinsed, placed together on a wooden board and beaten with a mallet, thus forming a small sheet on the board. The third step consists of drying and smoothing.

1.3.2.2 Felt

Felting techniques go back into prehistory [4]. Plant fibers or animal hair are separated from their original linking as much as possible and spread in thick layers onto a cloth or mat. Then they are covered by another cloth and beaten by foot stamping or with heavy wooden sticks to entangle them and stick them together. In another way, the ground mat bearing the fibers is rolled and the roll is beaten. The mat is unrolled and rolled again several times. In wet felting, water is used to soak the fibers and help felting.

1.3.2.3 Papyrus

Papyrus, the most commonly used writing material of Ancient Egypt and Classical Antiquity, was made in Egypt from the beginning of the 3rd millennium BC. The triangulated stem of the papyrus plant is peeled and the pith cut into thin, small strips. A first layer of wet strips placed vertically side by side with a slight overlap is laid onto a board. Then, a similar layer of horizontally oriented stripes is laid above it. Beating with wooden sticks and pressing the still wet layers leads to a sheet of entangled fibers, most remaining in the original linking of the pith. After drying and smoothing several sheets are glued together to form a roll, ready to be written on. Gluing of several papyrus sheet fragments, usually recycled material, results in board or papier-mâché.

New papyrus rolls are very strong and flexible, an ideal writing material. They were exported in large quantities into the Mediterranean area until the 8th century AD. Parchment replaced the dwindling supply from Egypt. When paper was imported from the East, it was given the name of the Egyptian writing material because of its resemblance to papyrus.

1.3.3
Paper

1.3.3.1 Invention of Paper

The oldest papermaking technique, pouring pulp into a primitive mould, is still in use at a few locations in the Himalayas, in some remote spots of China and in Southeast Asia. It shows clearly the descent from tapa and felting techniques. From recent findings of the oldest papers in Chinese tombs or in refuse heaps of military posts it must be concluded that some kind of paper was produced in China since the final centuries BC. Nevertheless, the Chinese chronicles state that in 105 AD in Loyang, the court official Cai Lun invented papermaking from textile waste, i. e. from rags, and propagated paper as a writing material [5]. This was the birth of paper as we know it today.

1.3.3.2 Chinese Paper

Chinese papermakers improved the effectiveness of the production, replacing the pouring technique by dipping the bamboo screen into a vat filled with diluted pulp. After lifting the mold out of the vat and dewatering, the newly formed sheet of paper was immediately couched on a wooden board or a plastered wall to let it dry. The flexible bamboo screen was rolled off and could be reused with the vat. Thus, the handicap of waiting until a sheet dried on the mold, was surmounted. Because of rag and paper mulberry shortages, they chose bamboo as a further source of fiber [6] the pulping of which took several months.

China developed many kinds of specialty papers (sized, coated and dyed paper; anti-moth paper; waterproof paper); over-size sheets were made by couching the wet borders of smaller sheets together, and decoration watermarks were added by putting leather or board figures on the screen before pouring the pulp. Paper served for almost everything: writing, drawing, wrapping, clothing, protection from wind and rain, decoration, windows, even for making balloons and kites, and, last but not least, for making paper money or special currency to be burned in honor of the ancestors.

1.3.3.3 The Eastern Spread of Papermaking

Chinese papermaking techniques were introduced into Korea at an early date, and reached Japan in 610 AD. In both countries, fibers of the paper mulberry were mainly used. In Japan, splash dipping was developed, using a big mold suspended on a teetering twig [7]. Japanese papermakers were fond of art papers for decoration purposes. The ultimate in Japanese papermaking was the production of Shifu, paper yarn woven into heavy, beautiful fabric.

1.3.3.4 **The Spread of Papermaking into Central and Southern Asia**

At an early date (4th to 6th centuries AD), it is attested that there were Chinese papermakers in Central Asia along the Silk Road, using the very old technique and local fiber plants like black mulberry. There, Tibetans learned the papermaking craft and transferred the knowledge into the high valleys of the Himalayas where they used local plants like the roots of Stellera Chamaejasme. From Southern China, the old-fashioned pouring technique spread into the emerging kingdoms of South Eastern Asia. India kept its traditional use of bark, textile cloth and palm leaves as writing materials for a long time. Only at a later period (11th century AD?), was papermaking introduced from the north through contacts with Central Asia and Persia [8].

1.3.3.5 **Arab Paper**

The Arabs, in the course of their eastern expansion, became acquainted with the production of the new writing material reaching Samarkand. Subsequently, papermills were set up in Baghdad, Damascus, Cairo, and later in the Maghreb. Having no paper mulberry trees and using screens made of reed, the Arabs made thin sheets of poorly beaten rag pulp and coated them on both sides with starch paste (from wheat or rice) which could be colored. This gave Arab paper its good writing properties and its fine appearance but also made it prone to damage due to humidity, crumbling or insects. In the 11th century AD, Arab papermaking knowledge spread into the Byzantine world and into medieval Europe, especially Spain (Xativa, Cordoba) and Italy (Amalfi, Genoa).

1.3.3.6 **Medieval European Paper**

Papermakers from Genoa and Fabriano tried to improve the Arab technique. They still exploited linen or hemp rags to get pulp, but improved the beating. Water power was used to drive heavy stamping mills, huge oak trunks comprising four to six large troughs with three or four heavy wooden stampers each beating the rags in fresh circulating water. The rags were transferred from trough to trough every six hours to ensure a better degree of refining. Further improvements were molds consisting of a wooden frame with inlaid copper or brass wire, heavy screw presses, and the replacement of starch sizing by dip sizing in animal glue.

This is the origin of the division of labor leading to a considerable increase in production: Work at the vat normally involved four people: the vatman, who made the sheet using the mold; the couchman working alongside the vatman, placing the sheet on felt; the layman, who removed the moist sheets from the felts, and the apprentice, who had to feed pulp to the vat and provide vat heating. The press was operated jointly by this team. Depending on the format, up to nine reams (4500 sheets) of paper were made during a working day averaging 13 to 15 hours. The paper was dried by women hanging it on ropes in the drying loft. Apart from different sizes, three main sorts of paper were produced: writing paper (for letter and chancery use), printing paper (mostly unsized) and cheap wrapping paper (also broke, screenings), used also for drafts.

As a further consequence of the change in mold construction, watermarking was invented in medieval Italy. The real watermark, a bright figure in the paper sheet, is seen by the naked eye. In hand papermaking, it is formed by a curved wire which is sewn onto the screen of the mold; the wire reduces the thickness of the sheet, thus making the figure transparent. The watermark serves as a trademark and provides the historian with an unsurpassed dating and authenticating tool. By comparing a watermark with others of a certain date or origin, the paper historian will be able to determine the age and origin of a document or print. Shadow watermarks are produced on a mold bearing a fine, embossed woven wire, showing an image like a black and white photograph.

1.3.3.7 **Mechanization and Industrialization**

In Europe, technical progress continued. In the 16th century, glazing the sheets by hand using a glass or stone burnisher was supplemented by the use of the glazing hammer, similar to a forging hammer. Towards the end of the 17th century, a most efficient tool, the so-called "hollander" beater, supplemented or even replaced the stamping mill. As the rotating knives of the Hollander beater cut and shorten the fibers more than a stamper, the ageing of paper was accelerated. This phenomenon is true also for the change in sizing. To improve the solubility and the penetration of the animal glue solution, alum was added, leading to acidic deterioration of paper.

Further development of printing during the 18th and 19th century led to a steeply rising demand for paper, especially for new printing grades. This and the tremendous upsurge in papermaking soon led to a serious shortage of raw material and to regulations governing the trade in rags, to ensure the local production of paper for administrative purposes. Rags of minor quality, even cotton and wool were used, together with fillers like starch or kaolin. So systematic search for rag fiber substitutes was needed [9].

Since the 17th century, there had been some concentration of handicraft activities in big factories, consisting of several mills, which still depended on skilled papermakers organized in open guilds. The efforts made to improve paper quality (woven wire molds since 1738) and to step up production as much as possible employing local people and developing auxiliary mechanical means (rag cutter, rag digester, hollander beater, vat paddles, strainers, couching press, hydraulic press, glazing table, glazing hammer, calender) culminated in the design and construction of paper machines.

1.3.3.8 **Paper Machines**

A Frenchman, J. N. L. Robert, built the first paper machine, patented in 1799. It was driven by one worker using a crank. The diluted pulp contained in a large vat was hurled into a wooden chest by a rotating paddle wheel and directed onto an endless wire screen of laid type. The screen bearing the forming paper web was moved forward, horizontally shaken and passed a pair of couch rolls equipped with felts. The web, still moist, was then taken by a worker and cut into large pieces which were hung on ropes to dry.

This machine was further developed in England by Bryan Donkin and by the Fourdrinier brothers. Soon, other types were developed, e. g. the cylinder machine (Bramah, 1805; Dickinson, 1809) in which a cylinder with mounted wire-screen rotates in a vat filled with pulp. Other types were the mold-chain machine (Fourdrinier, 1806) and the twin-wire machine. Flat-type and cylinder machines gained ground in the 19th century and were extended to include a dryer section (Crompton, 1820) and a reeler, somewhat later (1850) also a calender section. Steady improvements led to a considerable increase in production. The paper machine heralded industrialization. In this new situation, the small operators who were unable or unwilling to afford machines tried to survive with piece work or by producing special grades and cardboard, but they were sooner or later compelled to discontinue their activities. Others had to adapt their existing buildings or set up new mills elsewhere.

The decisive step in developing the US paper industry was initiated by Joshua Gilpin (1815). Special paper machines were successfully built (e. g. the so-called "Yankee" cylinder machine), and soon the US paper production became the largest in the world.

1.3.3.9 Pulping and Sizing

In European medieval papermaking, the rags were moistened and exposed to air in order to rot for weeks before beating (fermentation). This helped to dissolve dirt, yarn knots or knit links and was equivalent to a modern enzymatic fiber treatment. During beating, slaked lime was added to the slurry, which resulted in fiber swelling, fiber bleaching and improved fiber separation and quality [10]. Even after washing and beating, particles of calcium carbonate and magnesium carbonate remained sticking to the fibers and got into the vat and into the paper sheet. There, they acted as a buffer, neutralizing acids and thus inhibiting the ageing of old hand-made papers.

In the 18th and 19th centuries, efforts were made to improve the efficiency of rag pulping. Rag cutting machines and rag digesters replaced old-fashioned breaking and boiling. The stampers were replaced by the hollander beater and later by refiners. To obtain rag substitutes on an industrial scale, in 1774, Claproth in Leipzig promoted de-inking, using a kind of bentonite. Straw was propagated as a raw material but failed because of poor paper quality (Koops, 1800). Only the invention of the stone groundwood process (Keller, 1843) and of chemical pulping (soda process: first patents, 1851: Watt, 1854: Mellier; sulfate process: Dahl 1884; sulfite process: Tilghman 1866) solved the problem of getting large fiber quantities.

Dip sizing of paper bundles in a solution of animal glue was replaced by pulp sizing, using rosin and alum (Illig, 1807). The resulting acid conditions in papermaking are in a large part responsible for the poor ageing behavior of machine-made paper until the 1980s, especially of wood-containing grades in which lignin reactions are triggered.

1.3.3.10 From Industrialization to Automation and Globalization: Technical and Economic Trends of the 19th and 20th Centuries

Several partly overlapping periods may be distinguished, each marked by definite trends. Rising capital investment was needed to mechanize papermaking, and the lack of rag supply was a problem for the papermakers. In consequence the introduction of a pulping section in a papermill or the construction of independent pulp mills became a priority task.

The evolution of the paper machine depended on progress in engineering and metallurgy. Until turbines replaced the venerable waterwheels, water energy was too slow and too poor to drive an improved paper machine. Even the introduction of steam engines did not help much; only when the steel quality available allowed the use of high pressure or superheated steam, did progress in papermaking begin. But the problem of power transmission to the different parts of the paper machine remained. Here the introduction of electricity, permitting the installation of individual drives to every part of the machine, triggered a leap into the future: The web width was enlarged, working speed increased considerably and machines designed specifically for the production of particular paper and board grades (e. g. multicylinder machines) were developed.

Alongside the development of printing in the 19th century, new paper grades were created, together with some kind of paper specialties like punchcards, stand-up collars, tube papers, flong, pergamyn, ammunition papers, envelopes, tobacco paper, toilet paper etc. The size of a pulping plant and of a paper machine grew to such an extent, that new factory complexes had to be erected, and there were also changes in research and development, marketing, controlling and transportation. In most cases, this evolution led to commercial group building and mergers.

Since the 1980s, the use of new materials (thermomechanical pulp, deinked recycled fibers, new fillers, process chemicals and dyes) and new web forming principles (e. g. twin-wire or gap formers), neutral sizing and – the most effective change – automation have brought further progress. This led to further specialization in specific paper types, development of new paper grades (e. g. LWC papers, technical papers). In consequence, corporate mergers and international company groups came up with raw material supply and trading organizations of their own and unprofitable operations were shut down.

Environmental problems, documented in the 19th century already, also triggered changes. New forestry principles have been introduced, fiber recycling covers more than half the fiber demand; heat recovery, closed water loops and the replacement of aggressive chemical treatments in pulping have helped to improve the poor ecological image of the paper and pulp industry.

Paper production and consumption increased from medieval times to the end of the 18th century by a factor of 50 (Fig. 1.3). Since then, paper and board have become a world-wide, large-scale commodity with exponential growth. The FAO statistics substantiate a forecast of about half a billion metric tons in 2010, of which about 2/5 will be produced in the fastest growing industrial market, Asia.

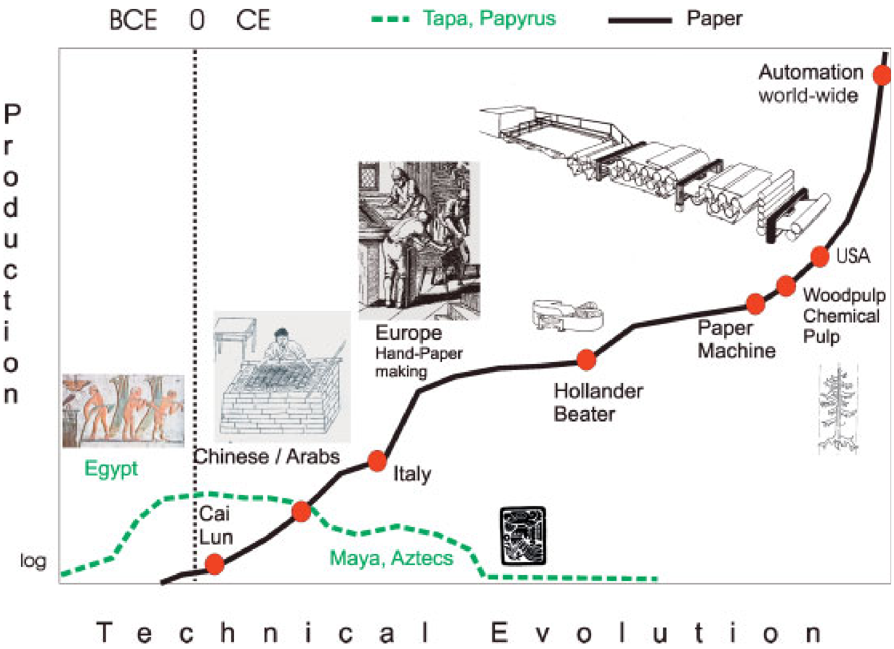

Fig. 1.3 Development of paper technology (source: Basler Papiermühle).

1.4
Economic Aspects
Gert-Heinz Rentrop

In 2002 the world production of paper and board was ca. 331 × 10^6 t. Although paper and board are used in some form or other in all parts of the inhabited world, the production is left to a limited number of countries. More than 9000 paper machines are responsible for production in 111 of the approximately 200 countries in the world, whereby the 15 largest producer countries alone account for 82 % of total world production (Table 1.2).

The various requirements for the production of paper are not met everywhere. For instance, suitable raw materials must be available, including water, energy, and trained personnel. Furthermore, the construction of paper mills requires a very high investment, and a sufficiently large market and a favorable location are both essential prerequisites for economic papermaking. For these reasons, the modern paper industry is based mainly in the coniferous forest zone of the Northern Hemisphere, with centers in Europe, North America, and in Japan.

World paper production has increased more than sevenfold since 1950 when production was ca. 44 × 10^6 t (Table 1.3). During this time, the regions which did not belong to the classical paper producing countries – above all China – have come to the fore, and their share of world production grew from ca. 3 % in 1950 to

Table 1.2 Production of paper and board by country, 2002.

Country	Production, 10^6 t	Share, %
United States	80.8	25
China	37.8	11
Japan	30.0	9
Canada	20.0	6
Germany	18.5	6
Finland	12.7	4
Sweden	10.7	3
South Korea	9.8	3
France	9.7	3
Italy	9.2	3
Brazil	7.7	2
UK	6.2	2
Russia	5.8	2
Spain	5.3	2
Taiwan	4.3	1
96 other countries	62.2	18
World total	330.7	100

Table 1.3 World production of paper and board (10^6 t).

	1950	1960	1970	1980	1990	2000	2002
Europe	13.194	25.826	45.377	59.495	65.873	100.065	101.290
East	2.840	5.765	10.560	14.103	3.538	11.257	12.780
West	10.354	20.061	34.817	45.392	62.335	88.808	88.510
North America	28.286	39.393	56.323	71.179	87.985	106.603	100.949
United States	22.108	31.255	45.186	57.789	71.519	85.832	80.871
Canada	6.178	8.138	11.137	13.390	16.466	20.771	20.078
Japan	0.873	4.513	12.973	18.087	28.086	31.828	30.033
China	0.511	1.914	3.750	5.100	13.719	30.900	37.800
Others	0.876	3.279	11.264	18.257	43.142	54.585	60.632
World	43.740	74.925	129.687	172.118	238.805	323.981	330.704

Table 1.4 World production of paper and board by region (%).

	1950	1960	1970	1980	1990	2000	2002
Europe	30.1	34.5	35.0	34.6	27.6	30.9	30.6
East	6.5	7.7	8.1	8.2	1.5	3.5	3.9
West	23.6	26.8	26.9	26.4	26.1	27.4	26.8
North America	64.7	52.6	43.4	41.3	36.8	32.9	30.5
United States	50.5	41.7	34.8	33.6	29.9	26.5	24.5
Canada	14.2	10.9	8.6	7.7	6.9	6.4	6.1
Japan	2.0	6.0	10.0	10.5	11.8	9.8	9.0
China	1.1	2.6	2.9	3.0	5.7	9.5	11.4
Others	2.1	4.3	8.7	10.6	18.1	16.9	18.3
World	100.0	100.0	100.0	100.0	100.0	100.0	100.0

13% in 1980, and to 30% in 2002. At the same time, the circle of paper producing countries has widened considerably from 61 to 111 and now includes a large number of developing countries. In these countries, the tendency towards self sufficiency is influenced by national economic considerations and the need to save foreign exchange for paper imports (Table 1.2).

In 2002, Europe, North America, Japan and China produced 82% of the total world production (Table 1.3). However, the development in these regions has varied considerably. China's paper production has increased more than threefold since 1980 and it is now the second largest paper producer in the world. In Japan, the paper industry has developed from a low during the postwar years to become the third largest paper producer. In the last four or five decades, Western Europe has more or less been able to maintain its share of world production. North America has had to accept large losses of its share of production, which has, however, been increasing relatively constantly (Table 1.4).

In 2002 graphic papers accounted for 43% of total paper production. This included newsprint (37×10^6 t) and other printing and writing papers (104×10^6 t). The production of packaging papers was 153×10^6 t, and that of the remaining papers and boards was 37×10^6 t (Table 1.5).

At present, a nearly one-third (100:330) of the world production of paper and board is sold across borders. In 2002 exports and imports accounted for about 100×10^6 t.

The net imports to the United States, i.e. imports minus exports, amount to 7.3×10^6 t which corresponds to a quota of 8% (based on the consumption). In contrast, Canada with its comparatively low population, has net exports amounting to 12×10^6 t which is 60% of its paper production. The major part of Canadian exports goes to the United States. Western Europe with 9.5×10^6 t, a quota of 11%

Table 1.5 World production of paper and board, arranged according to main types (2002).

Paper and board type	Production, 10^6 t	Share, %
Newsprint	37	11
Other printing and writing papers	104	32
Packaging papers and boards	153	46
Other papers and boards	37	11
Total	331	100

(based on the internal production) is a net exporter. Western Europe as a whole has more than 380×10^6 consumers and is the largest market in the world.

In Japan the amounts imported and exported balance out at ca. 1.5×10^6 t. China is a net importer with 4.8×10^6 t, a quota of 11%. Of the remaining regions, the countries in Africa and Asia are the largest net importers. The imports and exports of South and Central America are roughly balanced.

World consumption of paper and board in 2002 was 331×10^6 t. The United States has by far the highest consumption of all countries, followed by China and Japan. Germany is the fourth largest consumer, above the United Kingdom (Table 1.6).

Looking at the world paper consumption from a geographical point of view, it is apparent that the industrial countries of Western Europe, North America, and Japan not only produce but also consume the bulk of the paper (Table 1.7).

There is also a relatively rapid increase in the consumption of paper in the remaining regions, especially in Asian countries such as China, South Korea and Taiwan, which are becoming increasingly important for the international paper market. In the past 40 years, countries in South and Central America as well as in Eastern Europe and Africa have increased their share of world paper consumption annually. Improvements in the living conditions in these regions have been accompanied by a corresponding increase in the consumption of paper. The rise in both the standard of living and the individual income is as important a prerequisite as the spread of literacy for the consumption of writing paper and printing products. Another important factor is the build up of export and consumer industries with their demand for packaging materials.

The amount of paper consumed, however, is not an adequate measure of the standard of living of a country. The relative per capita consumption can only give a very rough indication of the living standard because other factors such as the average income, way of life, and consumer patterns must also be taken into consideration. In terms of paper consumption, the countries can be grouped according to their per capita consumption. For example, while the average consumption in Western Europe is 204 kg and in North America 280 kg, the per capita consumption in Eastern European countries is 36 kg, in Latin America 33 kg, and in

Table 1.6 World paper and board consumption by country, 2002.

Country	Consumption, 10^6 t	Share, %
United States	88.1	27
China	42.6	13
Japan	30.0	9
Germany	18.2	6
UK	12.4	4
Italy	10.9	3
France	10.8	3
South Korea	8.1	3
Canada	7.7	2
Spain	6.9	2
Brazil	6.8	2
Taiwan	4.6	1
Russia	3.8	1
Australia	3.6	1
The Netherlands	3.5	1
186 other countries	72.7	22
World total	330.7	100

Africa only 7 kg. Paper consumption per inhabitant is less than 1 kg in about 25 developing countries.

A comparison between population and paper consumption in different regions shows that Asia, which represents 60% of the world population, accounted for only 34% of world paper consumption. Conversely, North America has 5% of the world's population but a consumption of 29% (Table 1.8). An important indicator for the development of paper consumption is not only the gross national product but also the population growth (Table 1.7).

World population has more than doubled from 2.5×10^9 in 1950 to 6.2×10^9 in 2002. The per capita consumption of paper worldwide was 18 kg in 1950 and 53 kg in 2002, an increase of 294%. Thus the relative consumption of paper per capita has increased considerably faster than the world population. It is obvious that these average global values do not reflect the substantial regional differences.

In summary, the largest growth percentage potential for paper consumption is in the Third World countries, especially in Asia and Eastern Europe, while in-

Table 1.7 World paper and board consumption by region (%).

Region	1950	1960	1970	1980	1990	2000	2002
Europe	27.3	33.6	34.7	33.9	26.4	28.3	27.5
East	6.3	7.7	8.3	8.5	1.4	3.1	3.6
West	21.0	25.9	26.4	25.4	25.0	25.2	23.9
North America	64.2	50.9	43.4	38.4	35.2	31.0	29.0
United States	60.6	47.7	40.7	35.8	32.8	28.6	26.6
Canada	3.6	3.2	2.7	2.6	2.4	2.4	2.4
Japan	2.0	5.8	9.8	10.5	11.9	9.8	9.1
China	1.1	2.4	2.6	2.9	6.1	11.4	12.9
Others	5.4	7.3	9.5	14.3	20.4	19.5	21.5
World	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 1.8 Population and paper consumption by region (2002).

Region	Population		Paper consumption	
	$\times 10^6$	%	10^6 t	%
Europe	729	12	91	28
Africa	878	14	6	2
North America	312	5	96	29
Central and South America	529	8	19	6
Asia	3706	60	114	34
Australia/Oceania	30	1	4	1
World	6184	100	330	100

dustrialized countries such as the United States, Japan, and the Western European countries have relatively low growth rates, but still represent, in absolute terms, a considerable market potential.

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2
Raw Materials for Paper and Board Manufacture

2.1
Fibrous Materials

2.1.1
Overview
Jürgen Blechschmidt

Paper production is mainly based on fibrous raw material which may consist of primary or secondary fibers. Primary fibers are obtained directly from plant raw materials, mainly from wood and annual non-wood plants. Industrially, mostly thinnings and sawmill wastes are used. Secondary fibers are produced from recovered paper. Rags are used only in very small amounts. Synthetic and mineral fibers do not play an important role.

As its name indicates, chemical pulp is obtained by chemical pulping from wood or annual non-wood plants, mechanical pulp is produced by mechanical defibration of wood. Worldwide, wood is 90% of the raw material source. The use of annual non-wood plants is especially suitable for regions with low wood resources, larger areas that are not used for agriculture and larger surpluses of agricultural remains (e.g. straw). Fiber production from non-wood plants is more expensive and causes more environmental pollution than that from wood. Chemical pulp from jute, flax, hemp, sisal and bagasse are suitable for special paper grades (e.g. filtration papers, lightweight printing papers). In tropical and subtropical countries, fiber wood is grown mainly in plantations.

In chemical pulp production yields of 45 to 55% are obtained. The yield in mechanical pulp production is about 80 to 95%. Compared with chemical pulp, about twice as much mechanical pulp can be obtained from the same amount of wood. Additionally, dissolved substances in chemical pulping charge the water circuits and effluents much more and have to be processed with high expenses. Mechanical pulping is an energy intensive process. 1.3 to 3 MWh t^{-1} are consumed, depending on the product (paper grade) and the process design. During chemical pulp production, energy is produced by burning black liquor. A modern kraft mill can deliver a power surplus of about 30 MW.

Handbook of Paper and Board. H. Holik (Ed.)

ISBN: 3-527-30997-7

Table 2.1 Development of consumption of pulps and paper worldwide (according to: Jaakko Pöyry, World Paper Markets up to 2010).

	1980		**1990**		**2000**		**2010**	
	10^6 t	**%**	**10^6 t**	**%**	**10^6 t**	**%**	**10^6 t**	**%**
Recovered paper	60		100		160		195	
Recovered paper processed (90 %)	54	31	90	37	144	45	176	44
Chemical pulp	93	54	120	50	145	46	180	46
Mechanical pulp	25	15	30	13	30	9	40	10
Pulps total	172		240		319		396	
Paper and board total	171		240		320		422	
Ratio chemical pulp/mechanical pulp	3.7		4.0		4.8		4.5	

Before the invention of the mechanical and chemical pulping processes in the 19th century, rags (used textiles) were the only raw fiber source. The development of the worldwide use of fibrous raw material since 1980 is shown in Table 2.1. In the next ten years, the worldwide consumption of pulp fibers is expected to be 46 % for chemical pulp, 10 % for mechanical pulp and 44 % for recycled paper pulp.

2.1.2
Chemical Pulp
Sabine Heinemann

Chemical pulp is produced by chemical pulping of vegetable raw materials such as not only hardwood and softwood, but also from straw from different kinds of cereals, bagasse, reed, or esparto grass, and from other annual non-wood plants.

During chemical pulping, the most of the lignin is removed from the raw material. The yield of the pulp is therefore only 45 to 55 %. Two main industrial processes of chemical pulping are used:

- The sulfate process with sulfate pulp as product
- The sulfite process with sulfite pulp as product.

The alkaline sulfate process uses sodium sulfide and sodium hydroxide as pulping chemicals. The acidic sulfite process is based on calcium, magnesium, and sodium or ammonium bisulfide. Worldwide, the sulfate process is used in up to 90 % of cases.

The lignin content that remains in the pulp after the pulping process can be further reduced by bleaching. The development of bleaching agents with zero chlorine or low chlorine content like oxygen, hydrogen peroxide or ozone leads to a higher residual lignin content in the so-called TCF (total chlorine free) and ECF (elementary chlorine free) pulps compared with the conventionally bleached pulps.

The quality of pulp depends on the kind of wood used. Softwood pulps have longer fibers, resulting in higher strength, whereas hardwood pulps with shorter fibers for instance produce a more uniform sheet. Paper containing only chemical pulp as the fiber component is called wood-free paper, i. e. it has only a low residual lignin content.

Sulfate pulps have distinctly higher strength than sulfite pulps, especially if they are unbleached. That is why unbleached sulfate pulps are mostly used in papers with high strength demand such as corrugated board, packaging papers, or technical papers. Highly bleached pulps are used in high-quality printing papers.

The dominant process of semi-chemical pulping is the neutral sulfite semi-chemical process (NSSC), with sodium or ammonium sulfite as the digestion chemicals. The pulp yield is in the range 70–80 % depending on the wood species, most commonly hardwood species like birch, beech, maple, oak and eucalyptus. This pulp is used for fluting production – often as the sole component in furnish.

2.1.3
Mechanical Pulp

Mechanical pulp is produced from wood by mechanical defibration. Different processes are in use:

- Stone groundwood (SGW) is produced by the mechanical defibration of round wood logs by a grinding stone.
- Refiner mechanical pulp (RMP) is obtained by mechanical defibration of woodchips in a refiner and is carried out without pre-treatment. Defibration takes place under atmospheric pressure. The wood chips are defibrated at temperatures of about 100 °C, mostly in two stages with consistencies of 20 to 30 % in the second stage.
- In the refiner process with thermal pre-treatment (TMP), wood chips are treated with steam at 110 °C to 130 °C for 2 to 5 min before they are defibrated under high pressure.
- In the refiner process with chemical pre-treatment (CTMP/CMP), wood chips are impregnated with chemicals before they are mechanically defibrated in the refiner under high pressure of about 3 bar or at atmospheric pressure, mainly in two stages.

The CTMP and CMP processes differ in the intensity of the chemical treatment and the yield. The yield of softwood CTMP is about 91 % to 96 %. CMP is more heavily chemically treated and therefore has more the character of a chemical pulp, i. e. higher strength properties at a cost of lower light-scattering coefficient (see Table 2.2). For hardwood, the yield of CMP can decrease to 80 %.

During mechanical defibration, lignin is plasticized and remains in the pulp. This is the reason for the lower strength properties but higher light-scattering

Table 2.2 Characteristics of mechanical, chemimechanical and chemical pulps.

Pulp type		**Mechanical pulp**				**Semi-chemical pulp**	**Chemical pulp**
		SGW	**TMP**	**CTMP**	**CMP**		
Yield	%	97	95	90		80 70 60	40
biological oxygen demand (BOD)	kg t^{-1}	10	20		50 100		200
grinding or refining energy	kWh t^{-1}	1200	2200	2500	1000	500 200	100
freeness CSF	ml	100	120	200	400	600	800
tensile index	Nm g^{-1}	30	40	50 60	70	80	100
light-scattering coefficient	m^2 kg^{-1}	65	60	50	40		30

coefficient and opacity compared to chemical pulp. The residual lignin in mechanical pulps results in a poorer and less stable brightness level. Mechanical pulps cannot be brightened by oxidative and reductive bleaching to the same extent as chemical pulps as only negligible delignification takes place compared to the bleaching of chemical pulp.

Paper grades that contain pulp produced by mechanical or chemimechanical processes are referred to as wood-containing papers. Mechanical pulps are mainly used in short-life printing papers, hygienic papers and board.

A comparison of some of the main characteristics of chemical and mechanical pulps: yield, BOD (biological oxygen demand), grinding or refining energy (in the case of chemical pulp for final pulp preparation), freeness, tensile index and light scattering coefficient, is given in Table 2.2. The yield decreases from 97% for SGW to 40% for chemical pulp (kraft type) and the effluent impact increases i.e. the biological oxygen demand increases. Specific energy consumption is lower for conventional chemical pulps than for chemimechanical pulps but chemical consumption is higher.

Freeness is measured as about 100 ml for (fines-containing) stone groundwood (SGW) and 780 ml for chemical pulp with high long-fiber content.

Chemical pulps have a higher strength potential (tensile index) but lower light scattering ability.

Light scattering values are given for the pulp before undergoing additional mechanical treatment. Post-refining of mechanical pulp increases the light scattering coefficient whereas refining of chemical pulp decreases this property.

2.1.4

Recovered Paper, Recycled Fibers

Hans-Joachim Putz

2.1.4.1 Role of Recovered Paper in the Paper and Board Industry

In the past chemical pulp was the most important raw material for paper production, but now this has been replaced by recovered paper. 158 million tons of this raw material were used globally in 2002. This volume exceeds the total volume of woodpulp, i.e. chemical pulp (117 million tons) and mechanical pulp (36 million tons) [1]. These figures show that recycled fibers play a very important role today in the global paper industry as a substitute for virgin fiber pulps.

Figure 2.1 shows the global increase in recovered paper usage, compared to paper production since 1961. Globally the use of recovered paper increased by approximately 5.8% annually whereas annual paper production growth was only 3.6%.

The paper industry is the exclusive relevant user of recovered paper as a secondary raw material – at least in terms of material recycling. Various recovered paper processing systems with mechanical and chemical unit processes prepare recycled fibers for the production of paper and board grades. These processing systems use different recovered paper grades that contain either chemical or mechanical fibers or, mainly, an undefined mixture of both. Some paper and board grades can be made from recycled fibers exclusively. This includes paper grades such as corrugating medium and testliner or newsprint in Europe. For newsprint and other grades blends of recycled and virgin fibers are also used. The proportion of recycled fibers

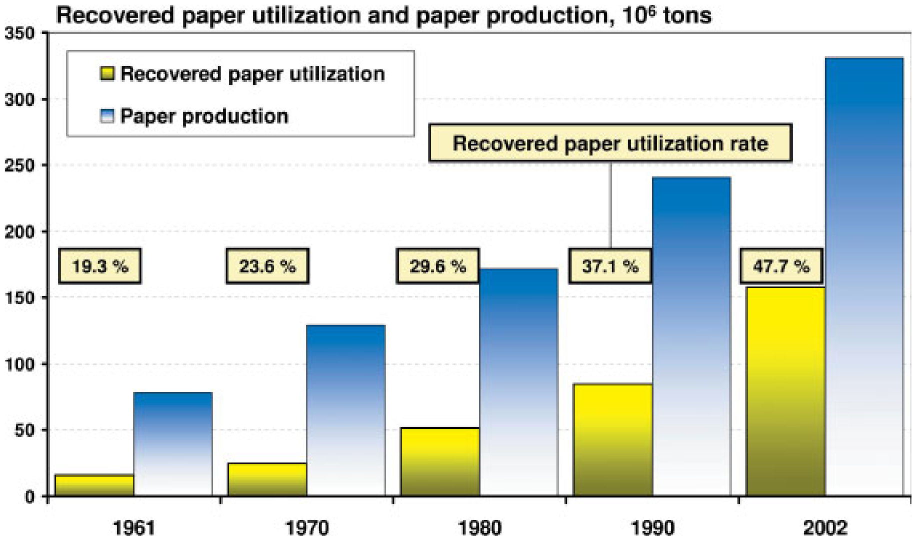


Fig. 2.1 Global development of recovered paper utilization and paper production (1961–2002) [1–5].

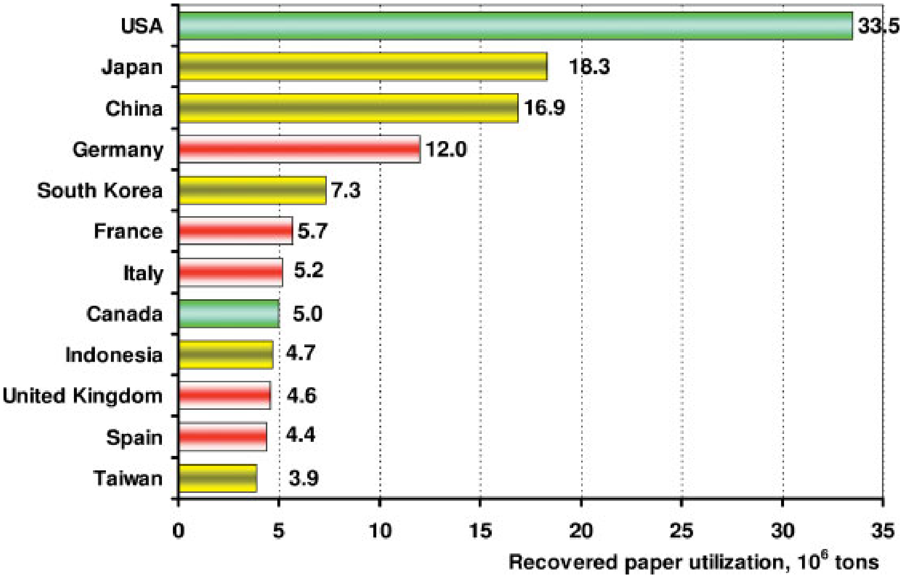


Fig. 2.2 The 12 largest recovered paper consuming countries in the world (2002) [1].

in the raw material furnish can vary from about 5% for fine papers to 100% depending on the paper grade or geographic region.

Figure 2.2 shows the largest recovered paper consuming countries. They used in total 122 million tons in 2002 corresponding to 77% of the global recovered paper consumption.

2.1.4.2 Main Definitions for Statistics

Consideration of recovered paper use and recovery of used paper products requires definitions. Statistical definitions can be related to the world, a continent, a country or a certain region (e.g. Europe) or to a certain category of paper products (e.g. graphic papers or newsprint). Differentiation is given by three statistical parameters:

- Recovered paper utilization rate, in percent, is the amount of recovered paper used as raw material in the paper industry, in tons, divided by paper production, in tons, on an annual basis, multiplied by 100.
- Recovery or collection rate, in percent, is the amount of collected recovered paper for material recycling, in tons, divided by paper consumption, in tons, on an annual basis, multiplied by 100.
- Recycling rate, in percent, is the amount of recovered paper used as raw material in the paper industry, in tons, divided by paper consumption, in tons, on an annual basis, multiplied by 100.

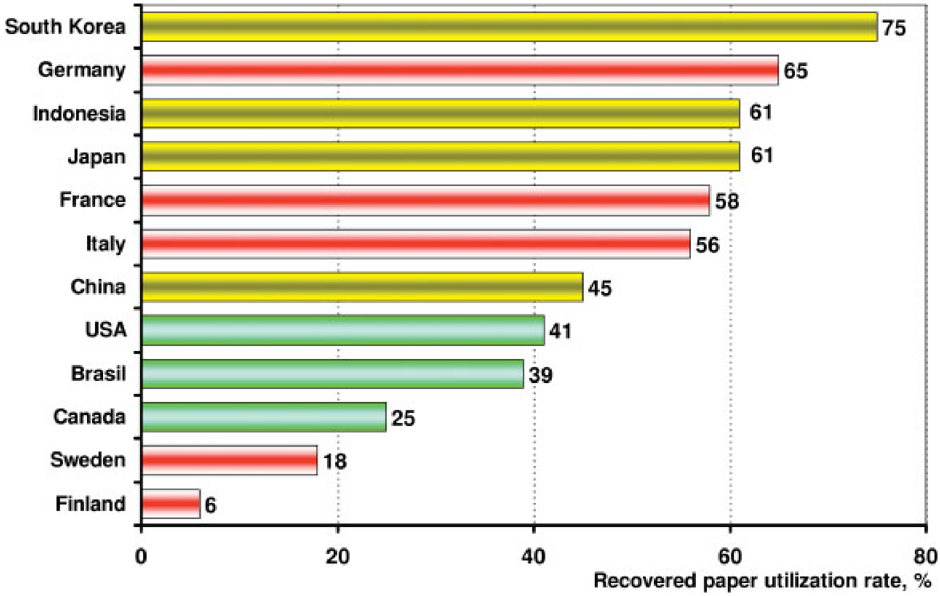
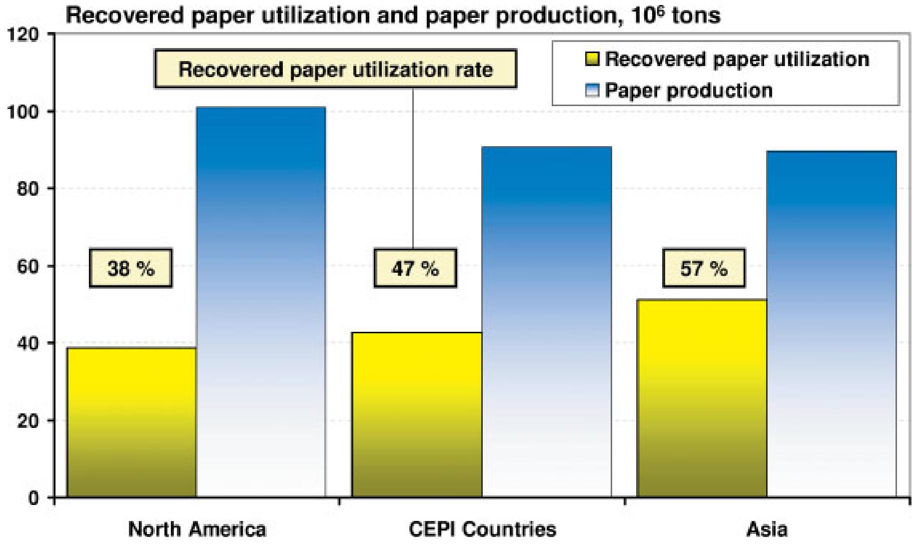


Fig. 2.3 Utilization rates of recovered paper of the 12 largest papermaking countries in the world (2002) [1].

From these definitions it becomes obvious that the utilization rate is related to recovered paper usage in paper production, whereas the recovery rate is related to the amount of collected paper related to paper consumption. Both rates can be affected directly either by the paper industry by the use of more or less recovered paper in paper production or by the waste management industry collecting more or less recovered paper from the paper consumed. The recycling rate is a more theoretical value putting recovered paper usage in relation to paper consumption. A high level of recovered paper usage in paper production combined with strong net paper export rates will result in a high recycling rate, which has to be satisfied by recovered paper imports from abroad.

Recovered paper utilization rates globally and nationally may be used for comparison. Such statistics can give, however, a false impression of the recycling activities in different countries as the following discussion explains. The range of national utilization rates extends globally from 5% to more than 100%. Figure 2.3 shows the 12 largest papermaking countries, accounting for almost 80% of the global paper production in 2002 of 331 million tons. Simultaneously, they consumed about three quarters of the world's recovered paper volume. Heading the list are South Korea, Germany, Indonesia and Japan with utilization rates above 61%. The lowest utilization rates are for Finland and Sweden. This is because more than 80% of their paper production is exported due to their low population figures and related low level of national paper consumption.



[1] CEPI countries are all EU countries plus the Czech Republic, Hungary, Norway, the Slovak Republic and Switzerland.

Fig. 2.4 Recovered paper utilization rate and paper production in Asia, the CEPI countries[1] and North America (2002) [1].

Figure 2.4 shows the utilization rate for the three largest paper production regions in the world where the paper industry uses 85% of the global recovered paper volume: Asia, Europe and North America. Paper production in these three regions is between 90 and 100 million tons each, resulting in recovered paper utilization rates of roughly 57% in Asia, 47% in Europe and 38% in North America.

2.1.4.3 Utilization Rates for Different Paper Grades

Utilization rates for different countries should not be compared without further comment. It is important to know the structure of the production program of the different national paper industries in the main product categories of packaging papers and board, graphic papers, household and hygiene papers as well as specialty papers because the utilization rates for these product segments differ significantly.

In Fig. 2.5 for the CEPI countries the recovered paper utilization by the main paper categories is presented and additionally the utilization rates are given. The *x*-axis is a summarizing ordinate representing the total paper production in the CEPI countries of 91 million tons, subdivided into the production of the various paper categories. The broader a single paper category, the larger the paper production (for example, the biggest category, with 34 million tons, is other graphic papers). For each paper product category (e.g. newsprint) the used recovered paper

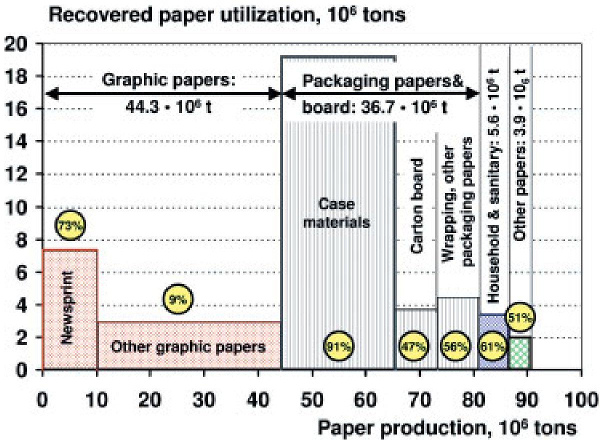


Fig. 2.5 Recovered paper utilization by paper grades in the CEPI countries (2002) [6].

volume is shown on the *y*-axis. In the circles the corresponding recovered paper utilization rate is given. It becomes obvious that the highest volume of recovered paper is used in the production of case materials (19.2 million tons). The second highest recovered paper utilization rate of 73% is in newsprint with a volume of 7.4 million tons. In the other paper categories between 2.0 and 4.4 million tons of recovered paper are used, resulting in recovered paper utilization rates between 9% and 61%.

Traditionally, packaging papers and board have the highest recovered paper utilization rate. In the CEPI countries this ratio has reached almost 75%. Demanding quality specifications have to be fulfilled by these recycled fiber-based paper and board grades to ensure trouble-free converting, for example, to corrugated board boxes or folding boxes and adequate functional characteristics of the finished products. Occupying second place is the utilization rate of household and hygiene papers (61%). Due to high yield losses in the flotation and washing steps, the proportion of recycled fibers in hygiene paper is not higher than 40% on average. The figure of 40% deinked pulp comes from about 60% yield of about 65% utilization rate. The group of other papers, comprising gypsum liners, special papers for waxing, insulating and roofing, achieve a 51% utilization rate in the CEPI countries, but there are also many specialty paper grades such as cigarette paper, filter paper, or banknote paper which never can use recycled fibers.

Finally, the level of the utilization rate for graphic papers is only 23%. Due to the wide spectrum of the paper grades produced, a distinction is necessary for this product segment because newsprint has reached a level of 73%. The utilization rate of the other graphic papers averages only 9%. Included among these other graphic papers are wood-containing and woodfree papers that are coated or uncoated. Some use 100% recycled fiber furnish, e.g. recycling copy papers.

2.1.4.4 Resources of Recovered Paper

Before using recovered paper for paper production its recovery is necessary. Resources of recovered paper are in general collection from industrial enterprises (e. g. printing houses), business operations (e.g supermarkets) or offices and from private households and small commercial enterprises. Whereas the recovery of used paper from industry, business operations and offices has a long history and can be easily managed, recovery of used paper from private households is more complex. Additional recovered paper resources cannot be expected in the first category, because these paper grades mainly belong to the so-called "pre-consumer" grades, are of high quality and are already almost 100 % recovered. Collected paper from private households is "post-consumer" recovered paper which is usually mixed and always requires a sorting process.

As far as national recycling activities are concerned, an assessment of the paper recovery rates of different countries is more relevant than a comparison between national recovered paper utilization rates. Figure 2.6 shows the collection rates vs. the utilization rates of recovered paper in the CEPI countries. The bubble size is equivalent to the tonnage of recovered paper used in each country. Due to intensified collection in each country the average rose from 41 % in 1991 to 56 %, corresponding to a total volume of recovered paper of 46 million tons in 2002. It becomes obvious that the highest collection rates in the CEPI countries are by Germany, Switzerland, the Netherlands, Norway, Sweden and Austria, whereas the highest utilization rates are reached in Ireland, Denmark, Spain, Greece, the United Kingdom and Hungary. The largest tonnages of recovered paper are used in Germany, France, Italy, the United Kingdom and Spain.

The maximum paper recovery rate in an industrialized country with a well-developed infrastructure is about 80 % [7]. This theoretical limit of the recovery rate

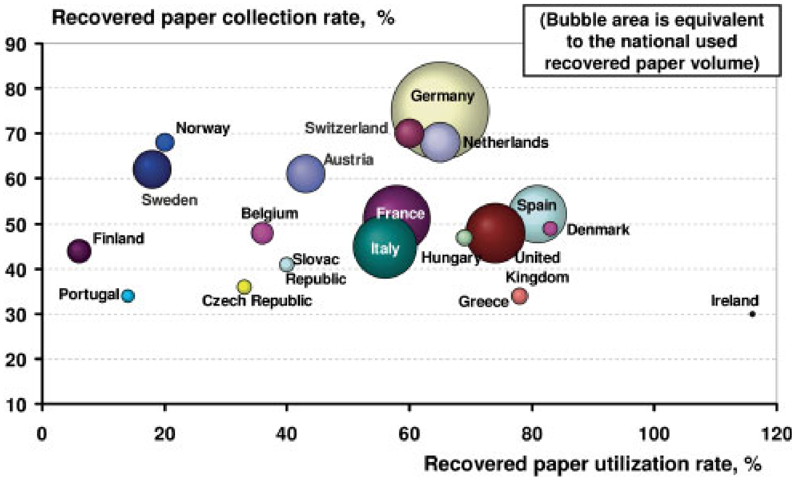


Fig. 2.6 Recovered paper utilization and collection rates vs. utilization rate in CEPI countries (2002) [1].

occurs since approximately 20% of the used paper products are not collectible, because they are contaminated, long living products or are destroyed by disposal or burning. This includes hygiene paper, specialty paper products, long-life paper products, papers used in industrial applications, and papers used for other purposes in private homes such as fuel or compost material. Considering the theoretical recovery rate of 80%, the recovery rate of 75% already achieved in 2002 in Germany is equivalent to a paper collection efficiency of about 94%. Collecting additional used paper is probably not economically feasible.

At the global level, no data are available for the different sources of collection systems of recovered paper by tonnage. In Europe, CEPI has conducted recovered paper surveys which found, for 2002, the following five sources of recovered paper:

- Recovered paper from households: 38%
- Recovered paper from trade and industry: 33%
- Recovered paper from converting and printing: 15%
- Recovered paper from offices: 10%
- Recovered paper from unsold newspapers and magazines: 4%.

The recycling rate was introduced by CEPI for the first time as the relation between recovered paper utilization and paper and board consumption. Related to the consumption of paper and board the figure indicates the internal material recycling of recovered paper in a country or a region, so long as no net import of recovered paper occurs. Nevertheless, recycling rates close to 100% indicate that either a large amount of recovered paper is imported or a high volume of produced paper and board is exported. Figure 2.7 shows the development of the recycling rates in the CEPI countries from 1991 with an increase of 2.2% p. a. until 2002, when it was approaching 52.7% and it should reach 56% in 2005, far from the theoretical or practical limit.

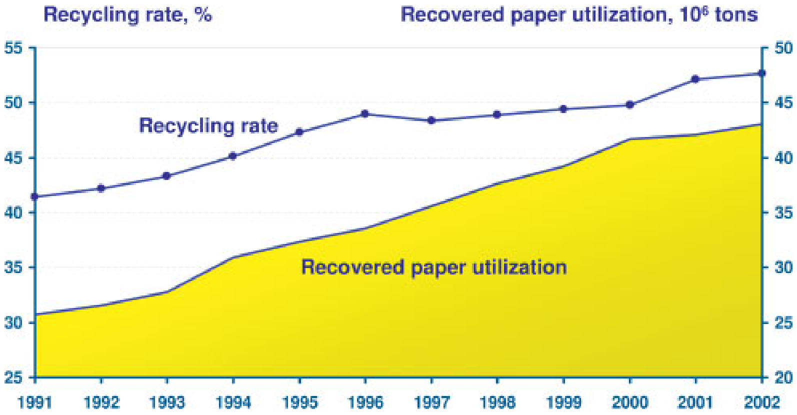


Fig. 2.7 Development of recycling rate and recovered paper utilization in the CEPI countries (1991–2002) [6].

2.1.4.5 **Lists for Recovered Paper Grades**

Globally no common list of recovered paper grades exists. A European Standard was established in 2001 by CEN (European Committee for Standardization) as EN 643 for Europe [8]. All recovered paper grades are classified into the following five groups:

- Ordinary grades
- Medium grades
- High grades
- Kraft grades
- Special grades.

Recovered paper grades are generally not defined by physically verifiable quality characteristics. Instead, the naming of recovered paper in the list uses one of the following criteria:

- Places of occurrence, such as supermarket corrugated paper and board (1.04)
- Former paper grades of which the recovered paper consists, such as mixed magazines and newspapers (1.10)
- Mixed categories such as mixed sorted papers and boards (1.02).

Globally and in Europe, the use of deinked pulp (DIP) in newsprint dominates (55%–65%), followed by hygiene papers (20%–15%) and printing and writing papers (about 12%). Therefore, another very important paper grade in Europe describes a wood-containing recovered paper mix, commonly used for deinking. It is called "Sorted graphic paper for deinking" (1.11) and originates primarily from household collections.

The complete list of recovered paper grades is published in the Annex of Volume I and is available also on the website of GesPaRec (www.altpapier-rohstoff.de).

Recovered paper grade lists are not comparable between Europe, USA and Asia. Therefore recovered paper grades are summarized very often in the following four groups:

- Mixed grades: comprising always a mixture of various paper and board grades used for the production of packaging paper and board.
- Corrugated and kraft grades: comprising predominantly packaging paper and board grades used for the production of packaging paper and board. The term OCC is also very often used for this recovered paper grade and stands for "old corrugated containers".
- Deinking grades: comprising exclusively graphic paper grades used – after a deinking process – predominantly for the production of graphic and tissue papers.
- High grades: comprising predominantly white lightly printed graphic papers and board (very often woodfree), recovered by separate collection and therefore relatively clean.

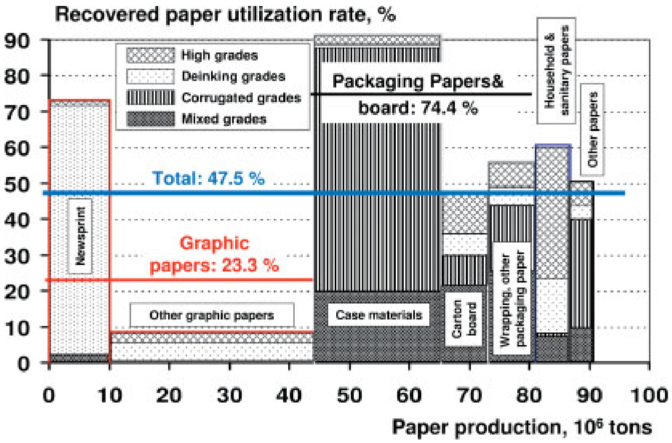


Fig. 2.8 Recovered paper utilization by grade in the CEPI countries (2002) [6].

2.1.4.6 Use of Recovered Paper Grades

Figure 2.8 shows that the use of recovered paper in paper production in the CEPI countries varies greatly by grade of recovered paper. In 2002, the consumption of recovered paper of all CEPI countries was as follows:

- 41% OCC grades
- 26% Deinking grades
- 20% Mixed grades
- 13% High grades.

Whereas mixed grades and OCC grades (91% by weight) primarily find use in the production of packaging papers and board, the majority of all deinking grades (80% by weight) go to graphic paper production. These recovered paper grades are also used for household and sanitary papers with the addition of nearly two-third high grades. The production of other papers requires various proportions of all four recovered paper grade groups.

The total amount of 43 million tons of recovered paper was used:

- 45% for the production of case materials
- 17% for newsprint production
- 10% for wrappings and other packaging papers
- 9% for carton boards
- 8% for household and sanitary papers
- 7% for other graphic papers
- 4% for other paper grades.

The individual paper grades need specific recovered paper grades as raw materials. Thus collection and sorting of these resources has to be done in such a way as to satisfy the needs of the paper industry.

2.2
Non-fiber Raw Material

2.2.1
Pigments as Fillers
Maximilian Laufmann

Mineral fillers have long been used in papermaking. While they can be found in different paper and board grades, printing and writing papers represent by far the most dominant area for their application. Initially, they were added to increase the weight of the sheet and to improve the writing properties. Today, there are several further functional reasons for the use of fillers in printing and writing papers.

2.2.1.1 Why Use Fillers?

Fillers are applied to the paper mainly

- to improve the optical properties, such as brightness and opacity
- to improve the smoothness of the sheet surface (i. e. decreased roughness, especially after calendering)
- to improve the sheet formation by filling the voids between the fiber matrix
- to enhance printability in the various printing processes due to a more uniform paper surface, higher opacity and better ink receptivity. The latter resulting in reduced printing ink penetration, wicking and ink strike-through to the opposite side of the sheet
- to improve the dimensional stability of the paper as most fillers remain inert when wetted, unlike the natural fibers usually used in papermaking.
- to improve the permanence of the paper (alkaline papermaking, calciumcarbonate ($CaCO_3$) filler)

As regular mineral fillers are, in general, lower in price than typical papermaking fibers, replacing fiber by mineral fillers usually provides better papermaking economics. Therefore, efforts are made to include as much filler in the paper as the technological demands can support.

The amount of filler (loading) in the paper has of course a strong impact on the sheet properties obtained. Figure 2.9 shows the influence of increased filler loading on some important paper properties. The results shown are based on a pilot study, using natural ground calcium carbonate (GCC) as filler in a wood-free fiber furnish. The basis weight was 80 g m^{-2}. In general, the influence of the filler at increased loading is magnified in both directions, desired and undesired. In particular the main location and distribution of the filler in the sheet has a major influence on the end performance. In the final sheet, the effect of a filler is dependent not only on the intrinsic properties of the filler particles, but also on the extrinsic influence of the filler on the fiber network. This includes for example the disruption of the fiber network by the filler.

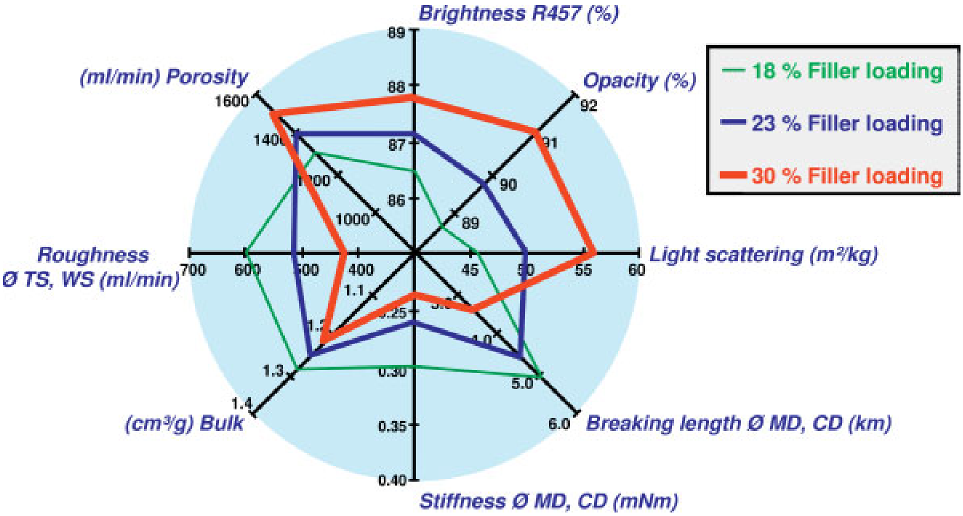


Fig. 2.9 Impact of filler loading degree on some important paper properties (pilot study, GCC as filler, wood-free furnish, 80 g m^{-2}) (source: OMYA).

The limits in terms of filler loading are set primarily by an accompanying reduction in stiffness and insufficient strength properties (tensile strength, tear resistance, internal bond and surface strength). Sufficient surface strength is particularly important in offset printing or, for example, in copier machines. Inadequately fixed filler on the paper surface can result in dusting (blanket piling) in the offset printing process or contamination of the copy machine. Typical filler loading levels in different European paper grades are given in Table 2.3.

Overall, the wood-free uncoated paper grades mentioned are loaded mostly with primary (fresh) filler only. The coating base papers are filled with coating pigment

Table 2.3 Typical filler loading levels in European printing and writing paper.

Paper	Filler loading (%)
wood-free uncoated (copy, stationery, offset)	12–26
wood-free coating base (single, double, triple coated)	12–20
wood-containing uncoated (super calendered, magazine, catalogues)	24–38
wood-containing coating base (LWC, MWC, HWC)	8–12
newsprint	2–18

coming from the coated paper broke plus some primary filler. The wood-containing uncoated papers can contain recycled pigment (originating from the use of recycled fiber furnish) plus primary filler or just 100% primary filler. Today newsprint is often made from recycled fibers, sometimes combined with virgin fibers. Newsprint, made from recycled fibers, contains substantial amounts of recycled pigment and, if sensible and possible, also some fresh filler, reaching up to 18% total filler loading. Newsprint paper based on virgin fiber only, carries almost no filler in the paper. However, more recently, virgin fiber newsprint paper can be found in the paper market, loaded with up to 12% chalk as filler.

Additionally worth mentioning is a development which increases the filler loading level effectively through the paper surface. GCC filler is added to the film press starch solution and penetrates together with the starch into the sheet. Thereby the wet end system is not affected at all and, at moderate loading increase, paper stiffness and strength are also unaffected. Paper caliper and bulk are reduced as in a conventional internal filler loading increase. Porosity is dramatically reduced by this method, allowing potentially also for some reduction in fiber refining [1]. Developments, in which the filler is preferentially positioned at specific locations in the *z*-direction of the sheet are also at a very early stage. Turning such concepts into practice will require new technologies and quite significant investment [2].

2.2.1.2 **Choice of Fillers**

The choice of fillers usually takes into consideration primarily the desired performance in a specific paper grade, the mill internal situation, logistical possibilities and consequences, the general availability of the product, and the costs, including the external and internal logistics.

Optimizing one type of filler for a specific paper grade usually results in a compromise between the obtainable properties with this filler. In cases where one single pigment does not meet all the requirements, filler combinations are applied. There is a continuous trend towards fully or partially replacing specialty pigments by regular or modified regular fillers. Table 2.4 provides an overview of the range of regular fillers and specialty pigments applied in the production of certain paper grades.

Of great importance are the potential interactions of the fillers with wet end furnish components like retention aids, starch, sizing agents, dyes etc. Therefore, the selection of the filler type and grade needs also to be made in the light of these possible interactions.

2.2.1.3 **Characterization of Fillers**

Chemical composition, particle morphology, particle size and particle size distribution, brightness, refractive index, specific surface, particle charge and abrasiveness are commonly used to characterize papermaking fillers. Table 2.5 summarizes some chemical and physical data of fillers and fibers. More detailed information is given in the following paragraphs.

Table 2.4 Paper grades and range of fillers and/or specialty pigments applied.

Paper grade	Filler/specialty pigment
wood-free uncoated (copy, stationery, offset)	PCC, GCC, PCC/GCC, talc/GCC (Asia only), amorphous silicate, calcined clay
wood-free coating base (single, double, triple coated)	GCC, PCC
wood-containing uncoated (super calendered, magazine, catalogues)	clay, clay/GCC, clay/PCC, recycled pigment/clay/GCC or PCC calcined clay, amorphous silicate
wood-containing coating base (LWC, MWC, HWC)	GCC, Talc, PCC
Newsprint/Directory	Recycled pigment, GCC, PCC, amorphous silicate, calcined clay, (TiO_2)
high opaques (thin print)	TiO_2, Zinc sulfide, PCC, amorphous silicate calcined clay
decoration paper	TiO_2, TiO_2/Talc, TiO_2/calcined clay or silicate
cigarette paper	PCC
white top liner	GCC, PCC, calcined clay

2.2.1.3.1 Brightness

Tappi brightness is measured at a wavelength of 457 nm. Fillers with high pigment brightness, like GCC or PCC, are in demand for the production of high quality printing and writing papers. Figure 2.10 compares the Tappi brightness of various fillers of different geographical origin as well as of highly bleached chemical and

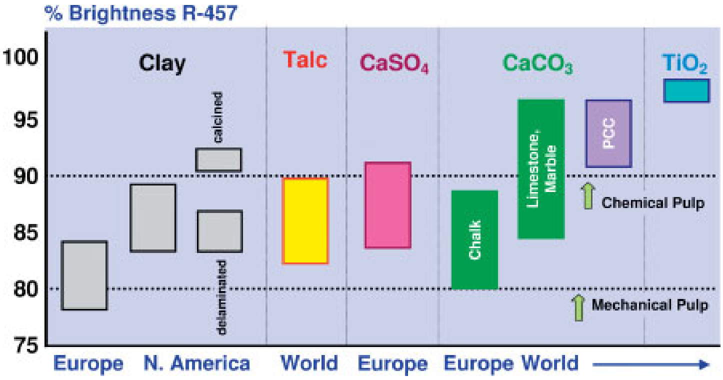


Fig. 2.10 Brightness (Tappi R-457) of various paper fillers and highly bleached mechanical and chemical pulp (source: OMYA).

Table 2.5 Characteristic chemical and physical data of regular fillers and specialty pigments.

Filler	Chemical composition	Crystal habit	Morphology	ISO Brightness %	Refractive index	Density g cm^{-3}	Specific surface m^2 g^{-1}
kaolin hydrous	$Al_4(OH)_8\ (Si_4O_{10})$	hexagonal (1:1 layer silicate)	hexagonal platelets	70–90	1.56	2.8	10–25
calcium carbonate	$CaCO_3$	trigonal					
– natural			rhombohedral scalenohedral aragonite rhombohedral	80–96	1.58	2.7	2–12
– precipitated			prismatic all forms can occur discretely, clustered or agglomerated	92–97	1.56	2.7	4–12
talc	$Mg_3(OH_2)\ (Si_4O_{10})$	hexagonal (2:1 layer silicate)	hexagonal patelets	70–88	1.57	2.7	5–20
gypsum	$CaSO_4$	monoclinic	needles	88–98	1.54	2.8	2–5
titanium dioxide rutile, anatase	TiO_2	tetragonal	isomorphic (round particles)	97–99	2.76/2.55	4.2/3.8	8–12
calcined clay	Al_2O_3/SiO_2	hexagonal (1:1 layer silicate)	fused platelets	89–93	1.56	2.7	15–25
synthetic, precipitated silicate, silica	mostly Al or Mg/ Ca-Silicates	mostly amorphous	irregular composite	93–96	1.55	2.1	40–70
aluminum, trihydrate, hydrated alumina	$Al(OH)_3/$ $Al_2O_3xH_2O$	gel, pseudohexagonal (pseudo boehmite)	irregular composite, hexagonal platelets	96–98	1.58	2.4	5–9
cellulose				90	1.60		
air					1.00		
fibers						ca. 0.7	1–2
fiber fines							6–8

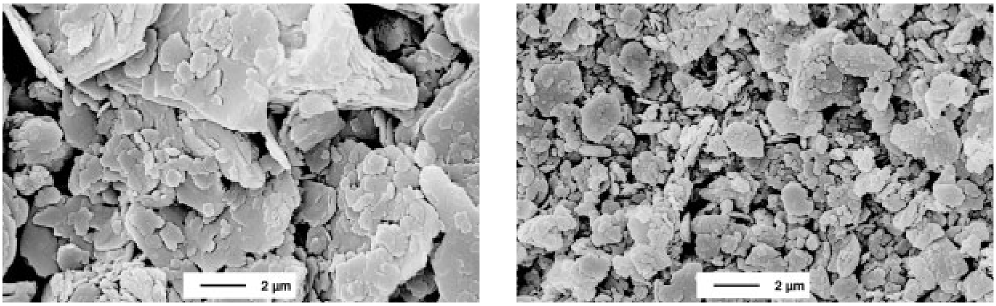
mechanical pulps (dotted lines). The brightness range of the different types of filler is given by the raw material quality used and the various processes (mechanical classification, magnetic separation, flotation, grinding, bleaching, precipitation etc.) applied.

2.2.1.3.2 **Refractive Index**

The refractive index indicates the extent to which a light beam is deflected when passing from vacuum into a given substance. The refractive index is given by the filler's chemical composition and molecular structure. Powders are usually measured in a refractive index matching liquid. The material, ground into a fine powder, is immersed in a series of liquids until scattering and reflectance disappear, i.e. the material becomes invisible. Of course the powder should not be soluble in the liquid. It can be tested either using a laser beam or by studying the turbidity with the eye or a turbidimetric method. The more the particles differ from the medium (i.e. the more their refractive indices differ), the more light will be scattered by the particles. If there is no difference at all, no light will be scattered. However, as calcium carbonate is birefringent (double refraction), the method described is not ideally suitable for this specific mineral. The higher the refractive index developed in the paper, the higher the amount of reflected and/or scattered light, which results in an increase in paper opacity. While titanium dioxide TiO_2 shows an extraordinarily high refractive index (rutile 2.75, anatase 2.55), other common fillers exhibit indices of around 1.55–1.65 (zinc sulfide 2.39). For comparison, the refractive index of cellulose, as used in papermaking, is about 1.60.

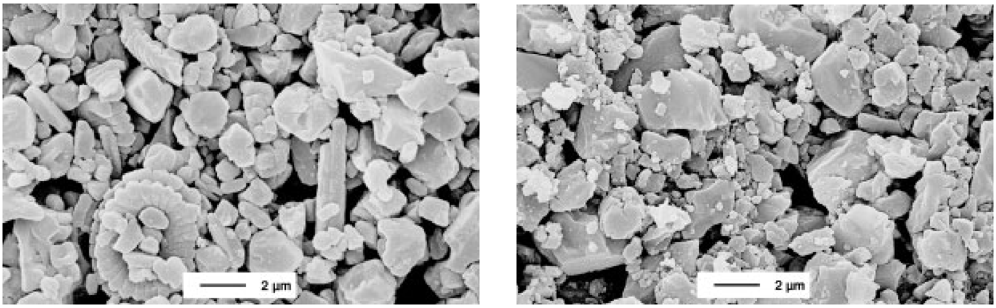
2.2.1.3.3 **Particle Morphology**

The structure of a filler can be observed and characterized best by scanning electron microscopy (SEM). The particle morphology has an influence on light scattering via the number and size of air microvoids in the sheet. For different morphologies, there is a different optimum for light scattering in terms of particle size. The particle morphology has an impact also on the packing of the filler particles in flocculates usually formed during the papermaking process. The results are morphology related differences in sheet drainage, drying behavior, and in paper properties such as bulk, porosity, ink receptivity, strength, dusting, etc. The sheet surface roughness and paper gloss after calendering, as well as the sheet compressibility (important in rotogravure printing) are also influenced by the morphology of the filler or specialty pigment applied. Figure 2.11 shows SEM pictures of various typical fillers and specialty pigments currently applied in the paper industry.



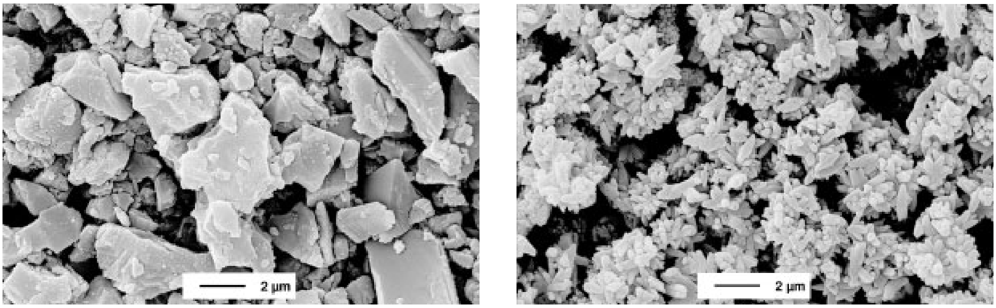
a Kaolin (hydrous, primary deposit) Europe, United Kingdom

b kaolin (hydrous, secondary deposit) North America, Georgia



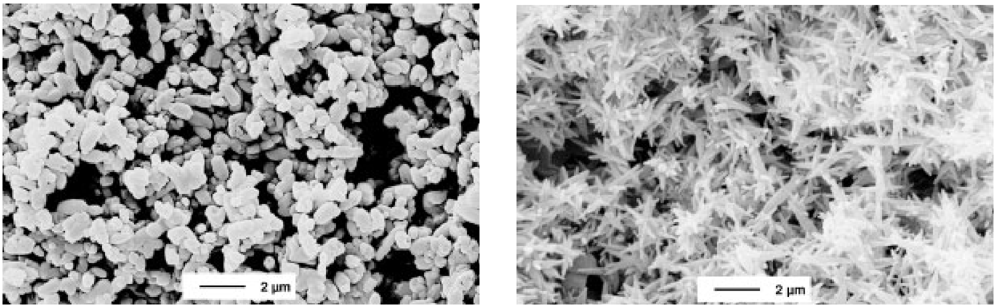
c natural ground calcium carbonate – chalk

d natural ground calcium carbonate – limestone



e natural ground calcium carbonate – marble

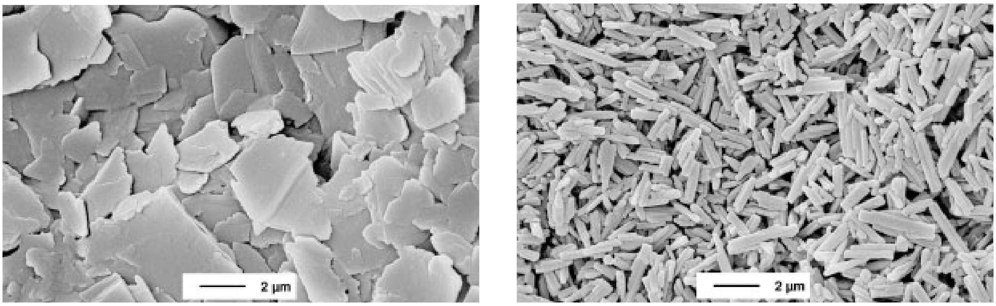
f precipitated calcium carbonate – calenohedral, clustered



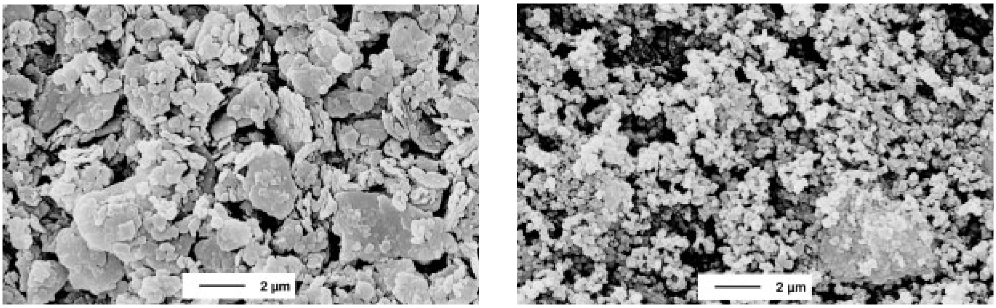
g precipitated calcium carbonate – hombohedral, clustered

h precipitated calcium carbonate – ragonite, clustered

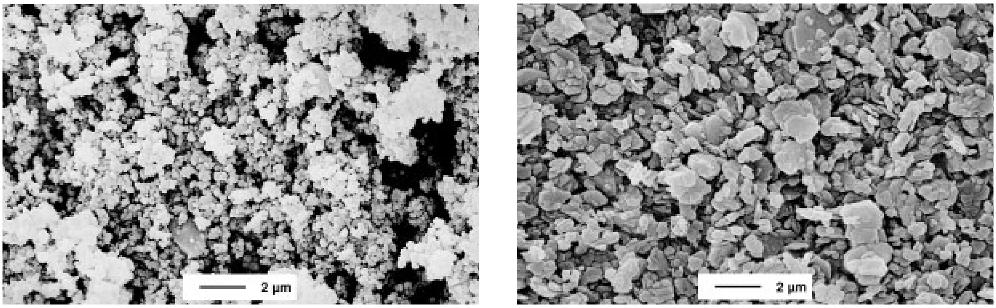
Fig. 2.11 Scanning electron microscope pictures of regular fillers and specialty pigments for paper. Main fillers: a–j, specialty pigments k–n.



i talc, Europe, Finland **j** gypsum (calcium sulfate)



k Calcined clay **l** titanum dioxide



m Mg-Al-silicate **n** aluminum trihydrate

Fig. 2.11 Scanning electron microscope pictures of regular fillers and specialty pigments for paper. Main fillers: a–j, specialty pigments k–n.

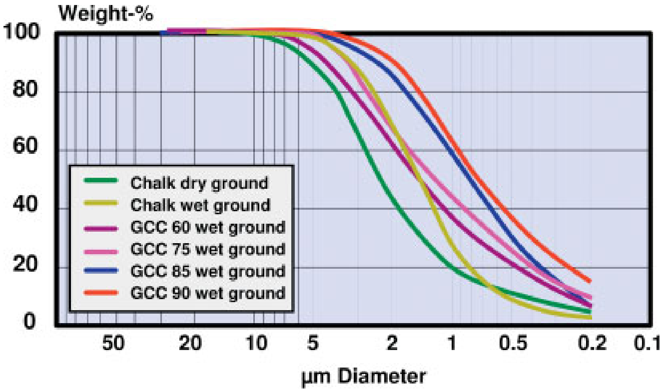


Fig. 2.12 Typical particle size distribution curves of GCC fillers (sedigraph method) (source: OMYA).

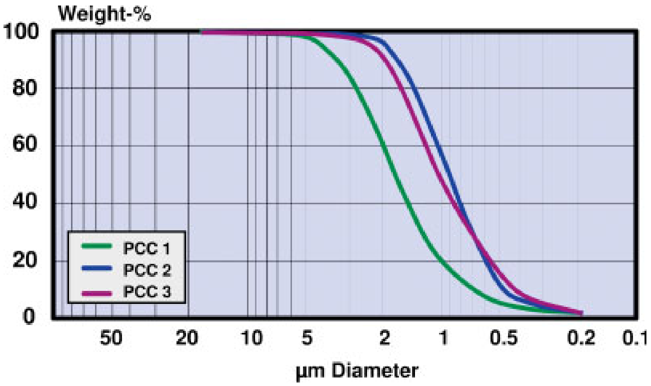


Fig. 2.13 Typical particle size distribution curves of PCC fillers (sedigraph method) (source: OMYA).

2.2.1.3.4 Particle Size and Particle Size Distribution

There are different methods (sedimentation, laser scattering/diffraction etc.) to determine the particle size distribution of a filler. However, the results obtained by the different methods are usually not directly comparable. Even comparing pigments with very different morphology by just one single method, does not provide correctly comparable particle size distribution curves. The sample preparation (state of dispersion) also has a great influence on the outcome of the individual measurement. Figures 2.12 and 2.13 show some typical particle size distribution curves (measured by the sedigraph method) of GCC and PCC based fillers.

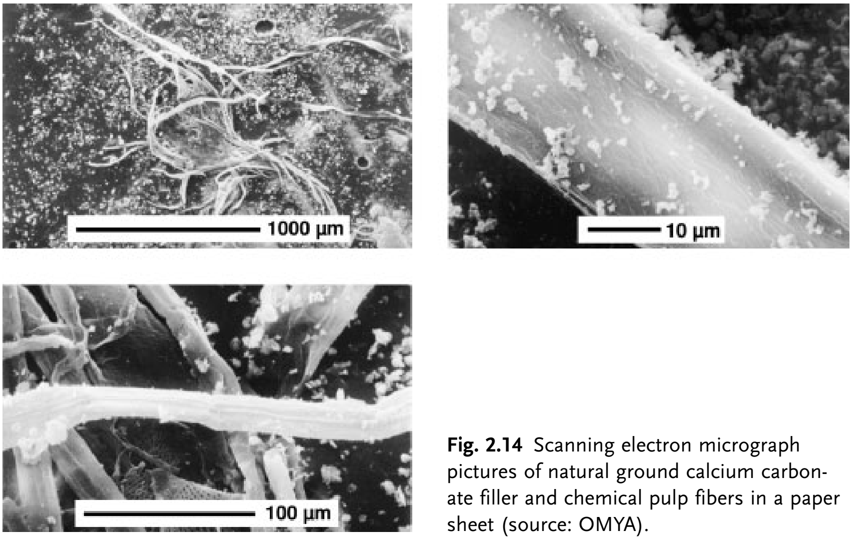


Fig. 2.14 Scanning electron micrograph pictures of natural ground calcium carbonate filler and chemical pulp fibers in a paper sheet (source: OMYA).

Figure 2.14 indicates the size relation between the GCC filler particles and the fibers in the sheet. As is clearly demonstrated, the filler particles are much finer than the fiber and, in particular, much smaller than the voids between the fibers.

In the papermaking process, most of the original filler particles form agglomerates or flocculates, by addition of different flocculating wet end additives. The degree of flocculation can be optimized by careful handling of the wet end chemistry. To obtain a highly uniform sheet, any excessive flocculation, of course, needs to be avoided.

In general the optical properties provided by a filler are also strongly influenced by its particle size and particle size distribution. Finer fillers, within limits, as well

Table 2.6 Light scattering ($m^2\ kg^{-1}$) of major fillers, specialty pigments and virgin pulps.

Material	**Light scattering ($m^2\ kg^{-1}$)**
kaolin hydrous	70–120
GCC	140–190
PCC	210–270
calcined clay	200–300
titanium dioxide	450–650
silicates/silica	280–340
chemical pulp	20–45
mechanical pulp	50–70

as steeper particle size distribution curves (more particles of similar optimum size) produce more light scattering, hence more opacity. Table 2.6 gives some typical light scattering ranges for major fillers, specialty pigments and also, for comparison, for some virgin pulps. However, finer fillers exhibit a more negative impact on paper strength properties than relatively coarse pigments of the same weight proportion. Non-platy large particles tend to be released out of the paper surface more easily than smaller particles resulting in, for example, more blanket piling in the offset printing process or the contamination of a copy machine.

2.2.1.3.5 **Specific Surface Area**

Usually the specific surface area is measured by the nitrogen-adsorption method (BET: *B*runauer, *E*mmet, *T*eller). The particle fineness, the particle size distribution and the particle morphology are, depending on the structure, indirectly reflected in the specific surface area of a filler. Finer nonstructured fillers exhibit a higher specific surface than coarser ones. There is a general direct correlation of the specific surface area of a filler and, for example, the internal sizing agent demand. Internal sizing agent is applied to the wet end in order to make the paper more hydrophobic. The specific surface area of regular paper fillers ranges between 4 and 12 $m^2\ g^{-1}$. Typical papermaking fibers exhibit a specific surface area between 1 and 2 $m^2\ g^{-1}$, while fiber fines show specific surface areas of 6–8 $m^2\ g^{-1}$. As one consequence, increasing the filler loading level usually significantly increases the additive demand, i. e. sizing agent, dyes etc. Specialty pigments applied as filler can reach specific surface areas as high as 70–80 $m^2\ g^{-1}$.

2.2.1.3.6 **Particle Charge**

The fillers applied need to be understood as part of the rather complex wet end chemistry in the papermaking process. The electrostatic charge (zeta potential), which surrounds the pigment, can be anionic or cationic. Depending on the type of filler, its origin, the specific chemicals applied in the production process and the dispersing treatment, the charge density can be on a quite different level. To obtain a good stabilization of a filler slurry, the dispersant applied needs to be highly charged. Typically the salts of polyacrylic acid are applied for this purpose of electrostatic stabilization as these provide the pigment surface with a distinct anionic charge. Low molecular weight and high charge density polydadmac, modified polyethylenimine or polyvinlyamine etc. can be used, for example, to develop a distinct cationic slurry stabilization.

The charge density of a filler slurry is of particular importance in the context of selecting the most suitable retention aid system. Today there are many retention systems available and the most suitable one has to be found for each individual filler application. The ordered addition of multi-polymer retention aid systems and, in particular, so-called microparticle systems offers efficient tools to retain anionic stabilized filler pigments at high production speeds effectively. Cationically charged, partly self-retaining, fillers are no longer much in use, one reason being

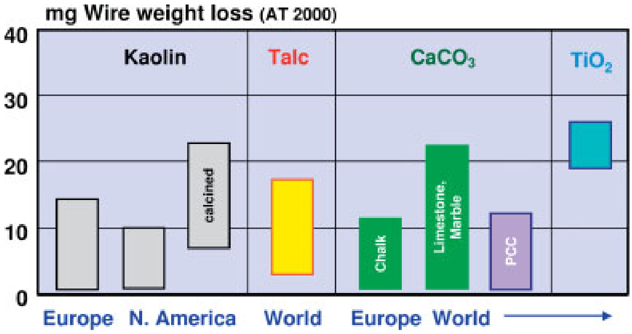


Fig. 2.15 Indicative abrasion ranges of various paper fillers (measured by laboratory (source: OMYA), method Einlehner AT 2000).

the potential for quenching the commonly applied negatively charged optical brightening agents.

5.2.1.3.7 **Abrasiveness**

The abrasion potential of fillers is influenced by the particle structure, the particle fineness and the particle hardness. Relatively coarse platy pigments tend to be less abrasive than non-platy ones of similar size. Increasing the filler fineness decreases the wire abrasion potential significantly. This is particularly pronounced when testing non-platy pigments. Large size non-platy impurities such as quartz increase the wire abrasion excessively. Any pigment which is harder than the synthetic wire, commonly installed in the paper machine, potentially initiates wear on the wire.

There are different laboratory methods of determining the potential abrasiveness of a filler. The most modern unit is the Einlehner AT 2000 abrasion tester. This instrument works by using a cylindrical ceramic body with specific slots and a wire made of synthetic filament. Figure 2.15 compares different paper fillers on a global basis by this specific method. Again, because of differences in the raw material used, the processes applied and the differences in particle fineness, abrasion ranges are presented as being indicative only.

Practical experience collected in recent years has shown, that wire abrasion is greatly influenced also by the conditions on the paper machine. In general, lower filler retention potentially increases wire wear. The wire drag load should be minimized, for example, by a low number of stationary drainage elements and optimized low vacuum loads. The dry suction box ceramic surfaces should display a low surface porosity and should be well maintained [3].

2.2.1.4 **Main Mineral Fillers**

The main mineral fillers (in terms of quantity applied) are kaolin (hydrous), GCC, PCC and talc.

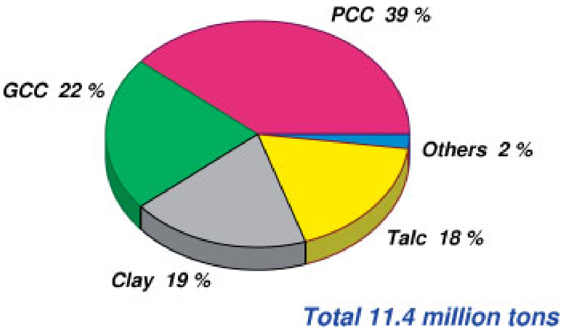


Fig. 2.16 Global paper filler (kaolin, GCC, PCC, talc and others) consumption in 2004 (source: OMYA).

Figure 2.16 depicts the global consumption of the different main types of virgin fillers applied in papermaking. The data refer to the market situation in the year 2004. The share given for talc includes the use of talc as filler as well as its application as a pitch control agent. Globally in 2004, the paper industry consumed 29 million tons of pigment for coating and filling. As indicated in Figure 2.16, for filling purposes alone, 11.4 million metric tonnes were used.

With the use of recovered paper in papermaking (e.g. for newsprint, SC-B, board, etc.) a substantial amount of secondary pigment is transferred into the new paper. This recycled pigment also acts as a filler. However, as the pigment is mostly agglomerated and the composition varies by nature, the resulting impact on paper quality is somewhat inconsistent. Recycled pigment cannot meet the quality and the range of functionality, as provided by the specifically designed virgin fillers.

2.2.1.4.1 **Kaolin (hydrous)**

This is used today predominantly in wood-containing uncoated papers (super calendered magazine papers, catalogues etc.) [4]. Kaolin deposits can be found at a number of major sites around the globe as a result of metamorphosis granite outcrops. The largest ones, from which paper fillers are extracted, are located on the South East coast of the United States (mainly secondary deposits) and in Cornwall in the South West of the United Kingdom (primary deposits). Primary kaolins are those which are found at the places where they were originally formed and are accompanied by the original matrix including partially altered and residual materials. Secondary kaolins have been moved from their place of origin and by progressive sedimentation become deposited at a different location. Other kaolin deposits of commercial interest occur in Russia, Central Europe (Czech Republic, Germany, France, Spain) (all primary), Australia (secondary), China (primary, secondary) and Brazil (secondary). Due to the presence of a very high ratio of kaolin, exploiting a secondary deposit source requires less processing than drawing from a primary deposit.

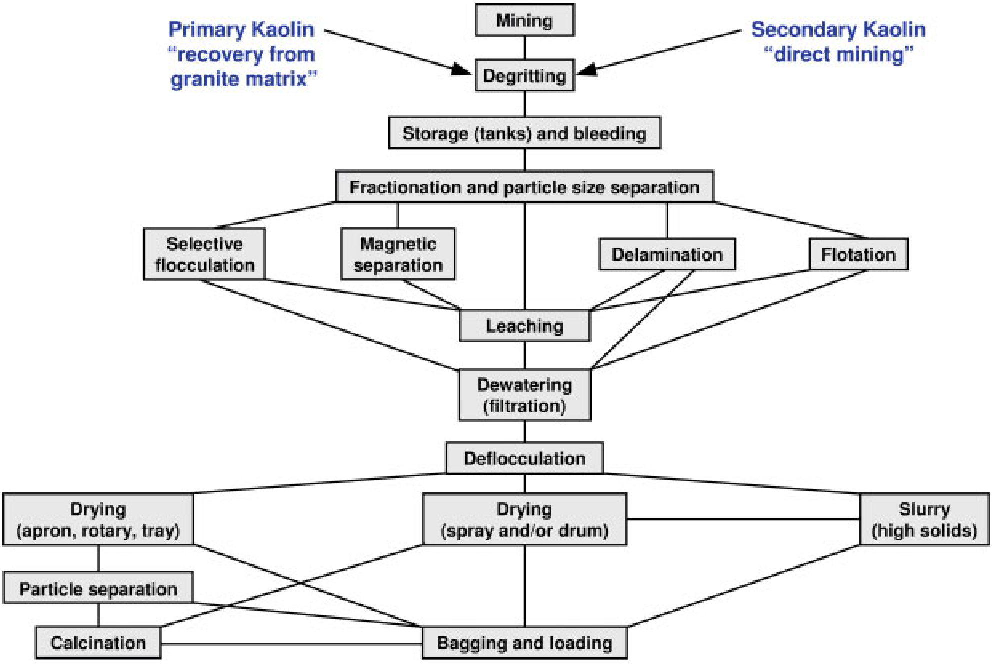


Fig. 2.17 Flow sheet for the wet processing of kaolin (source: H. Murray).

Kaolin processing involves purification of the kaolin-containing raw material by several techniques including mechanical classification, grinding, bleaching, magnetic separation and flotation. Kaolin is supplied as a slurry or dried in powder form (spray dried or in crumbles). Figure 2.17 shows a generalized flow sheet for the wet processing of kaolin, based on primary and secondary deposits.

The aspect ratio or platyness of kaolin is strongly dependent on the geophysical nature of the deposit. The aspect ratio expresses the relationship of the major diameter to the platelet caliper. Secondary kaolins tend to be of lower aspect ratio; some Brazilian examples, however, are exceptions to this rule. Primary Cornish kaolin, for instance, has an aspect ratio of 25–40:1, compared to Georgian kaolin with an aspect ratio of 12–25:1). The aspect ratio distribution throughout the various size ranges is also an important attribute of kaolin, with the presence of bentonite or montmorillonite at the fine end of the particle size distribution being a particular feature of some clays. The hexagonal crystalline platelets of kaolin produce a high gloss of the finished paper after calendering. This gloss development also depends on the degree of delamination, i.e. the extent to which the platelet agglomerates or stacks are broken into individual platelets. Due to its chemical composition, kaolin can be used as a filler in both acid and alkaline papermaking environments.

The brightness of regular filler kaolin is distinctly lower than most $CaCO_3$ based fillers. For this reason, in recent decades, kaolin has been largely replaced globally by $CaCO_3$ fillers in wood-free uncoated papers. Due to the continued growth of the higher brightness SC paper market (super calendered uncoated magazine paper, catalogues etc.), kaolin is being increasingly combined with or replaced by high brightness calcium carbonate based fillers in this area.

2.2.1.4.2 **Natural Ground Calcium Carbonate (GCC)**

This is predominantly applied in wood-free uncoated paper, mechanical uncoated papers (usually in combination with kaolin), coating base papers, newsprint and white top liner board.

Natural $CaCO_3$ constitutes the most frequently occurring type of sedimentary rock on our planet. It covers about 1% of the earth's crust. Natural $CaCO_3$ occurs in three major geological modifications. Chalk was and is formed in the oceans through biomineralization and the reactions of calcium salts with the CO_2 in the air. By geological transformation (pressure) and thermal metamorphosis (heat and pressure), it is modified into limestone and marble.

Natural $CaCO_3$ for the paper industry is processed at numerous locations around the globe: for example, in North America (Vermont, Canada, British Columbia, Alabama), in Europe (Norway, Finland, France, Spain, Germany, Austria, Italy, Turkey), in the Far East (South Korea, Taiwan, Indonesia), in Australia and New Zealand. In addition there are active plants located in Latin America (Mexico, Chile, Brazil), Russia, China and South Africa [5].

GCC fillers are produced by pre-washing the raw material, followed by grinding, fine grinding and screening the product. Undesired impurities in the raw material are removed by magnetic separation and flotation. Figure 2.18 shows a typical production process flowchart for GCC fillers, based on limestone or marble raw material.

The production, shipping and application of GCC fillers in wet (slurry) form has become by far the most preferred practice. GCC filler slurries exhibit a solids content of 65–72% (by weight) and are usually stabilized by using an anionic grinding and dispersing agent. Specifically, cationically stabilized GCC filler products are also available.

The structure of GCC filler is rhombohedral. Because of the high brightness demand, GCC fillers based on limestone and marble are preferred by the paper industry. Lower brightness chalk is increasingly used as a filler in the production of regular newsprint, where there is less demand for brightness. The fineness of GCC fillers for paper is generally much greater than kaolin based fillers, particularly those sourced from primary kaolin deposits. This is required, for example, for obtaining high light scattering, low abrasiveness and low dusting out of the paper surface in the printing process.

$CaCO_3$ is soluble under acid conditions, and therefore requires a near-neutral or slightly alkaline pH papermaking environment [6]. To be able to use $CaCO_3$ as a filler and/or as a coating pigment, numerous paper and board mills around the globe have converted their wet end systems from acid to neutral and slightly alkaline pH. Historically, paper was mostly produced at acid pH (< pH 7). Paper pro-

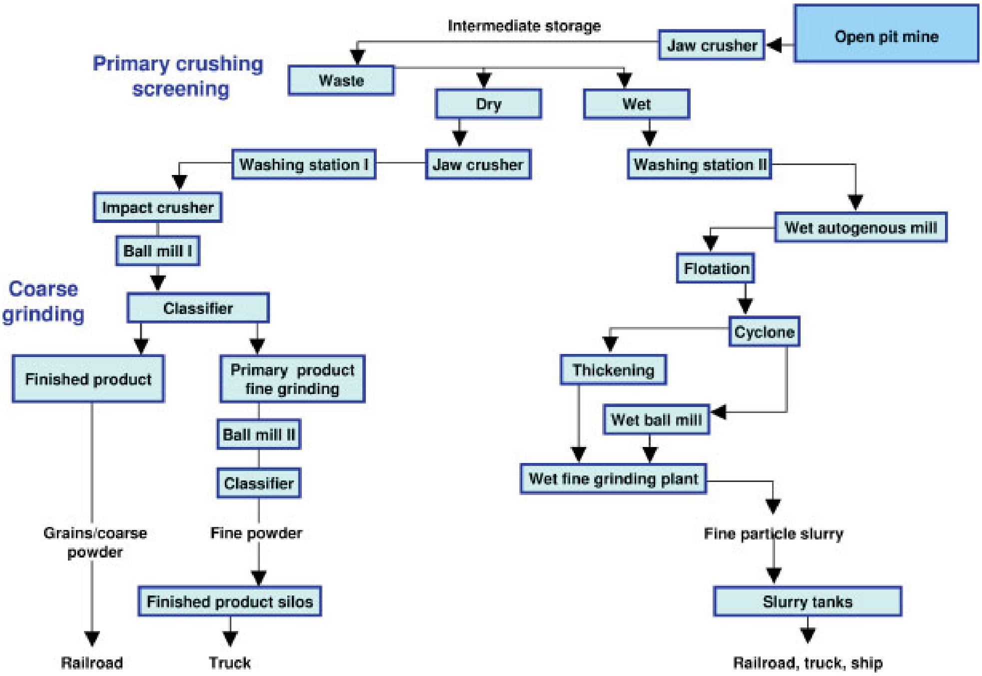


Fig. 2.18 Flow sheet for the processing of natural ground calcium carbonate (source: OMYA).

duced in such a manner decomposes relatively quickly and therefore presents a serious problem for the conservation of documents in libraries etc. Complicated and expensive measures are applied to save valuable documentation printed, unfortunately, on acid made paper. Wood-free paper, produced in the slightly alkaline mode and containing some $CaCO_3$ filler for buffering, exhibits a dramatically im-

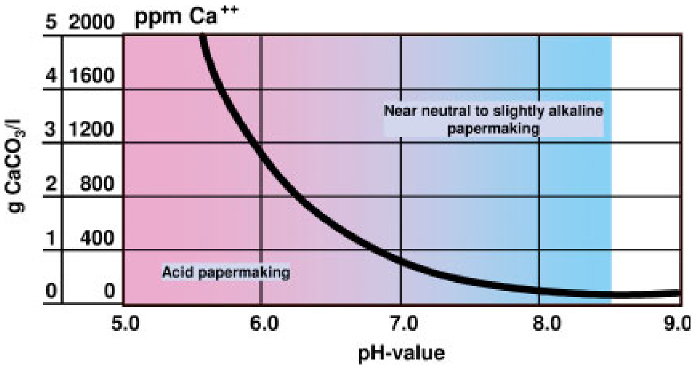


Fig. 2.19 Solubility of calcium carbonate ($CaCO_3$) versus pH of the environment (source: OMYA).

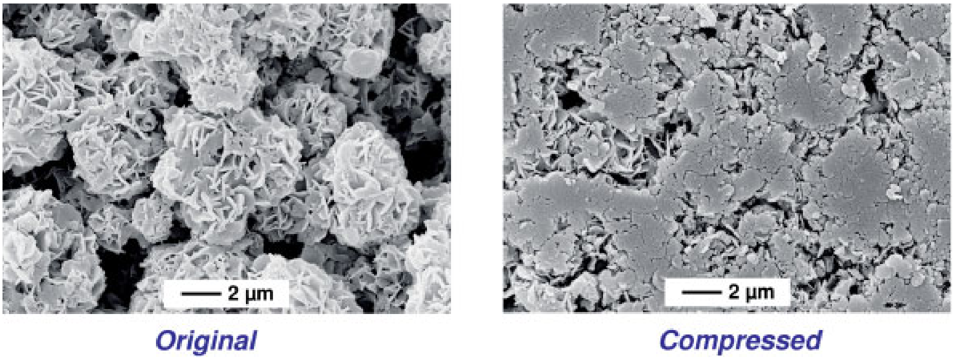


Fig. 2.20 Modified ground calcium carbonate in its original state and after compressing (source: OMYA).

proved permanence and can be stored for hundreds of years under regular conditions. Figure 2.19 depicts the solubility of $CaCO_3$ relative to the pH of the environment.

2.2.1.4.3 Modified Natural Ground Calcium Carbonate (GCC)

In a more recent development, finely ground GCC has been specifically modified into a pigment with a completely different morphology and consequently different properties. Figure 2.20 shows modified GCC particles in their original state and after compressing (calendering). It should be mentioned that the modified GCC also exhibits an extraordinarily high specific surface area of up to 80 $m^2\,g^{-1}$ BET. Providing high brightness, easy gloss development and good printability in offset and rotogravure, this modified GCC has already found its way into the commercial production of SC (super calendered) paper. As specialty pigment, it is applied in conjunction with regular $CaCO_3$ fillers [7].

2.2.1.4.4 Precipitated Calcium Carbonate (PCC)

This is also predominantly applied in wood-free uncoated paper, wood-containing uncoated paper (in combination with kaolin), wood-free coating base paper, directory grades and white top linerboard [8]. In order to control porosity and burning rate, PCC is also widely used as a filler in the manufacture of cigarette paper.

One very important raw material for the production of PCC is a suitable deposit of natural $CaCO_3$. Only rather few limestone deposits meet the stringent demands for the production of high quality PCC. Carefully selected limestone is calcined at 800–900 °C to obtain calcium oxide (CaO or quicklime), requiring energy and releasing CO_2. The quality and uniformity in quality of the lime used has an immense influence on the quality of the final PCC product. The addition of water (exothermic reaction) produces calcium hydroxide ($Ca(OH)_2$ or slaked milk of

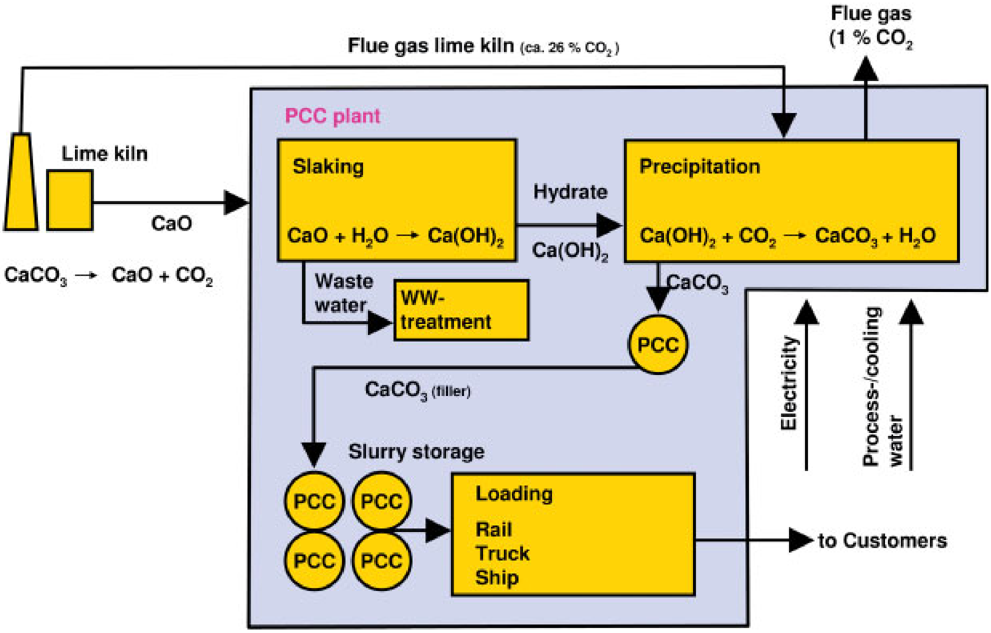


Fig. 2.21 Flow sheet for the production of precipitated calcium carbonate (source: OMYA).

lime). The usually applied carbonation process consists of bubbling CO_2 through the slaked milk of lime. At the end of the process there exists once again $CaCO_3$, now in the form of PCC. The process can be manipulated, within limits, to influence particle shape and fineness. PCC is often produced in plants located on-site at the paper mill, but there are also many so-called off-site production units. A generalized flow sheet for the production of off-site manufactured PCC is presented in Figure 2.21.

Various investigations and development work have been carried out in order to produce PCC directly in, for example, a high consistency stock. However, so far there has been no major breakthrough into the commercialization of such processes [9, 10].

The morphologies of PCC used as fillers are commonly scalenohedral (rosette-shaped), rhombohedral (cubic-shaped) or aragonite (needle-shaped). The type of morphology is defined by process parameters like temperature, pressure, reaction speed, additives etc. The particles can be arranged as individual discrete, clustered or agglomerated. These different arrangements represent an additional tool to influence the overall pigment performance.

Currently the most common PCC morphology applied around the globe is the clustered scalenohedral one. This rosette-shaped type of PCC provides increased caliper and bulk to the paper (compared to kaolin or GCC). However, as a consequence of this higher bulk, strength properties are reduced and the sheet becomes distinctly more open and permeable. An extra high bulk providing PCC in general tends also to exhibit a lower light scattering potential. Combining different carefully selected morphologies assists in the optimization of specific paper properties. Although particle morphology and fineness can be influenced largely in the PCC production process, in the end a suitable compromise addressing the different properties desired by the papermaker has to be found.

$CaCO_3$ in the form of PCC, as true for GCC, is naturally soluble under acid conditions and therefore requires a near neutral to slightly alkaline pH environment. Residual calcium hydroxide $Ca(OH)_2$ in the PCC can require extra measures for pH control of the final product and the paper mill wet end system. Despite reported developments in providing so-called acid tolerant PCC, intended to remain stable against dissolution under acid (< pH 7) conditions, papermakers, it seems, continue to make the conversion to slightly alkaline or alkaline papermaking when considering the use of $CaCO_3$.

2.2.1.4.5 **Talc**

This is applied in wood-free uncoated paper in Asia Pacific, often combined with GCC. In Europe it is used in a few cases as a primary filler in wood-containing coating base paper and wood-containing uncoated paper, in the latter case in combination with kaolin.

Talc is found naturally throughout the world within an assembly of various minerals and as a secondary pigment. It is a hydrous silicate mineral that is very soft (Moh's hardness 1, compared with pure $CaCO_3$ being typically 3 and diamond 10) and has a low abrasiveness. It is chemically inert, very platy, water insoluble, organophilic and hydrophobic. As a result of the pronounced platelet structure found in pure grades, the use of such talc as filler provides a high smoothness and gloss to the paper at calendering. Due to its hydrophobic nature, talc has some limits in the use of offset printing papers when used alone, and so should be used judiciously in combination with other hydrophilic minerals such as $CaCO_3$ or kaolin. Talc has particular merit when used in rotogravure printing papers.

Micronised talc is applied to control pitch and stickies, originating during wood fiber processing depending upon the variety of fiber in use. Talc for sticky control can also be found in paper mills processing recovered paper. Talc particles are adsorbed on the surface of the resin or the sticky component and render these interfering substances harmless by covering them or being incorporated into them.

2.2.1.4.6 **Gypsum (Calcium Sulfate)**

This is used only on a very small scale as a filler in printing and writing papers. In recent years, gypsum as filler has been replaced by GCC at various locations. Gypsum on the other hand is largely applied in the manufacturing of gypsum board. Gypsum board is made up with a high percentage of calcium sulfate material and

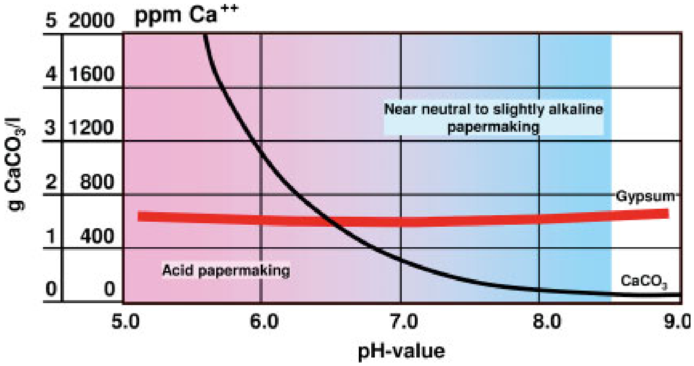


Fig. 2.22 Comparison of the pH related solubility of gypsum and calcium carbonate (source: OMYA).

lined with reinforcing sheets of paper. It is used in building construction for walls and ceilings.

Gypsum can be sourced from either natural deposits or as a byproduct, for example in the production of fertilizer or citric acid. Another gypsum byproduct originates from the desulfurization of flue gases emitted by power plants operating on the basis of fossil energy. Although available in huge amounts, so far all attempts to make this byproduct technically and economically useable as paper filler, have been unsuccessful. Gypsum may exist as different chemical structures ($CaSO_4$ $2H_2O$ dihydrate, $CaSO_4$ $1/2H_2O$ hemihydrate, $CaSO_4$ anhydrite) and in general exhibits a high solubility, more or less independent of the pH environment [11]. Figure 2.22 compares the solubility of gypsum and calcium carbonate versus the pH.

2.2.1.5 **Specialty Filler Pigments**

2.2.1.5.1 **Calcined Clay**

This is a specialty filler, applied to the sheet mainly in order to increase light scattering/opacity and to reduce the ink print-through potential. Typical areas for the application of calcined clay are lower basis weight uncoated wood-containing papers (i.e. telephone directories, low basis weight newsprint and SC paper etc.).

In the calcination process of kaolin, the water of hydroxylation (14%) is first driven off at temperatures of 500–700 °C. On continued heating up to 900–1000 °C the particles begin to fuse together into secondary particle aggregates, accompanied by an increase in brightness. Further agglomeration results in tertiary particles. The final result is a large number of kaolin-air interfaces and relatively high internal pore volume leading to increased light scattering and opacifying properties.

2.2.1.5.2 **Titanium Dioxide**

This is a specialty and particularly effective filler. It is applied in specialty papers, often at low basis weights, with particularly high demand in dry and wet opacity and sheet brightness. TiO_2 can be found in thin print paper, i.e. bible paper, high opaque grades, label paper and decoration paper.

Titanium is the fourth most abundant chemical element found on earth. In nature, titanium occurs only in the form of oxides or mixed oxides with other elements. Mineable deposits are generally of volcanic origin. The titanium dioxide pigment industry uses between 90 and 95 % of the global titania ore extracted.

Titanium dioxide is a synthetic material, commercially produced by the sulfate or the chloride process. It exists in three modifications with different crystal lattice structures and therefore different physical properties. The modifications are rutile, anatase and brookite. Only rutile (hexagonal close packing of the oxygen atoms) and anatase (cubic close packing of the oxygen atoms), which differ from each other in some of their physical properties, are of technical importance. The typical refractive index for rutile is 2.75 and 2.55 for anatase (cf. $CaCO_3$ 1,58). In comparison to other pigments TiO_2 exhibits also an extraordinarily high density (3.9 g cm^{-3} anatase, 4.2 g cm^{-3} rutile). Rutile gives higher brightness (but less blue whiteness) and opacity, while anatase supports optical brightening agents better as it absorbs less ultraviolet light. Compared with the rutile form, anatase has a lower Moh's hardness of 5.5 to 6.0 instead of 6.5 to 7 [12].

Even at only low addition levels, TiO_2 has a remarkable effect on paper opacity due to its unmatched high refractive index and high light scattering potential. Because of its high refractive index, TiO_2 is the only pigment, which also provides high opacity when the paper is wet (label paper). The extra high refractive index is also important for providing opacity in the manufacturing of decoration paper. In the production process of this specialty paper, resin penetrates completely throughout the sheet structure, thereby filling up the voids and diminishing pore structure volume with resulting reduced light scattering. Because of the extreme fineness (average particle size 0.2–0.25 µm) and the complex chemistry in application (for example high amounts of cationic wet strength agent etc.) TiO_2 filler pigments can be difficult to retain in the paper web.

Due to its high cost, TiO_2 is often used in combination with extenders. These extenders are other less costly minerals (for example $Al(OH)_3$, synthetic silicate and silica, barium sulfate), which are capable of replacing TiO_2 to a limited extent while producing similar results. The effect of providing wet opacity to the sheet by TiO_2, however, cannot be reached by using extenders alone. No extender matches the extra high refractive index of TiO_2. The closest to TiO_2 in terms of refractive index is zinc sulfide with a value of 2.37.

2.2.1.5.3 **Amorphous Silicates and Silica**

These are also specialty pigments, mostly used in lower basis weight newsprint and directory paper. These pigments are added in small percentages (sometimes applied in combination with regular paper fillers), to enhance paper brightness and opacity as well as absorption properties, e.g. reduction of print-through.

Amorphous silicates are produced by destabilization of soluble silicates to yield amorphous discrete particles in varying degrees of aggregation. The high specific surface area in combination with an organophilic surface is responsible for the excellent ink adsorption characteristics. Amorphous silicate also has the potential to increase somewhat the bulk of the paper sheet.

In a recent development, Mg-Al-silicate was coprecipitated with a rhombohedral-shaped precipitated calcium carbonate as core, as one single product. This development has already found its way into commercial application. One target is to reduce the ink print-through in lower basis weight newsprint or directory paper at lower cost than regular Mg-Al-silicates [13].

2.2.1.5.4 Aluminum Trihydrate (Hydrated Alumina)

This represents a specialty filler which contributes to paper brightness, ink receptivity and acts as a flame retardant. The effect on flame retardancy can be explained by the 35% of bound water based on material weight. The bound water is released at temperatures above 150 °C. The raw material source for the production of aluminum trihydrate (ATH) is bauxite. Bauxite is a blend of Al_2O_3, Fe_2O_3, SiO_2, H_2O, TiO_2 and other minerals. To produce ATH it is necessary to stabilize the alumina content and to separate out the other minerals. This is done by the so-called Bayer process. After final filtration, the clear liquor of sodium aluminate is seeded with specially prepared fine crystals of ATH. This seeding causes the sodium aluminate to decompose to ATH or $Al(OH)_3$ which forms a precipitate.

Some bauxite ore deposits exhibit a rather high purity and brightness. Such material can be converted directly into filler grades. The physical difference between a fine precipitated ATH and a fine ground ATH is small.

2.2.1.5.5 Other Fillers

It must be mentioned, that there are several other industrial minerals being used directly or indirectly as paper fillers. These materials include barytes, barium sulfate, calcium sulfite, zinc oxide, zinc sulfide, diatomaceous earth, mica, bentonite and pyropholite. Synthetic organic fillers are, for example, based on polystyrene or urea-formaldehyde. Local availability, cost and the need for obtaining certain special properties are the deciding factors in the selection of these materials. However, the total volume is quite small in comparison to the major fillers and specialty pigments, as described above.

2.2.1.6 Outlook

There is a continuous demand for technical and economic development in the various paper grades. In this context, the quality and choice of filler is also often reconsidered. Brightness, opacity and surface properties like smoothness, uniformity, surface strength and printability will continue to be of great importance. To address these demands, further specific pigment developments and the combined application of different filler grades can be expected. Costructuring different pigments and coprecipitation could represent suitable tools to reach some of the functional targets. Investigations on how to further increase the filler loading in various paper grades are constantly ongoing. Maintaining stiffness properties at increased loading and cost effectiveness are some of the challenges. At the already very high filler loading levels as practiced in Europe, each % point of further increase represents a particularly significant success. Filling through the surface of the sheet could be an additional tool for completely new developments. Positioning the fillers at a specific location within the z-direction of the sheet (multilayering) is in an early stage of investigation. Replacing more expensive specialty pigment applications by regular fillers is always of interest. Calcium carbonate based fillers will penetrate the paper market even further, as for example currently observed in the area of higher brightness SC paper.

Much emphasis is given today on seeking the potential of nanotechnology in the area of papermaking. It remains to be seen if nano per se will provide innovative products, but there are materials available now, primarily in structured forms of PCC or surface modified GCC that provide nanoscale features on the surface of otherwise microparticles. Properties so far indicate high absorption potential, and their use in digital inkjet printing and as specialty fillers are being evaluated intensively [14, 15].

2.2.2
Coating Pigments

Werner Kogler†, Thoralf Gliese, and Werner J. Auhorn

2.2.2.1 General Overview

Coating improves the surface quality of paper and board resulting in higher brightness, smoothness and gloss as well as better opacity and generally significantly improved printability. Pigments are the main coating components for improving the surface properties of coated paper and board grades. Usually they account for 80–95% of the total dry coating weight or, as a volume fraction, 70–80% of the solid material of the coating. This is based on a pigment density of about 2.5 g cm^{-3} and a density of the rest of the solid material in the coating of about 1.0 g cm^{-3}. In 2004 a total of approximately 18×10^6 tons of coating pigments were used worldwide in the paper and board industry, which means nearly 2/3 of the total usage of fillers and coating pigments. Kaolin (Clay) has been the biggest coating pigment in the past, but its share dropped to 42% in 2004 while natural ground calcium carbonate (GCC) took over the No. 1 position with 51% share. Recently precipitated calcium carbonate (PCC) with a present share of 3% switched from the status as a special coating. Pigments also largely determine the cost of the coating. A sizeable number of white pigments are available for surface finishing in the paper and board industry. A large majority of these are of natural origin, being physically and chemically homogenous minerals formed by inorganic processes. Organic products like plastic pigments may also be used in coating colors in special cases. A more detailed description of the pigments used as fillers, their origin,

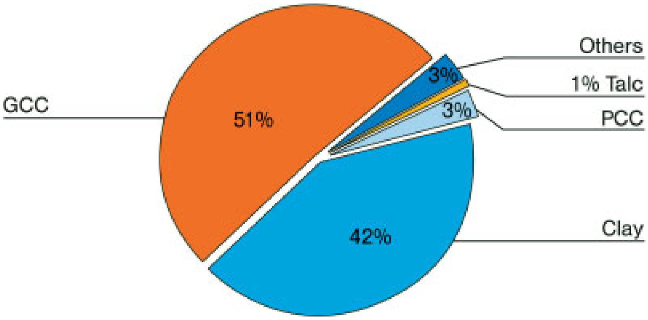


Fig. 2.23 Pigment to a main pigment.

preparation and properties is given in Section 2.2.1 and a more detailed description of those used as coating is given in Chapter 7.

The pigments can be classified as:
- Main pigments:
  - ground calcium carbonates (GCC)
  - kaolin clays
  - precipitated calcium carbonates (PCC) (recently switching from a special pigment to a main pigment)
- Special pigments:
  - talc
  - gypsum (calcium sulfate)
  - plastic pigments (e. g. polystyrene)
  - satin white (calcium sulfoaluminate)
  - barium sulfate
- Additional pigments:
  - calcined clays (kaolins)
  - titanium dioxides
  - alumina trihydrates

Central properties of pigments are particle size and size distribution, particle shape and shape distribution, refractive index, light scattering and light absorption and density. The properties of coating color and the final coating can be influenced and explained to a great degree by these factors. The following simplifies how different quality parameters of coated paper can be improved by changing specific pigment properties:
- better gloss by increase in platiness and/or decrease in particle size
- higher opacity by increase in refractive index and/or decrease in particle size
- higher brightness by decrease in light absorption
- higher porosity and ink absorption by decrease in packing (less compact pigment layer), e. g. through mixing of different particle shapes

Table 2.7 Physical and optical properties of coating pigments (main source: [16]).

Pigment	Chemical composition	Most particles (µm)	Particle shape	Density (kg dm^{-3})	Refractive index	ISO-Brightness
Kaolin clay	$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$	0.3–5	Hexagonal platy	2.58	1.56	80–90
GCC[a]	$CaCO_3$, $MgCO_3$ (2–3 %)	0.7–2	Cubic, prismatic, platy	2.7	1.56–1.65	87–97
PCC[b]	$CaCO_3$	0.1–1.0	Variable, usually rodlike	2.7	1.59	96–99
Talcum	$MgO \cdot 4SiO_2 \cdot H_2O$	0.3–5	Platy	2.7	1.57	85–90
Gypsum	$CaSO_4 \cdot 2H_2O$	0.2–2	Roundish	2.3	1.52	92–94
Plastic pigment						
– solid	Polystrene most common	0.1–0.5	Spherical	1.05	1.59	93–94
– hollow		0.4–1.0	Spherical	0.6–0.9	1.59	93–94
Calcined kaolin	$Al_2O_3 \cdot 2SiO_2$	0.7 (median)	Aggregated plates	2.69	1.56	93
Titanium dioxide						
– anatase	TiO_2	0.2–0.5	Rodlike	3.9	2.55	98–99
– rutile	TiO_2	0.2–0.5	Roundish	4.2	2.70	97–98
ATH[c]	$Al(OH)_3$	0.2–2	Platy	2.42	1.57	98–100

a Ground calcium carbonate (calcite), b Precipitated calcium carbonate, c Alumina trihydrate.

- higher bulk and better coverage by decrease in packing (decrease in density) through mixing of different particle shapes.

Table 2.7 gives an overview and comparison of the most important physical and optical properties of coating pigments. Besides the main pigments for paper coating, only the most important special and additional coating pigments are described in more detail in this section (for others see Section 2.2.1).

2.2.2.2 Main Coating Pigments [16–19]

2.2.2.2.1 Kaolin Clays

Kaolin clays in paper coating have probably been used since the second half of the 19th century when paper coating was developed. Since that time they played a dominant worldwide role as a coating pigment almost until today. Kaolin is one of the most widely occurring minerals. Kaolinite, the principal constituent of kaolin is a layered aluminosilicate having the chemical formula $Al_4Si_4O_{10}(OH)_8$. Kaolin is an intrinsically valuable coating pigment because of its platy particle shape, good color (white or near white), and the relative ease with which it can be processed to a fine particle size.

2.2.2.2.2 **Ground Calcium Carbonate (GCC)**

GCC as a coating pigment was successfully introduced in 1973. It marked an epochal step towards lower production costs and improved paper and print quality by the successful development of "high solid" coating in the 1980s. Herewith GCC allows reduced binder requirements and drying energy savings. The development of finer-grade carbonates with particle sizes down to 99% < 2 μm and special particle size distribution curves covers a broad spectrum of whiteness, paper and print gloss, as well as opacity. High solids coating colors offer excellent runnability even at the highest coating speeds of > 1800 m min^{-1}. This also explains the over proportional growth of ground calcium carbonate as a coating pigment during the last three decades, whereas kaolin is stagnating and talc is showing constant growth, especially for gravure coating colors.

2.2.2.2.3 **Precipitated Calcium Carbonate (PCC)**

PCC allows the production of coating pigments with specific morphologies by controlled synthesis. Particle size, particle size distribution, and particle shape can be controlled. The surface properties of the calcium carbonate particles can also be changed if needed. Commercial PCC pigments typically have $CaCO_3$ contents higher than 97%. The remainder is $MgCO_3$ (magnesium carbonate) and other residues. Industrially, it has been found practical to produce PCC near the paper mill by using what are called satellite plants. This saves inbound transportation costs because the necessary CO_2 gas (40% of the final product weight) can be taken from a local source and because calcium oxide can be delivered to the PCC satellite plant in a dry form. Outbound savings are possible as well because the produced coating or filler pigments can be delivered in a slurry form to a paper mill, possibly through a pipe.

2.2.2.3 **Special Pigments**

2.2.2.3.1 **Talc**

Talc as a coating pigment was introduced industrially in Finland and France in 1982. Since then, talcs have become widely used in light weight coated (LWC) gravure and coated fine papers in offset formulations. Recently another use has been found for talc in the coating of special papers. In some applications, e.g. coating paper for gravure printing, talc can technically replace clay if it is economically viable and vice versa due to the similar platy form of the particles. The characteristics generally differentiating talcs from delaminated Georgia kaolin clays (US) or Cornish kaolin clays (UK) are hydrophobicity, low cohesion between the crystal layers inside the talc particles, resulting in extremely low friction coefficient, softness and low abrasivity in spite of a large particle diameter. The brightness of European coating talcs varies from ISO brightness 82 to 88, depending on the origin.

2.2.2.3.2 Gypsum

Gypsum consists of calcium sulfate crystallised with different degrees of hydration, all of which can be referred to as gypsum. However, in most cases, gypsum refers to calcium sulfate in the dihydrate form, and the other forms are distinguished from each other by additional names (e. g., hemihydrate, calcined gypsum, and stucco gypsum). The rate of solubility of gypsum of pigment fineness is high, so the solubility easily reaches equilibrium in, for example, the water circulation of a paper machine. A saturated gypsum solution contains approximately 2.1 g l^{-1} of $CaSO_4$, which equals 2.5 g l^{-1} as dihydrate and 580 mg l^{-1} as a calcium concentration. Gypsum in itself is a neutral salt that, unlike carbonate, does not buffer the pH of circulation water. When it comes to solubility, it makes no difference whether gypsum pigment is used in an acidic or neutral papermaking process. The major advantages of gypsum pigment include brightness, bulk and offset printability. Additional optical brighteners used with gypsum are very effective.

2.2.2.3.3 Plastic Pigments

Plastic pigments are used in paper coatings to provide a surface with the desired appearance and printability. If properly chosen and formulated, these pigments provide a coating with surface smoothness, brightness, opacity, as well as a balance of ink holdout and ink receptivity upon which to print. Organic pigments, commonly referred to as “plastic pigments”, are used as partial replacements for inorganic pigments to improve the optical and print properties of coated paper and paperboard. There are two general classes of plastic pigments used in the preparation of coatings for paper and paperboard: solid bead and hollow sphere. Both are available in a variety of particle sizes and compositions and, in the case of hollow spheres, in a range of void volumes. All plastic pigments are supplied as polymeric particles dispersed in water. In the case of hollow-sphere pigments, those particles are water-filled spheres. During drying the water diffuses through the shell, leaving an air-filled core – hence the term “hollow sphere”. Plastic pigments are used in paper coatings wherever improvements in finishing efficiency, sheet gloss, or print gloss are important. They are used extensively in coated folding boxboard, woodfree coated printing papers, and they are also used in LWC and ULWC papers.

2.2.2.3.4 **Satin White**

Satin white (calcium sulfoaluminate) is still of some importance in paper coating. This pigment has very fine particles; it is extra white, and has a low density. It increases ink absorption and gloss. The disadvantages of satin white are its sensitivity to increases in temperature and decreases in pH, and its high adhesive demand.

2.2.2.4 **Additional Pigments**

2.2.2.4.1 **Titanium Dioxide**

Titanium dioxide pigments show extremely high refractive indices. This, and their whiteness, i.e., their high reflectance in the visible region of light, as well as their optimal particle size, make them the most effective white pigments. Titanium dioxide exists in three crystal forms: anatase, rutile, and brookite. The first two are stable and therefore of commercial importance. Titanium dioxide pigments are used in paper coatings to increase the opacity of coated paper. To ensure good optical efficiency of titanium dioxide in coatings, TiO_2 pigments must be properly dispersed in the coating color. Undispersed aggregates or agglomerates diminish the optical efficiency of TiO_2 pigments. Rutile slurry pigments are usually the most effective titanium dioxide grades in paper coatings because they have the highest TiO_2 content and refractive index, as well as optimal particle size and particle size distribution.

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3
Chemical Additives

Werner J. Auhorn

3.1
Introduction

Natural chemical additives have played an important role in the raw material preparation stage since the earliest beginnings of handmade papermaking more than two thousand years ago. Up to the end of the eighteenth century, chemical additives from natural resources were used to increase paper strength, to generate better writing and printing characteristics, to enhance paper brightness, and to color it. With the invention of the papermaking machine, chemicals began to contribute to industrial papermaking processes. It was only when newly developed bleaching chemicals came into use that wood pulp as a new source of raw material could be exploited to the full. The chemical additives assisted the automation and productivity of the papermaking process as well as the enhancement of paper quality and thus contributed to a large degree to the growth of the paper industry in the first half of the twentieth century. The past 50 years have been characterized by the increased use of recovered paper and white natural pigments as fillers and for paper coating, as raw materials, by an ongoing improvement of the paper machine productivity, and an emphasis on economics, ecology and quality. All this has been, and still is, supported by chemical additives and their creative application.

On a global view, paper and board today consist of nearly 99 % natural materials: Virgin fibers from chemical and mechanical pulps contribute 48 % of the total raw material consumption; recycled fibers 40 %; non-fiber material as fillers and coating pigments 9 % with the remaining 3 % being “chemical additives” (solid materials). In addition, 3 % of so-called *basic* and *bleaching chemicals* are added, mainly in the production of chemical, mechanical and deinked pulps (Fig. 3.1). These chemicals do not remain in the pulp (they are decomposed and are contained in the cooking liquor and the untreated waste water) and thus do not appear in the paper but they are a significant factor in production costs (Fig. 3.2). By mass starch accounts for 1.7 % of the world paper production, which is more than 50 % of all chemical additives. Traditional papermaking chemicals such as aluminum sulfate and nowadays other aluminum compounds are still used at a rate of 0.3 % on

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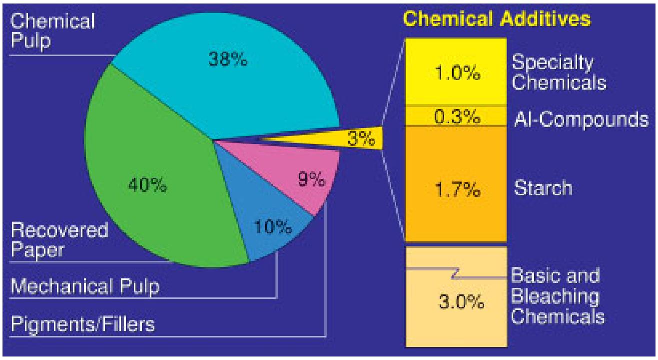


Fig. 3.1 Mass shares of groups of chemical additives and raw materials for paper production in 2004 (worldwide average figures based on 350 × 10^6 tons of paper and board production).

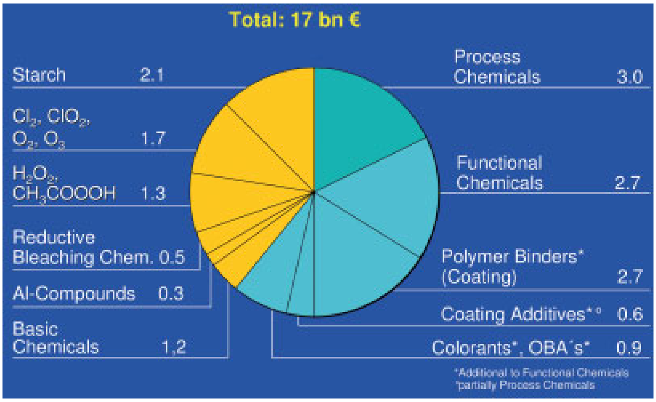


Fig. 3.2 Global consumption of chemical additives (turnover in billion €) for pulp and paper production in 2004. (OBA = optical brightening agents.)

paper, 10% of the total dry based mass of chemical additives. Pure synthetic chemicals – called “specialty chemicals” – account for only 1%, relative to the paper and board production. The market for chemical additives is currently estimated at 17 billion € worldwide. 28% of this is basic and bleaching chemicals, mainly used in the production of pulp and 72% is chemical additives used in the production of paper and board. On average, chemical additives account for approximately 5% of the cost of the finished paper and board, varying for the individual paper and board grades.

The wide variety of specific demands that are placed on the different paper and board grades cannot be fulfilled with natural raw materials alone. It needs chemical additives with very specific performances, the so-called “specialty chemicals”,

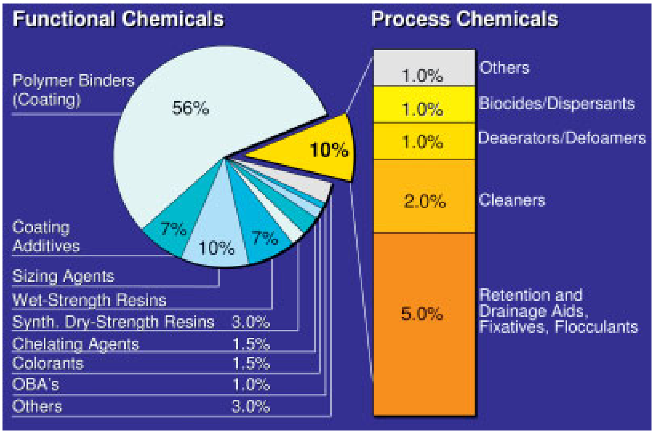


Fig. 3.3 Specialty chemicals for paper and board production in 2004 (mass shares of solid substances; total amount 1% on paper/board production).

and their intelligent application. Some of these additives are used in order to obtain certain properties of the finished paper e.g. colored sheets, resistance against ink or water, high gloss, good and appealing printability or high strength for packaging. This group of chemical additives is called "*functional chemicals*". Other chemical additives are used to solve or prevent problems in the paper manufacturing process, to improve the efficiency of the production process and/or to protect the environment. The latter type of additives for instance helps to reduce the consumption of fresh water and energy, prevent foam and deposits, improve drainage or reduce fiber loss. This second group of additives is called "*process chemicals*" (Fig. 3.3.) [1–3].

3.2
Basic Chemicals [4–7]

Wood is a natural composite material and is far more complex than any man-made composite. Wood consists of fibers with lignin as a glue in between, and is thus a "fiber composite material". The purpose of the pulping process is to separate the wood into individual fibers and to make the fibers suitable for papermaking. For that the lignin and, to a large extent also the hemicellulose, must be either dissolved and degraded in the chemical pulping process or removed, as is done in thermochemical pulping, or more or less softened as in thermomechanical pulping.

For chemical delignification and defibration of wood several basic chemicals are used, depending on the process (see Volume 1). In kraft pulping, which is the dominant alkaline process, the main active compounds are sodium hydroxide (NaOH) and sodium sulfide (Na_2S). In addition, soda (Na_2CO_3), sodium sulfate

(Na_2SO_4), sodium chloride (NaCl), sodium chlorate ($NaClO_3$) and sulfuric acid (H_2SO_4) necessary for chlorine dioxide manufacture, and calcium carbonate ($CaCO_3$) are used. In a modified kraft process polysulfide is used by adding elemental sulfur to the cooking liquor. Some pulp mills use unmodified anthraquinone (AQ) to stabilize carbohydrates against alkaline degradation by slowing down the peeling reaction and hereby gain a few % higher yield. In industrial sulfite cooking of the wood chips, calcium, ammonium, sodium and magnesium hydrogensulfite – $Ca(HSO_3)_2$, $NH_4(HSO_3)$, $NaHSO_3$, $Mg(HSO_3)_2$ – as well as sulfur dioxide (SO_2) are applied. Neutral sulfite semi-chemical (NSSC) pulping uses a solution of sodium sulfite and carbonate or bicarbonate to impregnate the wood chips.

Solvent-based pulping (Organosolv) is still in a very early stage of industrial development. In this chemical pulping method the delignification of the biomass (usually wood) is done in an organic solvent or solvent plus water system. There are a variety of processes, which use different solvents e. g. ethanol, methanol, acetic acid, formic acid, often in combination with sodium hydroxide, alkaline sulfite, and/or anthraquinone.

In the production of mechanical pulps (stone groundwood, thermomechanical pulp/TMP) sodiumsulfite or sodium hydrogensulfite is sometimes added to support softening of lignin and the defibration. These chemicals are generally used to produce chemimechanical pulp (CMP) or chemithermomechanical pulp (CTMP). Sodium hydroxide or soda is very often applied to control the pH during or at the end of the production process.

Recovered paper is disintegrated in water at a consistency of 4–30 %, depending on the machine type. For the production of packaging paper no or only a few chemicals e. g. dispersant, wetting agent (nonfoaming detergent) are used in the disintegration. Using recovered paper to produce a white paper stock a relatively high amount of different chemicals has to be added, to separate the printing ink and adhesives from the recovered paper. By volume the most important chemicals in this so-called "deinking process" are sodium hydroxide, hydrogen peroxide, sodium silicate (water glass) and fatty acid [5].

3.3
Bleaching Chemicals [4–7]

When chemical pulp, mechanical pulp and deinked recycled fibers are used in the production of white papers e. g. printing and writing papers, hygiene paper (tissue) or white top of board, these pulps have to be bleached up to a certain brightness. The bleaching of chemical pulp (see Volume 1) is carried out in several stages, with the elimination of residual lignin as far as possible being the primary objective of the first stage. The subsequent bleaching stages are responsible for brightening the pulp. Bleaching chemicals can be classified according to the particular groups they prefer to react with. Cations or radicals in acid medium react primarily with phenolic structures of lignin, alkaline nucleophiles attack carbonyl groups as follows:

- Group I: Cl_2, O_3, peroxyacids react with all aromatic lignin units, with phenolic groups and their double bonds.
- Group II: O_2, ClO_2 react primarily with free phenolic hydroxy groups.
- Group III: H_2O_2 in alkaline conditions react mainly with certain functional groups in lignin, e. g. carbonyl groups.

Accordingly, bleaching is divided into pre-bleaching and final bleaching. After the basic chemical pulping process the following bleaching chemicals are added separately in several steps, for which certain abbreviations have been introduced [4, 6].

3.3.1
Bleaching Substances

- Chlorination (C) with chlorine, an effective, selective and inexpensive bleaching agent that reacts very fast with lignin. For environmental reasons during the last ten years chlorine is being substituted by chlorine dioxide, ozone and/or oxygen all over the world. In Europe substitution is already 100 %. In this particular case bleached pulp is called “Elementary Chlorine Free – ECF”.
- Alkaline extraction (E) with sodium hydroxide, both to extract kraft lignin precipitated on the fiber surface and remove degraded lignin moieties originating from the preceding acid bleaching stages (e. g. ozone or chlorine dioxide).
- Sodium or calcium hypochlorite bleaching (H) is mainly applied to eliminate residual lignin and to control the viscosity in the case of the production of soluble pulp. Today hypochlorite is largely substituted by chlorine dioxide.
- Chlorine dioxide bleaching (D) – The production of chlorine dioxide is carried out by the reduction of sodium chlorate. The bleaching effect of chlorine dioxide is based on the oxidation of lignin. It has an exceptionally positive effect on pulp brightness. Chlorine dioxide can be applied in several bleaching stages of an ECF-sequence, e. g. as a pre-bleaching stage in connection with alkaline extraction (DOE), in the first stage in final bleaching to remove the residual lignin and activate the remaining chromophores to be removed in the final bleaching stage (DIE, DIEOP), and in a final bleaching stage to achieve the target brightness (D2, D3).
- Oxygen bleaching (O) – The treatment of pulp with oxygen under alkaline conditions is a chlorine-free alternative to pre-bleaching. Sodium hydroxide and oxidized white liquor are used as the alkali source. Under these conditions, oxygen also attacks carbohydrates to a considerable extent so appropriate conditions have to be applied to avoid cellulose degradation. Consequently, oxygen bleaching is less effective than conventional pre-bleaching with chlorine. With sequences containing only alkaline bleaching stages, a high final brightness is also possible, but these stages are most suitable as oxygen chemical sequences in fiber lines that also bleach pulp with the use of chlorine dioxide.
- Ozone bleaching (Z) – Because oxygen delignification is limited, additional delignifying agents must be used before final bleaching. Ozone is a possibility, but

it requires new technology. Like oxygen, ozone is only slightly soluble in water and is also very unstable.

- Peroxide bleaching (P) – Hydrogen peroxide (H_2O_2) in an alkaline medium is well suited to the final bleaching of chemical pulps and leads to high brightness stability. Originally sodium peroxide and, since 1950, hydrogen peroxide (as a 50% solution) were used to bleach mechanical pulps, where they destroy the chromophoric groups present in lignin by cleaving conjugated double bonds by an oxidation process. Hydrogen peroxide bleaching is carried out in the presence of NaOH, sodium silicate and also very often chelating agents (see Section 3.6.3). Depending on the individual process conditions for mechanical pulp and the initial brightness, 1 to 2% peroxide (100% active substance) leads to a brightness increase of up to 10 to maximally 18 points, relative to an absolute brightness level of 74 to 80% measured at TAPPI Standard 457 nm wavelength.

  In the production of deinked pulp (DIP) from recovered paper hydrogen peroxide is the most favorable bleaching chemical. This process requires an alkaline medium obtained by adding NaOH, and also sodium silicate (water glass) to stabilize the hydrogen peroxide. Under these conditions the necessary swelling of the fibers will be achieved, making it easier to detach the printing ink/dye particles from the fibers. Saponification of rosin and synthetic binders/adhesives also occurs.

  Furthermore peroxide bleaching strongly increases the amount and influences the composition of dissolved colloidal substances (DCS). A high amount of DCS results in a high COD (chemical oxygen demand) load in the process water and in a loss of quality of the mechanical pulp, e.g. strength properties.
- Dithionite (hydrosulfite) bleaching (Y) – In the late 19th century sodium bisulfite ($NaHSO_3$) was developed as the first bleaching agent for mechanical pulp. Because of its very limited brightness increase a few years later sodium dithionite ($Na_2S_2O_4$) – a further reductive bleaching agent – came to the market. Sodium dithionite is supplied as a white crystalline powder (88% active substance) or as a liquid with approximately 13% active substance. It can also be produced on-site from commercial solutions containing sodium borohydride and sodium hydroxide. Such solutions typically contain 12% sodium borohydride, 40% sodium hydroxide and 48% water (the molar ratio is 3.2 mole NaOH to 1 mole $NaBH_4$). When making dithionite, more sodium hydroxide and sulfur dioxide or sodium bisulfite is added in a continuous process. Hereby sodium bisulfite is then reduced by borohydride and one atom of borohydride reduces eight sulfur atoms.

  For optimum bleaching efficiency stock consistency should be 5%, temperature 60 °C and pH 6. At these conditions addition of 1.2% (100% active substance) to dry pulp leads to a brightness increase of 10 to 12 points. This means a brightness of 70 to 76% (at TAPPI Standard 457 nm) can be reached, depending on the wood quality and on the initial brightness (see also Volume I). There is nearly no increase in dissolved colloidal substances (DCS) with dithionite bleaching. Dithionite is also very often used for the final bleaching of deinked pulp (DIP). For maximum brightness levels of the mechanical or deinked pulp, e.g. above 72 or 74%, a two-stage bleaching process is applied with hydrogen peroxide in the first stage and sodium dithionite in the second one. In most cases this combination is also the most economic one.

- Formamidine sulfinic acid ($CH_4N_2O_2S$) (FAS) is another strong reductive bleaching agent, produced from hydrogen peroxide and thiourea. FAS is a white to slightly yellowish crystalline powder with a purity of 99%. The reaction conditions are in a wide range of pulp temperature (60 to 120 °C), pulp pH (6.5 to 10.0) and pulp consistency (4 to 30%), therefore FAS is more often commercially applied in pulp bleaching of recovered papers than in bleaching of mechanical pulps.

3.3.2
Bleaching Auxiliaries

These products enable a more efficient bleaching of the chemical, mechanical and deinked pulps and lead to increased whiteness. They are generally based on surface active agents, i.e. wetting agents (see Section 3.6.7.) which are resistant to bleaching chemicals as well as chelating (complexing) agents (see Section 3.6.3.). Some of the transition metals (e.g. Fe, Mn, Cu) in pulp can reduce the bleaching effect due to catalyzed decomposition reactions of dithionite and the re-oxidation of reduced chromophore groups. Chelating agents also prevent transition metal ions from catalyzing peroxide decomposition. Since the beginning of peroxide bleaching of mechanical and deinked pulps, sodium silicate (Na_2O 3–4 SiO_2) has been used as an additive. Addition of 0.5 to 3% (41 °Be' solution calculated on dry pulp) stabilized peroxide, acts as a buffer and has the ability to form metal complexes. Small amounts (0.05–0.1%) of magnesium sulfate (usually in the form of Epsom salts, $MgSO_4$ $7H_2O$) are commonly included in the peroxide bleach liquor or added separately. Magnesium acts as a stabilizer of peroxide, probably together with sodium silicate.

3.4
Starch [3, 8]

3.4.1
Products and Market Figures

Starch plays a dominant role amongst chemical additives that are used for the manufacturing and upgrading of paper and board (see Fig. 3.1 and 3.2). It was used in papermaking even before the invention of handmade papers, being detected in sheets of papyrus. Starch derivatives are mainly used for dry strength improvement of paper and board and as a binder for pigment coating. As a biopolymer, starch can be provided in sufficient quantities. The total world production of all kinds of starch at present is 48.5×10^6 tonne p.a., 52% of which is produced in the USA, 17% in Europe and the remaining 31% in the rest of the world. The

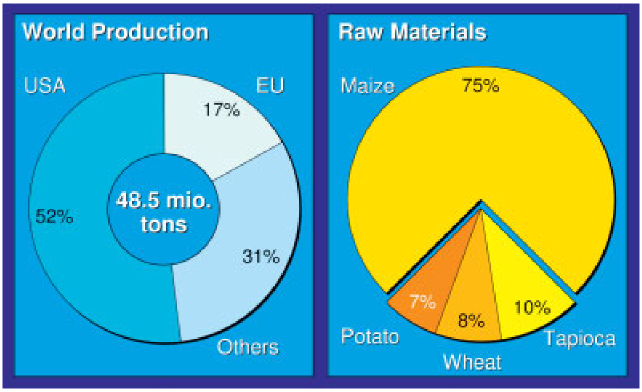
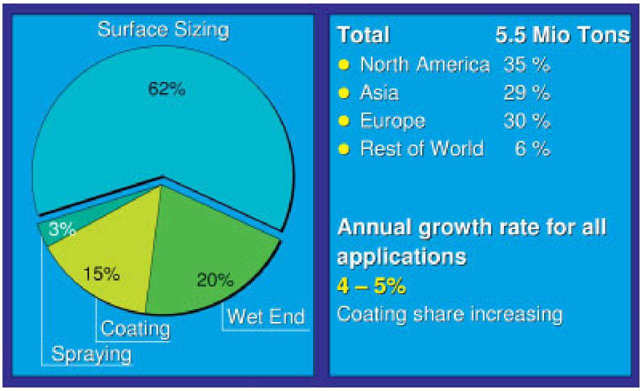


Fig. 3.4 Starch production and raw materials worldwide in 2002 (in million tons p. a. and % shares).



Total	**5.5 Mio Tons**
● North America	35 %
● Asia	29 %
● Europe	30 %
● Rest of World	6 %

Annual growth rate for all applications
4 – 5%
Coating share increasing

Fig. 3.5 Starch usage in paper and board production in 2004 (consumption in different applications and local areas).

dominant raw material for starch production is corn (maize) with a share of 75 %, followed by 10 % tapioca, 8 % wheat and 7 % potato (Fig. 3.4). In the paper industry about 5.5×10^6 tons p. a. of starch were used worldwide in 2004, with nearly equal amounts in North America, Asia and Europe. The total spectrum of starch applications in the paper industry now includes wet-end addition for dry strength improvement as well as improvement of filler and fines retention, and application in the surface sizing, pigment coating, and converting adhesive functions (Fig. 3.5) [3].

3.4.2

Chemistry, Modification and Conversion Technologies, Properties

Starch is chemically similar to cellulose. It is a polymer composed of glucopyranose units linked through carbons. The vast majority of starches occur as a mixture of linear and branched molecules. The linear fraction is called amylose and the branched one amylopectin. For efficient usage of starch in papermaking the native starch has to be modified. Unmodified starches are available that differ in properties such as amylopectin to amylose ratio, granule dimensions, gelatinisation temperature, and the molecular weights of the component fractions. In addition to these variables, modified starches greatly extend the number of potential wet-end starch additives available for a given application. Much research has been carried out that has resulted in the development of new applications for starch in papermaking. Physical, chemical, and genetic modifications and combinations have further improved starch application potential. The following modification methods are practised:

- Physical modification
- Fractionation into amylose and amylopectin components
- Thermomechanical conversion
- Acid hydrolysis
- Chemical modification
- Oxidation
- Derivatization
- Enzyme conversion

Thermomechanical conversion, acid hydrolysis, and enzyme conversion all lead to a decrease in the molecular weight of the starch and a corresponding decrease in the solution viscosity. This makes the starch more manageable, for instance for its application onto the paper surface in a size-press or film-press. For that a certain low viscosity of the starch solution is necessary. On the other hand a reduction in the molecular weight of the starch means a loss in its potential for improvement of paper strength. This means that maximum strength improvement by surface application requires the optimal ratio between the viscosity and the pick-up of the starch solution in sizing. Improvement of up to 30–60% in paper strength properties is reached by surface treatment of paper. This explains why today 62% of all starches used in the paper industry are for surface sizing (Fig. 3.5).

Native starch as such is not suitable for wet-end usage because of its very low retention in the paper sheet (≤ 40%), which is undesirable from both the economic and environmental standpoints. To obtain good starch retention on papermaking stock, it is necessary to attach cationic substituents to the starch molecule. Starches are cationized with either tertiary (diethylamine ethyl chloride hypochloride) or quaternary (epoxy propyl trimethyl ammonium chloride) amine groups. The cationic charge of the tertiary group depends on pH, with decreasing charge at higher pH values above 6. Quaternary cationic groups retain their complete charge at all pH levels. Typical commercial wet-end cationic starches have a degree of substitu-

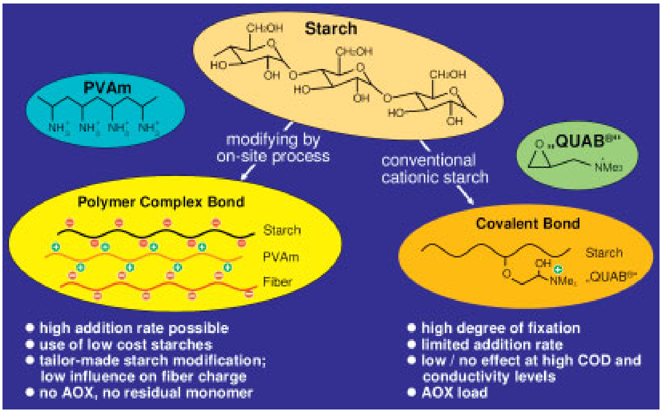


Fig. 3.6 Starch modifications for wet-end application (PVAm = polyvinylamine), (QUAB = quaternary ammonium compound).

tion (d. s.) of cationic groups ranging from 0.01 to 0.05. In other words, 1–5 of 100 anhydroglucose units contain a cationic group. For example, a starch of molecular weight 4×10^6 and a d. s. of 0.01 will have approximately 250 cationic charges per molecule. These cationic starches are produced by the starch manufacturers. Due to the ionic reaction with the paper stock, addition rates above 1.5 % lead to an undesirable change in the charge in the stock suspension, causing problems during paper production and leading to a high COD load in the circuit water system and in the untreated waste water.

Alternatives to these covalently bonded cationic charges are cationic polymers, which react with native or slightly anionic starches by fixation and/or precipitation. Such polymers can be used in the paper mill during or just after the cooking process of starch. A very effective polymer is polyvinylamine [23]. It forms, e. g. with native potato starch or mildly anionic corn starches and the paper fibers, a very stable complex, which results in very good retention up to an addition level of 5 % starch. Figure 3.6 shows a model of such an on-site process. This wet-end application allows much greater improvements in paper strength than with cationic starches and gives results very close to those obtained with surface application of starch [24]. The mechanism of dry strength improvement by wet-end starch is based on interfiber bonding. Here its free glucose hydroxy groups participate in hydrogen bonding with fiber surface cellulose molecules, which means a "chemical hydration" of the fiber compound system. Additionally wet-end starch improves the sheet formation by improved retention of fines and fillers and also provides more uniformly distributed fiber-fiber bonds by hydrogen bonding.

3.4.3

Starch Application

As can be seen from Fig. 3.5, 80 % of total starch consumption in the paper industry is used for surface application, either for surface sizing (62 %), or for spraying (3 %) on the wet paper web or between two layers in board manufacturing, or as a coating binder (15 %). The main role of surface size is to promote surface properties, e. g. strengthen the paper surface and to bind particles such as fibers and pigments more strongly to the surface. Additionally, the starch is expected to add internal strength to the sheet through a liquid penetration in the z-direction. Opposite to wet-end application, where starch retention is crucial, starch applied to the surface is generally 100 % retained.

For production of woodfree uncoated and coated fine papers up to 40 kg starch per ton of paper are applied. 3 to 10 kg starch is added at the wet end, with the aim of internal strength improvement and retention increase. The major share of the starch is added to the sheet in surface treatment. A mass balance on a typical fine paper machine has shown, that more than 90 % of the added starch is retained in the final paper product. Losses occur mainly during the sheet forming process in the wire section due to insufficient retention. Starch which is not held back in the paper is discharged with the process effluents to the waste water treatment plant, where a complete biodegradation process follows.

Packaging paper, e. g. testliner and corrugating medium, made from 100 % recovered paper, can only be produced economically and in the required quality by adding cost effective dry-strength agents, i. e. biosynthetic starch products. Therefore these papers are produced with an average starch consumption of 40 kg t^{-1}, mainly by surface application. A further 25 kg (t corrugated box board)$^{-1}$ is applied as an adhesive in the converting plant. This means that a high amount of starch is returned to the production process via recovered papers, where it is nearly not retained in the paper sheet. Therefore this uncontrolled starch quantity leads to a considerable load in the white water circuit (usual COD levels from 5.000 to 30.000 (mg O_2) l^{-1}) and finally also in the waste water. By applying starch with a size-press to the paper surface, the paper strength will be increased by 30 to 60 %. Additional energy is necessary for extra drying of the paper web and the paper machine runnability may decrease.

To improve productivity and reduce production costs, effective and well controlled starch application at the wet end is required (see Fig. 3.6). New practical experience shows that a starch-polyvinylamine complex can be an alternative to a surface treatment by size-press for strength improvement. A holistic picture of the application of starch based on analytical investigations (in produced paper, exhaust air, clarified waste water and soil) shows that starch is an extraordinary, environmentally friendly additive with a diversified functionality.

3.5
Aluminum Compounds [3, 9]

Aluminum compounds are widely used in the paper industry: in rosin sizing, as drainage and retention aids, and as fixing agents for anionic trash (dissolved organic compounds e. g. extracts from wood fibers, degraded starch). Important applications are the treatment of circuit water and effluents or the thickening of sludge, where the flocculation and precipitation effects of aluminum ions are utilised. The most frequently applied aluminum compounds are aluminum sulfate, polyaluminum chloride (PAC), polyaluminum hydroxidechloride sulfate, and recently also (poly)-aluminum nitrate and polyaluminum nitrate sulfate. Aluminum compounds have a favorable price-performance ratio. An analysis of the aluminum concentration in the production of a wood-containing printing paper (at neutral pH, with 0.45 % aluminum sulfate added to the white water) showed an aluminum level in the water circuit (at a pH of approx. 7.5) of about 0.1 mg l^{-1}, maximum 0.2 mg l^{-1} (determined by UV/VIS spectroscopy). This indicates that the paper retains nearly all of the aluminum added in the form of aluminum hydroxide. The anionic counterions sulfate and chloride, however, are nearly fully discharged into the effluent. The paper retains the share of ions dissolved in its residual moisture at the end of the drying section. Sulfate and chloride ions are nonvolatile, i. e. they are not released into the atmosphere. The loss via papermaking residues is negligible. The two anions may be considered environmentally harmless. As sulfate promotes the corrosion of concrete, there may be statutory discharge limits for this substance (500 mg sulfate l^{-1}). There are usually no restrictions, however, on the discharge of chloride.

The use of polyaluminum nitrate and polyaluminum nitrate sulfate is fairly new. The two compounds help to prevent or combat malodours caused by the conversion of sulfate into hydrogen sulfide under anaerobic conditions. The results of mill trials suggest that nitrate is converted into elemental nitrogen because no nitrate could be detected in the effluent – nitrate was found only in the white water. According to information from mills using large quantities of polyaluminum nitrate, a minor discharge of nitrate into the effluent can occur [3].

3.6
Functional Chemicals

All chemical additives which are used to obtain certain properties of the finished paper, e. g. color, improved resistance to ink or water, gloss, printability, strength, are called “functional chemicals” (see Fig. 3.3.).

3.6.1
Coloring Materials (Dyes) [3, 9–11]

3.6.1.1 General

Historically, dyes are the oldest class of synthetic specialty chemicals employed in the production of paper. Dyes are added to paper at a statistical average rate of only 150 g chromophore per 1 ton of paper and board worldwide. The turnover in dyes (total 500×10^6 €) accounts for 5% of the specialty chemicals applied to paper but only for 1,5% in view of solid mass addition (Fig. 3.2 and 3.3).

Colorants are used in paper manufacture for a variety of reasons, including eye appeal, color coding, and brand identification. The selection of suitable colorants depends for instance upon end-use requirements, physical and chemical properties, and handling characteristics. Coloring is done to achieve the following two general goals:

- to produce paper having a given color or shade
- to produce white paper having a desired tint.

Coloring is rather tricky:

- Process variables may interfere with dyes.
- Specific dyes react differently in different furnishes.
- Dyes may adversely interact with other additives – primarily through charge interaction – and interfere with them.

Additional parameters have to be considered:

- In the case of food contact, bleeding has to be assessed according to DIN EN 646
- For advertisement use the light fastness is important
- Dyes have to meet the toxicological and ecological requirements, e.g. German "Technical Regulations of Risky Substances" and EU guideline 2002/61/EG (19. 07. 2002). Therefore, no listed aromatic amines are released after reductive cleavage of any of the azo-bonds.

3.6.1.2 Classes of Coloring Material

3.6.1.2.1 Anionic Direct Dyes

These are the dominant class of dyes. They account for 52% of the total worldwide turnover, followed by basic dyes with 28% share (Fig. 3.7). Anionic direct dyes are the sodium salts of azo dyes containing sulfo groups to give water solubility. Another group are copper phthalocyanines which also contain sulfo groups (Fig. 3.8). They have a high affinity to bleached chemical pulps, and often do not need additional fixing agents, unless very deep shades with good bleed fastness are required (e.g. deeply colored napkins). Suitable fixatives are condensation products of organic amides with formaldehyde, however, they are not very well suited for the dyeing of wood-containing stocks because the incrusting components (binding

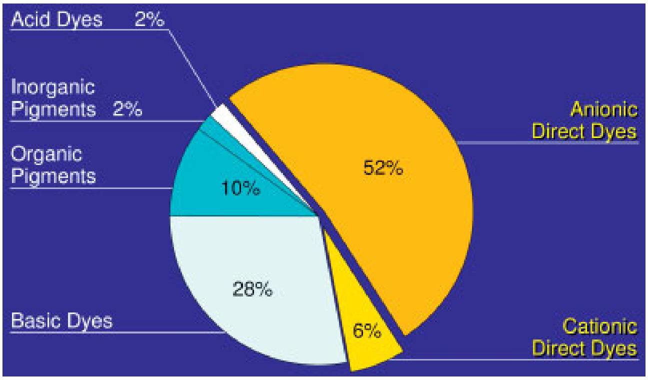


Fig. 3.7 Classes of coloring materials in 2004 (market shares at world wide turnover of 500 × 10^6 €).

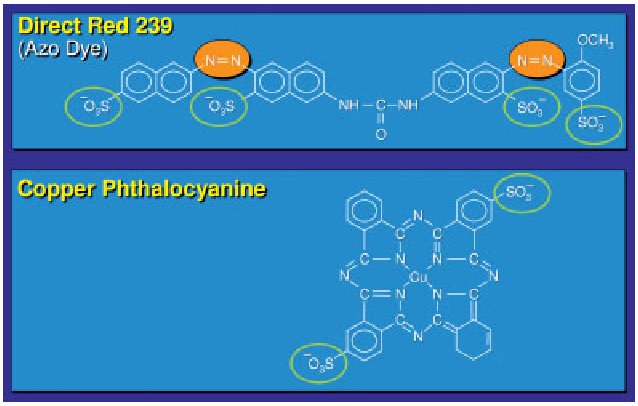


Fig. 3.8 Chemical structure of two direct dyes.

substances) of wood prevent uniform dyeing. Therefore a mottling tendency is occasionally observed with stock mixtures (bleached chemical and mechanical pulp; recovered paper). The lightfastness is usually good, but the colors attainable may not be as brilliant as with acid and basic dyes.

3.6.1.2.2 **Cationic Direct Dyes**

These retain the planar molecular structure of acid direct dyes, but cationic groups have been incorporated in the structure. This is to increase their affinity to paper fibers. They are moderately adsorbed on bleached lignin-containing stocks, and even in the case of deep shades, alum or a fixative is usually not required. These dyes produce fairly good bleed fastness. Combination dyeing with anionic direct dyes can be carried out to improve the fixation of the dyes on the paper machine and to reduce the contamination of the circuit process water and the waste water. In most cases combination dyeing leads also to an improved bleed fastness.

3.6.1.2.3 **Basic Dyes**

These are the salts (chlorides, hydrochlorides, sulfates, and oxalates) of color bases. They are soluble in acid aqueous solutions, and this is often the reason for the use of acetic acid to produce concentrated dye solutions. Such liquid dye formulations often contain 5–25% acetic acid and 5–20% of a glycol derivative for stability reasons, along with ca. 25% chromophor. The chromophors have a very high affinity for paper fibers, especially to unbleached and mechanical pulps (lignin-containing fibrous material) and also for fillers. This is due to their high cationic charge density, corresponding to a 99% fixation in the finished paper. Salt formation gives rise to very stable color lakes that are insoluble in water.

Anionic fixatives, e.g., the sodium salt of condensation products of formaldehyde and naphthalene sulfonic acid, also form color lakes of this type with cationic dyes. They are used to improve the fixation of basic dyes on bleached pulps that contain only small amounts of lignin. Better dye fixation always results in richer colors, improved bleed fastness, and less effluent staining.

Basic dyes are mainly used in the production of packaging papers (liner, testliner, corrugating medium; 55% of total volume), for tinting of wood-containing printing papers (20%) and colored, wood-containing printing/writing papers (15%).Within the class of basic dyes, brown grades have the greatest volume. The main reason for this is that recovered paper is nearly the sole source of packaging paper in many countries. Brown dyes in testliner should imitate unbleached kraftliner, enhance the visual appearance and characterize certain qualities. Two typical representatives of these dyes are “Basic Brown 1”, an azo-dye, and “Basic Brown 19”, a methine dye, corresponding to the international color index (Fig. 3.9). The strong cationic charge centers of both dyes give a very high affinity to the paper stock. Because of the molecule doubling the methine dye shows even better fixa-

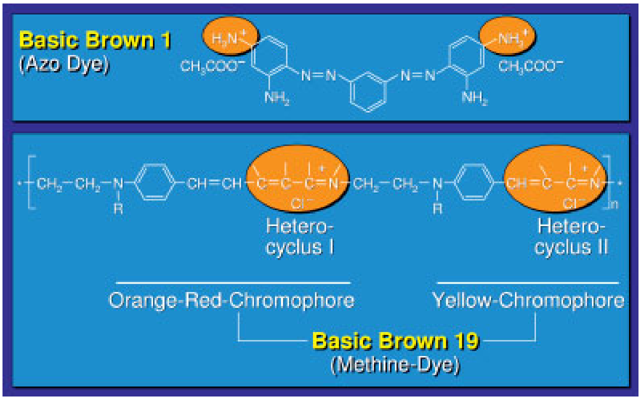


Fig. 3.9 Chemical structure of two basic brown dyes.

tion. Basic dyes are brilliant and tinctorially strong, resulting in good fastness to water and steam on groundwood-containing furnishes. Disadvantages are poor affinity to bleached furnishes, mottling tendency (i. e., parts of the paper stock or stock mixture are dyed more deeply than others), and poor lightfastness.

3.6.1.2.4 **Acid Dyes**

These are all water-soluble salts (usually in the form of the sodium or potassium salt) of colored organic acids which dissociate in water to form colored anions. Most acid dyes are azo dyes and are similar to direct dyes. These two groups overlap with no distinct boundary. Acid dyes generally contain more acid groups which gives rise to their greater solubility in water, compared to direct dyes.

Acid dyes have little affinity to paper fibers. Although the dye molecules penetrate well into the capillaries of the fibers, they must be fixed with aluminum sulfate (pH ca. 4.5) and cationic fixing agents, e. g., condensation products of dicyandiamide with formaldehyde, polyamines, polyvinylamines, in order to achieve a satisfactory dye yield. Further disadvantages are relatively strongly colored waste water/effluent and poor bleed fastness. Advantages of acid dyes are good solubility, no tendency to mottle on stock mixtures, and they are very well suited to dip and surface dyeing. Acid dyes are mainly used for (certain) writing and printing papers, decorative crepe paper, and carbon paper. The importance of acid dyes for paper dyeing has decreased tremendously because of their poor cost/performance ratio and the above mentioned waste water problems.

3.6.1.2.5 **Colored Pigments**

These fall into three classes: natural inorganic pigments, synthetic inorganic pigments, and synthetic organic pigments. The third class is by far the most important for the paper industry. The natural inorganic pigments such as ocher, terra sienna, or umber are of little significance at present. The synthetic inorganic pigments (iron oxide, cadmium, chromium oxide) the organic pigments (azo and polycyclic), and the metal complex pigments (phthalocyanine) are the important ones.

In the pigments the colorant is present in a water insoluble, finely dispersed form. The binding of the pigment to the fibers is improved by rosin sizing and the use of aluminum sulfate. The pH of the system must be kept below 5.0 in order to keep the alum in an active form for retention. Fixing agents and effective retention aids must be employed during papermaking in neutral or slightly alkaline systems. The lightfastness of pigments is excellent and mottling does not usually occur. The low tinctorial value of the colored pigments means that high loading levels are required to achieve strong colors, which leads to a weakening of the sheet and to high costs. Therefore these pigments are only used for specialty papers where a very high lightfastness is essential, e. g. bookkeeping and label papers, document and laminate base papers, lightfast printing and writing papers.

Colored pigments are applied more often in surface coloring and coating formulations where they are superior to soluble dyes, because they do not follow the water into the paper sheet when the starch or size or pigment coating is applied.

3.6.1.3 **Dyeing Processes**

3.6.1.3.1 **Stock Dyeing**

This is also called internal dyeing and is the most widely used paper dyeing process. Because of clean working conditions and the most efficient usage, the dyes are now mostly added continuously and fully automatically into the stock flow. More seldomly the dyes are metered batchwise in the pulper or mixing chest.

The choice of dye and the fixing and dyeing conditions largely depend on the raw materials used in papermaking (recycled fibers, stone groundwood, TMP, CTMP, unbleached or bleached chemical pulp, type and portion of filler) and on its preparation process e. g. a higher degree of beating of the pulp results in a deeper coloring. Fillers increase the required amount of dyes because they absorb dyes and, at the same time, reduce the coloration owing to their covering power and brightness. Fillers also lead to an increase in the two-sidedness of the paper sheet.

In continuous dyeing, the point of addition is also determined by a few factors e. g. high consistency dyeing at a stock consistency of 3–4 % (before mixing with white water ahead of the headbox) and alternatively low consistency dyeing at a stock consistency of 0.5–1.5 % (in front of the mixing pump or pressure screens). The pH conditions are very important. The addition of aluminum sulfate usually promotes the absorption of dyes and yields less colored waste water and effluent. In general, there is a trend towards paper production in the neutral or alkaline pH range. These conditions need dyes with a very good affinity to the paper stock in a neutral medium and/or very effective fixatives and retention aids.

The two stock dyeing processes have the following advantages and disadvantages:

Batch addition has the advantage of thorough mixing of the additives with the paper stock and optimal fixation due to longer contact time between the fiber and dye. The disadvantages are that the time required for color correction and color change is relatively long (loss of productivity). The handling of the dyes is more problematic with regard to clean working conditions and to an exact and regular metering control system. An integration of a continuous on-machine dye shade measurement with the metering of the dyes is not possible (less productivity).

Continuous addition has the advantages of a short length in the stock line that must be cleaned when the color is changed, and of less broke because the desired shade is attained more quickly (higher productivity). However, a lower color yield (low contact time) is obtained for intensely colored papers. The more complex equipment required for this dyeing process must be taken into consideration as well. On the other hand, control of the shade of the paper produced by continuous color measurements in the paper machine, and fast adjustment of the feeding pumps, lead to less broke and thus higher productivity.

A specialty of stock dyeing is the so-called *tinting*, mainly used for printing and writing papers. This procedure basically consists of counteracting the slight yellow tinge of all paper stocks by adding a violet dye or a combination of pure blue and a brillant red dye, which leads to a slightly blue shade. The human eyes perceive this shade as more bright.

3.6.1.3.2 **Surface Coloring**

Here liquid dyes are added e. g. during the size preparation for size press or film press application. Other additives e. g. starch, synthetic sizing agents, optical brighteners are also applied in this way. For such product combinations negative interaction of any kind must be avoided. An essential prerequisite for uniform dyeing is adequate and, above all, uniform absorbency of the paper. The advantages of this process are: quick changeover of shades, the possibility of only one-paper-side dyeing (typical paper grades for this are liner and testliner), absence of dyes in the water circuit, and, in the case of papers with higher basis weights (> 80 g m^{-2}), the saving of dyes. Nevertheless, compared with stock dyeing – the classical dyeing process – surface dyeing has gained acceptance only in individual cases because really uniform dyeing of the paper is difficult to achieve. It is occasionally advisable to combine stock and surface dyeing, e. g. to correct two-sidedness. The bleed fastness of surface dyed papers is generally lower than for internal dyed papers.

3.6.1.3.3 **Dip Dyeing**

A small group of specialty papers, called effect papers (flower crepe paper, tissue paper), is noted for its intense brilliant shades. The paper is passed through a dipping bath containing an aqueous solution of the dye or dye combinations. The excess dye liquor is pressed off between two rolls and the wet paper is creped, if required, before drying. Acid dyes are usually used because they have high solubility and bright shades. The low affinity of these dyes for fibers results in uniform dyeing, even in the case of papers with greatly varying fiber composition. The bleed fastness of dip dyed paper is poor, corresponding to that of surface-colored paper and even poorer than stock dyed paper.

3.6.1.3.4 **Surface Coloring by Coating**

In the usual coating process, the surface of the paper or board is covered with white pigments. In the case of colored coatings, the starting material is also a white pigment coating mixture, and the desired shade is attained by adding a dispersion of a colored organic or inorganic pigment. This coloring method and these colored pigments are mainly used for specialty paper and board e. g. for labels, documents, impressive image brochures and packaging materials. E. g. for a bronze-glazed paper surface aluminum or brass powder is added to the coating color, which produces a silver or gold effect or, in combination with soluble dyes, a metallic effect. Water-soluble dyes can be used only to a limited extent because, even with the use of fixatives, bleeding cannot be prevented (migration into the base paper and into moist surfaces). Also, the inadequate lightfastness compared to pigments limits the use of these dyes.

3.6.1.4 Requirements of Colored Paper and Board

Depending on the intended purpose of the paper, different *fastness properties* are required:

3.6.1.4.1 Light Fastness

This is defined as the fastness of a dyed paper to the action of light. It is determined by both the dye used and the raw materials of the paper. The degree of lightfastness is specified by a test method according to DIN 54 003, which is also used in the textile industry. Originally lightfastness was tested by exposing the dyed material to sunlight under defined conditions. Today artificial light with a radiation spectrum similar to sunlight is used (Xeno test apparatus or Fade-Ometer). The lightfastness cannot be given as an absolute value but can only be expressed in relation to a standard which is exposed simultaneously. In the textile and paper industry, the Blue Wool Scale is used as a standard for comparison. It consists of blue dyeings with lightfastness ratings from 1–8. Rating 1 signifies the lowest, and rating 8 the highest lightfastness. A dyed paper with a lightfastness of 1 will change its shade after one hour "sunlight" exposure. However, the shade will not fade completely until it has been exposed for several hours, depending on the depth of shade and the fibrous material. Since paper is normally not subjected to such severe exposure, a lightfastness of 1 is sufficient for all short-lived paper grades e. g. newsprint, magazines and grades based on mechanical pulps (e. g. for coating base paper, notepad) and/or mixed recovered paper (e. g. for liner, testliner). A lightfastness of 3 corresponds to a resistance of several days exposure. Dyes with this lightfastness rating can be used for most paper articles, provided that the paper stock, too, has approximately the same lightfastness e. g. for all kinds of high grade printing and writing papers. Dyed paper with a lightfastness rating of 5 does not undergo any change in shade, even on exposure to direct sunlight for several weeks, this rating is needed e. g. for document paper, photographic paper, laminating base paper.

3.6.1.4.2 Bleed Fastness

This is required for paper and board that are used for food-packaging and tissue papers (napkins and hygienic papers). According to the regulations, tests must be carried out in each case to determine whether and to what extent dye can migrate from a colored paper onto the packed foodstuff or to human skin. The paper may come into contact with water, dilute fruit acid, grease, oil, alcohol or alkali. A test specimen is placed between two uncolored glassfiber papers moistened by dipping into the test solution. This sandwich is then placed between two glass plates of the same size. The whole is then wrapped airtight in a polyethylene film and loaded with a certain weight. The specimen is kept in this condition for 24 h at 20 °C. After drying, the coloration of the glassfiber paper is compared with the Grey Scale to assessing the fastness to bleeding according to DIN 54002. It should be emphasized that the bleed fastness is not only dependent on the dye but also on the fibrous material and the type of dye fixation. A reliable prediction can be made only on the basis of tests with the paper in question. For napkins and hygiene papers a number of direct dyes are suitable and for wood-containing papers and testliner a good bleeding fastness can be obtained with basic dyes.

3.6.1.4.3 **Other Properties**

Rub resistance is required for album and wrapping paper and for cover board. Direct dyes are suitable for this purpose.

Acid resistance is required for parchment and vulcanized fiber base paper, writing, and printing paper. Organic and inorganic pigments, selected representatives of all colorant groups, are suitable for this purpose.

Solvent resistance is required for labeling paper (packaging of perfumes, medicines, and spirits). Special pigments are suitable for this purpose.

Heat resistance is required for cable and core paper and laminate paper. Organic and inorganic pigments are suitable for this purpose.

3.6.2

Optical Brightening Agents (OBA) – Fluorescent Whitening Agents (FWA) [2, 9, 11]

OBAs, also called FWAs, represent 3% by value and only 1% of the total dry amount of *specialty chemicals* (see Fig. 3.2 and 3.3). They increase the whiteness/brightness of paper and are preferably added to the stock. They are very effective when used with highly bleached pulps, and much less effective, or even ineffective, when applied to unbleached chemical pulps and mechanical pulps. OBA are also used in surface applications such as surface sizing and paper coatings.

OBA absorb light in the ultraviolet spectrum range (below 370 nm) and re-emit the light in the visible blue range (peaking at 457 nm). This results in a fluorescent effect with bright white in daylight masking the inherent yellowness of the raw materials. Any material that absorbs ultraviolet light will lower the efficiency of fluorescent whiteners. For example, lignin absorbs ultraviolet light and the higher the lignin content of the pulp, the less effective is the OBA. Hence, mechanical pulps and unbleached pulps are less susceptible to whitening with OBA. Some filler clays tend to counteract the fluorescence and reduce the effect of OBA. Fillers such as calcium carbonate and aluminum trihydrate reflect ultraviolet light, thereby enhancing the effect of OBA. A high pH (above 6) also helps to achieve maximum whiteness. On the other hand TiO_2 absorbs UV, thus OBA cannot be used in conjunction with high TiO_2 loading.

Substances of different chemical composition and different biological origin are used for fluorescent whitening of paper. Derivatives of diaminostilbene disulfonic acid have proved the most popular in industry because of their fastness properties. The active ingredient content is generally between 20 and 27 %. Their central part is disulfonated diaminostilbene. The types differ in the number of sulfonic acid groups in the side groups. The high-substantivity types with only 2 sulfo groups make up about 11 % of the market while tetrasulfonated derivatives with medium substantivity are about 80 %. The rest is low-substantive, hexasulfonated types.

The paper industry today needs fluorescent whitening agents to obtain high degrees of whiteness at reasonable cost, especially if the FWA (OBA) are combined with shading dyestuffs. This in turn leads to sharper contrasts in the printed image and thus helps to reduce the toner consumption of copiers, for example. Similarly, the color brilliance of color prints is improved. For application in the stock, high or medium-substantivity types are generally used, being 1 % of the commercial-grade product. For surface application in the size or film press, medium or low-substantivity types are used, the normal addition being 1.5 % and in exceptional cases up to 3.5 %. Low or medium-substantivity FWA are also the preferred products for coating application, the amount required being up to 1.5 % up to 3.5 % in exceptional cases. A maximum amount of FWA can be used in each application as the shade becomes greener. This will lead to a graying effect on the brightness.

3.6.3
Chelating Agents – Complexing Agents [3–5]

The presence of heavy metals negatively influences many production processes and paper properties. In particular, they interfere with the bleaching agents in chemical and mechanical pulp production, reducing their effect, so the task of chelating agents is to counteract this detrimental impact. Chelating agents can also reduce or stop uncontrolled decomposition of a hydrogen peroxide solution, which would result in loss of bleaching effectiveness.

Chelating agents that contain amino and carboxyl groups mask metal ions effectively. Chemical compounds of this type are nitrilotriacetic acid (NTA), ethylenediaminetetraacetic acid (EDTA), diethylenetriaminepentaacetic acid (DTPA), and hydroxyethylethylenediaminetriacetic acid (HEEDTA). Other complexing agents include the soluble salts of oxalic acid, citric acid, tartaric acid, gluconic acid, amines, and ammonia.

Both the demand for increased brightness and the technology trend to elemental chlorine-free and total chlorine-free bleached pulps has led to an increased use of chelating agents today, dominated by DTPA and EDTA.

In view of environmental protection, there exists a controversial discussion about the biodegradability of chelating agents. The results of newer investigations show that, under certain conditions, EDTA and, with some restrictions, DTPA, are fairly biodegradable. Their degree of biodegradability is still under discussion. It is strongly influenced by pH (optimum at pH 8.5–9), by ultraviolet light and by the effectiveness of adapted microorganisms. Up to 90 % biodegradability of EDTA is reached in some pulp and paper mills.

Of less importance are chelating agents based on polyphosphates, phosphonates, and hydroxycarboxylates as well as nitrogene free products like citrate, tatrate and gluconate.

3.6.4
Sizing Agents [2, 3, 9–11]

3.6.4.1 Fundamental Aspects of Paper Sizing

Sizing makes the native fiber network hydrophobic and thus prevents or reduces the penetration of water or other aqueous liquids into the paper. Sizing prevents the spreading and strike through of ink or printing colors. Papermaking fibers have a strong tendency to interact with water. This property is important for the development of strong interfiber hydrogen bonds, especially during drying, and is also the reason why paper loses its strength when rewetted. A high absorbency is important for a few paper grades such as toweling and tissue. Also corrugated medium paper must be "absorbent" to a certain degree to convert properly in the corrugating process. On the other hand such properties are disadvantageous for many paper grades e.g. liquid packaging, top layer of corrugated board, writing and printing papers and most of the specialty papers. The water and liquid absorbency can be reduced by the addition of sizing agents to the paper stock and/or by their application to the paper surface.

Since the invention of paper about 2000 years ago, it has been treated or saturated with mucilage and rice starch for surface glazing properties, so that people could write on it. After 1280 A.D. animal glue was the principal sizing agent. Alum (potassium aluminum sulfate) was used to harden the applied glue. Alum rosin sizing entered the scene in 1806 (Moritz Friedrich Illig). In 1876, papermaker's alum, $Al_2(SO_4)_3$, was introduced. Since the 1950s the various forms of rosin size (paste, dispersed, fortified), alkyl ketene dimmer size (AKD), alkenyl succinic anhydride size (ASA) and polymers mainly based on styrene acrylate and styrene maleinate (PSA) have come to the market. Today, beside starch for strength improvement (Fig. 3.2) and polymer binders for paper coating, sizing agents are the most important quality improving additives in paper manufacturing. Amongst the specialty chemicals, sizing agents represent a share of 10% in dry mass (Fig. 3.3.) and a total worldwide turnover of approximately 950×10^6 €.

3.6.4.2 Product Classes

The main classes of chemicals and their consumption as a proportion of the total worldwide usage of 350000 tons dry p.a. is shown in Fig. 3.10. Because of the trend to neutral or slight alkaline papermaking and the increasing use of calcium carbonate as a filler and coating pigment, the proportion and also the absolute volume of rosin will decline further and the synthetic products will steadily grow.

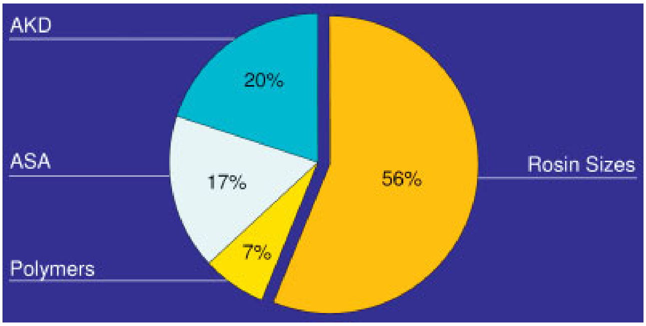


Fig. 3.10 Product groups of sizing agents worldwide in 2004 (% shares of solid or active substances).

3.6.4.2.1 Rosin-based Sizing Agents

These are still the most widely used of all wet-end sizes, because they are cheap to produce and are produced from regenerative raw materials. They are mainly used in acid and much less in pseudo-neutral pH conditions. They have the advantage that the degree of sizing can be controlled very easily, and the sizing effect is fully cured when the paper leaves the machine. In practical use there are different preparations of rosin, for which the following terms are used:

- *Free rosin*: Resin acids whose carboxyl groups are in the completely protonated form.
- *Dispersed size*: High (95–100%) free rosin dispersion of resin acids. The dispersed size particles are stabilized by surfactants, starch, polymers, or proteins.
- *Rosin soap size*: Rosin size composed of the sodium salts of resin acids. Formed by neutralizing (saponifying) resin acids with NaOH or some other sodium base, such as Na_2CO_3. Different forms of soap sizes are available, including paste, extended, and dry sizes.
- *Extended size*: A 50% solids product consisting of a 50:50 mixture of completely neutralized resin acids and urea.
- *Fortified size*: Rosin size that has been reacted with fumaric acid or maleic anhydride to form the Diels-Alder adduct. The reaction product contains extra carboxyl groups and produces more efficient sizing response than the unreacted resin acids. It is used as a starting material for other size products.
- *Dry size*: A 100% neutralized, dry rosin size product that dissolves easily in water.
- *Paste size*: An 80% neutralized rosin size product marketed as a 70–80% solids paste.

3.6.4.2.2 Synthetic Sizing Materials

These were only developed in the second half of the last century. Driving forces have been the increasing use of the cost and performance effective calcium carbonate as filler and coating pigment and also the need to produce paper with high and permanent paper strength. To enable its use the paper has to be produced under alkaline conditions. Other paper grades must have very hard sizing in order to resist edge wicking in liquid packaging applications or photographic base paper, or to exhibit hot water resistance for gypsum board. Many mills also seek an alternative sizing procedure to the wet-end application, e.g. in the form of a surface treatment in the drying section, to obtain higher efficiency.

- *Alkyl Ketene Dimer* (*AKD*) was the first synthetic size and appeared in the patent literature in 1953. Structurally, alkyl ketene dimers are unsaturated lactones. In the manufacturing process a frequently used synthesis route is: the acid chloride of a carboxylic acid is prepared (fatty acids, C_{16-22} homologs treated with, e.g. phosphorus trichloride, phosphorus pentachloride, thionyl chloride or phosgene), followed by intermolecular lactone ring condensation via a labile intermediate carboxylic acid obtained by dehydrohalogenation of the acid chloride with triethanolamine in an organic solvent. Newly developed processes work without any solvent. To handle and to use AKD in a paper mill, the wax must be converted into tiny particles (0.5–2 μm) dispersed in water. The emulsification is usually effected in a hot (75–90 °C) solution containing the cationic starch stabilizer (alternatively a cationic polymer e.g. polydadmac, polyvinylamine) and a small amount of surfactant, e.g. sodium lignin sulfonate, to which are fed AKD flakes. After melting the AKD, the mixture is forced through a microfluidizer and cooled. Small amounts of a promoter (cationic polymer with low molecular weight and high charge density) and biocide can also be included. The solid content of the commercial products varies between 6 and 30%. Some scientists believe that AKD reacts with the hydroxy groups of cellulose to form β-keto esters.
- *Alkenyl Succinic Anhydride* (*ASA*), as a synthetic sizing agent for paper, was first synthesized in 1974. It is composed of an unsaturated alkenic hydrocarbon backbone coupled to succinic anhydride. It is usually manufactured in two stages: First an unsaturated linear or branched olefin, e.g. a 1-alkene, is isomerized by moving its double bond randomly from its α-position. This will yield an ASA product that is liquid at room temperature, a condition important for easy emulsification of the size on application in the paper mill. In the second step, the mixture of isomerized alkenes is reacted with maleic anhydride to produce the ASA raw material. Normally ASA is a yellowish oily product. This 100% active substance can be stored as such for a long time but must be well protected from water or humidity.
- *Polymeric Sizing Agents* (*PSA*) are mainly based on styrene-acrylates, polyurethanes or styrene-maleic acid anhydride. They are either water-based dispersions or aqueous solutions. These products were developed around 1960. Since that time an increasing number of size-presses for strength improvement with starch have been installed.

  The *styrene-maleinate polymers* are anionic, aqueous solutions with a solid content of 20–30% and an alkaline pH (mainly containing the ammonium salt). They are specially designed for surface application. Their advantages are very good compatibility with all other anionic chemicals (e.g. native and anionic starches, CMC, optical brighteners, anionic polyacrylamides) and high stability in the size-press or in water doctors. The disadvantages of styrene-maleinate polymers are that the sizing effect depends on a certain amount of alum in the base paper, the improvement of printability on wood-free white papers is limited, and these products are not suitable for wet-end addition (internal sizing). In respect of this, the cationic *styrene-acrylate* dispersions are much more commonly used. They possess high paper stock affinity and the sizing effect is largely independent of the alum content and pH in the stock suspension. Therefore they can be used for nearly all paper grades, depending on the cationic density of the polymer. With increasing cationic density a reduction in the optical brightening and the paper brightness will occur. Most products of this class are suitable for wet-end and surface application. The sizing effect is developed within the paper machine. The sizing is improved by intense contact drying on hot metal surfaces (e.g. drying cylinders). The sizing obtained is resistant to acids and alkalis. The surface properties of the paper are improved, especially pick strength and printability and linting and dusting are also reduced.

3.6.4.3 **Application Advice**

- *Rosin*: The average addition rate is 1% solid calculated on paper, the individual rate depending on the required degree of sizing. With these products this degree can be adjusted very precisely and is fully obtained directly after the paper has been dried. The product is usually added to the stock suspension upstream of the headbox and then fixed chemically, in the simplest case with aluminum sulfate (alum). The retention of rosin size is in the region of 70% if the usual fixing agents are employed. Rosin sizes are not usually suitable for surface applications.
- *AKD*: As little as 0.005–0.008% reacted AKD is believed to yield sufficient monomolecular coverage of the paper stock, while dosage rates are considerably higher and typically vary from 0.05 to 0.2%, calculated as solid AKD wax based on paper stock. The stability to hydrolysis of most commercial products has been improved significantly in recent years. The ketone resulting from the hydrolytic decomposition of AKD is a solid (melting point 80–85 °C) which can be retained in the sheet but does not contribute to sizing. The risk of the formation of deposits is relatively low. For cost efficient sizing, the curing (orientation of AKD particles) must be initiated appropriately because chemical reaction alone is not sufficient. The curing can be improved by drying the paper web at high contact temperatures and to a very low moisture content e.g. before the size press, typically to 1–3%, especially on fast-running machines. Another way to speed up the curing before converting is to carry out AKD sizing in the presence of a so-called promoter resin, e.g. polyamide epichlorhydrin, modified polyethylenimine, polyvinylamine.
- *ASA*: This will not dissolve in water and, prior to application in papermaking, it must be emulsified on site at the paper mill. There, a small amount (3–6%) of

an activator is added, plus cationic starch and a synthetic cationic polymer which serve as stabilizers. Activators are surface-active agents that promote effective emulsification at low mechanical energy. Emulsion stability is best with synthetic polymer, and sizing efficiency is best with cationic starch, improving with the amount of starch used. The ratio of starch to ASA is usually in the range 2:1 to 4:1. Emulsification is primarily carried out in a continuously operated special automated equipment, and can be affected by both low and high shear procedures. Particle sizes in the range 0.5 to 2 µm can be obtained. Emulsification imparts a cationic charge on the oil droplets which helps to increase the stability as well as improving ASA retention on anionic fibers and sizing efficiency. Linear hydrocarbons are more hydrophobic than branched ones. However, the greater the hydrophobicity of the ASA molecule, the more difficult is the preparation of a stable quality ASA emulsion.

ASA undergoes the normal reactions of acid anhydrides. Of particular interest in conjunction with sizing is the reaction with alcoholic hydroxy groups to yield an ester, and the hydrolysis with water. Both reactions occur in the papermaking system. ASA is highly reactive, and the reactions proceed rapidly and irreversibly. Although this would provide satisfactory development of sizing on a paper machine, the hydrolysis of ASA is undesirable. The hydrolysis accelerates with pH, time, and temperature and leads to deposits and runnability problems on the paper machine. In order to limit the hydrolysis of ASA emulsions, the pH can be lowered immediately after the emulsification by addition of aluminum sulfate.

High solids retention is extremely important in ASA sizing. If this is guaranteed and ASA is applied correctly, a relatively small dosage of 0.1–0.2% based on solid furnish is required to produce the desired degree of sizing. Careful selection of retention aid is therefore an important part of the ASA sizing process. The great advantage in favor of ASA is the high rate of cure in comparison with AKD size. The reaction with cellulose hydroxy groups takes place rapidly in the dryer section of the paper machine at less than 5% web humidity. More than 90% of the attainable sizing potential is, in most cases, achieved before the size press unit. The reaction rate is influenced by the same parameters as the hydrolysis, that is primarily by pH, previous residence time, and stock temperature. The best conditions obviously depend upon the balance between the reaction rates with cellulose hydroxy groups and hydrolysis of ASA, and optimum sizing can be achieved at neutral rather than at higher pH, depending on the full set of system conditions.

- *PSA*: For *internal sizing* (wet-end addition) quantities of 0.5 to 1% (solid product on dry paper stock) are required to obtain a hard sized sheet, depending on the nature of the stock. The product is best metered continuously to the stock suspension before the pressure screens. The polymer must be prediluted with an in-line mixer to a concentration of 1–5%. A cationic retention aid, e.g. modified polyethylenimine, cationic polyacrylamide or polyvinylamine improves the fixation/retention and therefore gives a better sizing effect.

For *surface application*, first the compatibility with the other chemicals used in the preparation and also the shear stability have to be checked (e. g. with starch, optical brightener, dyes). It is advisable to meter the undiluted polymer by means of a piston pump to the circuit of the size-press, e. g. before the feed pump. To achieve a good effect, the PSA must penetrate sufficiently into the paper, e. g. an adequate quantity of sizing solution must be taken up. Quantities of 2–4 $g\,l^{-1}$ solid polymer in combination with 40–80 $g\,l^{-1}$ starch are normally sufficient to achieve a hard sized paper sheet; 1–2 $g\,l^{-1}$ solid polymer is sufficient for final sizing of a paper that has been presized internally.

3.6.4.4 **Requirements and Measurements of Sized Papers**

The purpose of sizing is to modify the surface of the fibers to control penetration of aqueous liquids into the paper. The penetration usually correlates with the absorbency, repellency (hydrophobicity), and spreading of the aqueous liquid concerned. Control of these important properties may be required for three purposes:

1. Control of the penetration rate of the aqueous phase in a converting operation such as size press treatment, coating, glueing (influences also the machine runnability).
2. Control of liquid absorption or wetting in a printing process.
3. Control of the serviceability of many grades of paper and board, e. g. milk/juice carton, packaging papers, wallpaper, printing writing papers, etc.

Besides a certain degree of water and ink resistance the papermakers and their customers often look for improvements in dimensional stability, surface strength (pick and rub), internal bond, linting, dusting, stiffness, smoothness, porosity, or friction coefficient, depending on the converting process and use of the paper.

Several test methods are used to measure the degree of water and ink resistance:

- *Water drop absorption*: the time required for defined droplets of water to be absorbed by paper.
- *Ink flotation test*: the time required for writing ink to penetrate through a floating piece of paper and to change the color of the upper surface.
- *Hercules sizing test*: the decrease in reflectance of the opposite side of a paper sheet which has been covered with a given amount of ink.
- *Cobb test*: the amount of water absorbed by a given area of paper in a specified period of time.
- *Pen and ink feathering test*: the extent of spreading of lines drawn on a paper sample with a steel pen and ink.
- *Contact angle*: the tangential angle from the horizontal which the base of a drop of liquid develops when carefully placed on a paper sheet.
- *Edge penetration/edge wicking test*: the lineal penetration of liquid in the in-plane dimension of the paper.

3.6.5
Dry-Strength Resins (DSR) [3, 9–11, 22–24]

Some of the specific mechanical properties important for paper are tensile strength, tearing resistance, folding endurance, bending resistance, burst and surface strength, internal bond and compression resistance. It is generally accepted that the major factors contributing to dry strength development in paper manufacture include Van der Waals forces, hydrogen bonding and ionic bonding. Because of the special effect of water on paper strength, it is common to distinguish between "dry" and "wet" strength properties of paper. The two subjects are obviously related, but wet strength will be treated as a separate topic. Paper strength is affected by many furnish and process variables. On the furnish side, longer softwood fibers produce stronger papers than shorter hardwood fibers. Fillers reduce strength. Alkaline pH conditions in the wet-end produce stronger papers, especially after aging, than do acid pH conditions. On the process side, both increased refining and wet pressing increase paper strength. The basic factors that influence paper strength are: individual fiber strength, interfiber bond strength, the number of interfiber bonds (bonded area) and the distribution of fibers (sheet formation). While the first factor cannot be influenced by strength additives, the remaining three factors can be strongly influenced by such products.

Many water soluble, hydrogen bonding polymers will act as dry strength additives. In fact, wood fibers contain their own natural dry strength additive in the form of hemicelluloses. It is well-known that the removal of hemicelluloses from wood fibers makes it more difficult to develop their bonding characteristics.

- *Starch*: In general starch derivatives represent the most common and by far the largest amount of dry strength additives (Fig. 3.1).
- *Vegetable Gums*: Much less important but also used are water soluble vegetable gums, such as locust bean gum and guar gum. These highly hydrophilic polymers have chemical structures which are similar to cellulose, enabling them to participate in extensive hydrogen bonding with fiber surfaces. The natural materials are nonionic and are not retained by fibers to any extent. Consequently, successful commercial products all have cationic groups attached to the main chain, which increases the attraction between gum molecules and fibers and results in improved polymer retention. Due to the combination of high retention and effective dry strength enhancement only 0.1–0.35 % of the material has to be added in most instances.
- *Polyacrylamide Resins*: The fully synthetic DSR are of growing importance. In Japan they already form the largest proportion of the total consumption of dry strength resins. Their worldwide consumption is an average of 300 g dry polymer per ton of paper or 3 % of the total amount of specialty chemicals (see Fig. 3.3). In the group of synthetic dry strength resins the polyacrylamide-based products are still dominant today. Since anionic polyacrylamides are negatively charged, they are not directly attracted to paper fibers. A cationic substance, such as alum or polyamide epichlorohydrin resin, must be used to promote their retention. To avoid the need for a cationic promoter, it is possible to incorporate

cationic groups (e. g. methacryuloyloxethyl trimethyl ammonium methosulfate, dimethyldiallyl ammonium chloride, vinyl benzyl trimethyl ammonium chloride, 3-acrylamido-3-methyl butyl trimethyl ammonium chloride) directly into the polyacrylamide backbone by copolymerization. When used as dry strength additives, typically 10% of the monomers will be charged and their molecular weight will be between 100 000 and 500 000. This range is low enough that the polymers will not bridge between particles and cause flocculation, and high enough to retard migration of the polymer into the fiber pores with concomitant loss of activity.

- *Polyvinylformamide/Polyvinylamine Resins* (*PVF/PVAm*): Recently developed new types of polymers in the form of polyvinylformamide and polyvinylamine are coming into use. All these water soluble polymers contain primary amino groups that can form hydrogen bonds with surface cellulose molecules in fibers and improve interfiber bonding. These polymers enable the papermaker to achieve combinations of paper properties that cannot be obtained through refining alone. For example, strength properties can be improved without affecting sheet bulk and/or appearance properties.

  The new DSRs are produced by polymerizing vinylformamide and then hydrolyzing it. This results in a chain type macromolecule with primary amino groups without using an additional monomer. These polymers can be varied within a very wide range of molar mass and charge density to optimize the performance. Medium or low charged polyvinylamines of medium molecular length give high performing dry strength resins. Further improvements in cost-performance can be achieved by product combinations, e. g. low/middle charged cationic polyvinylamine plus low molecular, middle/high charged anionic polyacrylamide or cationic polyvinylamide plus anionic polyvinylformamide.

  These products have no remaining monomers, and do not contain formaldehyde or organically bound chlorine, therefore they do not release chlorine to the effluent. The environmental advantages of this new group of DSRs is underlined by the fact that they have been approved by the German health authorities (BfR-Bundesinstitut für Risikobewertung) for food packaging paper and board. PVF and PVAm products also conform to the requirements of the United States Food and Drug Administration (FDA) regulation 21 CFR 176.170 (Components of paper and board in contact with aqueous and fatty foods), according to its current status. It may be added at levels of up to 1.5% solid polymer, expressed as a proportion of the dry, finished paper.

  Polyacrylamide- and polyvinylamine-based DSRs are mainly supplied as ready to use aqueous solutions or emulsions (10–40%) or as water soluble powders that must be dissolved prior to use. No other preparatory steps are necessary. The most beneficial way of application is to meter them continuously to the thick paper stock at a point of thorough mixing, e. g. at stock dilution. Addition rates of 0.1 to 0.5% of solid material are adequate for most uses. Excessive use can overcationize the stock suspension and reduce the effectiveness of the DSR and of other cationic additives.

3.6.6
Wet Strength Resins (WSR) [2, 9–11, 21–24]

Certain types of paper can only fulfil their purpose if they have adequate wet strength. Such papers include, for example, filter papers, hygienic papers, papers for bags, label papers, wallpapers, laminate base papers, packaging papers for moist goods and all papers which, in the course of further processing and use, risk breaking when rewetted. The required wet strength (up to 50% of the dry paper strength can be retained) is obtained with the aid of wet-strength resins. For extremely high wet-strength properties the most common WSR are urea formaldehyde resins (UF-resins) and melamine formaldehyde resins (MF-resins), These chemicals need acid pH conditions and the presence of alum in the papermaking process. For neutral pH conditions polyamide-epichlorohydrin resins (PAE-resins) are mainly used (e. g. for hygiene and laminate papers); polyethylenimine products are used for specialty papers such as industrial filter papers and shoe board.

The total consumption of wet strength resins, together with insolubilizers for coating (see 3.6.9.3.5.2), accounts for about 0.07% of the worldwide paper production or 7% of all specialty chemicals, calculated on the active ingredient (Fig. 3.3). Over the past years, consumption of PAE-resins has increased overproportionately. This is partly due to the trend from acid manufacturing conditions to the neutral pH range, where polyamide-epichlorohydrin resins are more effective than urea formaldehyde and melamine formaldehyde resins. However, the increasing importance of PAE-resins is no doubt also largely a result of the formaldehyde controversy of the early eighties. PAE-resins account today for about 45%, urea formaldehyde resins 15%, melamine formaldehyde resins 10%, glyoxal resins 15% and the remaining 15% are others, e. g. ammonium zirconium carbonate (as insolubilizer) and newly developed products e. g. polyvinylamines.

There are two theories regarding the mechanism of wet strength. The first states that the wet strength effect is due, at least in part, to a reaction between the resin and the cellulose, which leads to the formation of ether bonds. The second theory assumes that the wet-strength resins crosslink on exposure to heat in the dryer section to form a three-dimensional network, wrap themselves around the points where the fibers intersect and thus protect the points of intersection from water penetration and swelling. Given the short contact times with the steam-heated cylinder surfaces (less than a second in the case of the yankee cylinder used in hygienic paper production), wet-strength agents require a high level of reactivity to allow crosslinking to take place and bonds to form. At the same time, the wet-strength resins have to have a selective effect if they are not to react with the surplus hydroxy groups in the paper stock suspension. Therefore a healthy balance between reactivity and selectivity has to be found, so that the chemical reactions (crosslinking, formation of covalent bonds) are not completed at the end of the paper manufacturing process but continue during storage until maximum wet strength is reached one to three weeks later. This gradual curing should not be looked upon as a disadvantage as it is essential for good recycling of the paper machine broke.

3.6.6.1 Melamine-Formaldehyde Resins

In most instances, melamine is made from a basic product such as cyanamide. The melamine molecule is then condensed with formaldehyde to form a series of methylol melamines, e. g. monomethylol melamine and hexamethylol melamine. On introduction to a papermaking system, the melamine formaldehyde product can crosslink with itself forming an ether link or a methylene link, as well as crosslinking with a cellulose carboxyl group to form the covalent bond, both of which contribute to wet strength. The advantages of the melamine-formaldehyde resins are that they lead, with similar addition rates to UF-resins, to wet tensile strength levels up to 50% and to even higher wet bursting strength. MF-resins also provide a very high alkaline resistance, therefore such products are mainly used for label papers and banknote base papers.

3.6.6.2 Urea-Formaldehyde Resins

The formation of aqueous solutions of urea-formaldehyde condensation products involves the stepwise reaction of urea with formaldehyde, and the first step is undertaken at pH 7–8 to form dimethylol urea. Further reaction to a controlled degree with formaldehyde forms a condensation product in aqueous solution, which can be stored and transported. Urea-formaldehyde and melamine-formaldehyde resins are delivered in aqueous solutions with solid contents of 12% (MF) and 40% (UF) as well as in powder form (MF). They are mainly applied at the wet end, but they can be also used via surface application in the paper machine. Suitable feeding positions for the continuous wet-end addition are between the stock consistency controller and the mixing pump, shortly before final stock dilution, where an optimum of mixing is guaranteed. The UF-resins are the least expensive ones. An important area of application is in the manufacture of sack paper for shipping and cement packaging. With addition rates of 0.5 to 3%, calculated on dry paper stock, a wet-strength level of up to 40% of the dry-strength figure can be achieved.

3.6.6.3 Epoxidised Polyamide Resins

The chemistry of the production of polyamide resin is very similar to the original process by which nylon was produced. In the Nylon 66 process a dicarboxylic acid, such as adipic acid is reacted with a six carbon amine, for example hexamethylenediamine, to produce a synthetic fiber. In the case of polyamide resin, a dicarboxylic acid is reacted or condensed with an amine such as diethylenetriamine to form an amino polyamide. The secondary amine groups of this water soluble polymer are then reacted with epichlorohydrin to form the aminopolyamide epichlorohydrin intermediate. This is then crosslinked to build molecular weight whilst maintaining solubility. The polymerization reaction is terminated by dilution and acidification.

The amount of polyamide-epichlorohydrin resin required in hygienic paper production is between 0.1 and 4% dry substance, calculated on the paper. These resins are supplied in the form of aqueous solutions with a solids content of 12 to 25 %. They are effective in the pH range 5 to 8, although the best wet-strengthening effect is obtained in the neutral or slightly alkaline range; they are therefore often called neutral wet-strength resins. In the majority of cases, PAE-resins are added to the stock, preferably just before the last stock pump in front of the headbox. This ensures that the fiber/resin bond is not impaired by high shear forces. Depending on the amount added, the relative wet strength can be increased to over 35 % without significantly reducing the absorbency of the paper. Wet-strength resins in general also increase the dry strength of paper (i. e. tear and burst). They also have favorable effects on the dry and wet abrasion resistance of paper. Additionally the retention of fillers and fines is increased. A special effect of PAE-resins, even with small quantities, is to form a coating on the crepe cylinder of a hygiene paper machine to control the adhesion of the paper web on the cylinder.

The disadvantages are that the degree of whiteness is less stable than with UF and MF resins, and the AOX problematic. Much effort was put into developing "low-AOX" and recently also "AOX-free" polyamide-epichlorohydrin resins with no detectable amount of byproducts. At the same time, chlorine-free wet-strength agents have also been developed, e. g. modified glyoxals and polvinylamines, but often with higher costs. In the longer term, workplace safety aspects could lead to the application of these new products becoming successfully established in the market.

3.6.6.4 **Glyoxalated Polyacrylamide Resins**

These products are prepared by crosslinking a low molecular weight polyacrylamide (PAM) with glyoxal. The PAM is normally a copolymer of acrylamide and a quaternary ammonium cationic monomer which is prepared in aqueous solution. This results in a cationic polymer which is attached to pulp fibers. The cationic backbone is then crosslinked with sufficient glyoxal to react with most, but not all, of the PAM backbone amide groups. On storage, the resin continues to crosslink and can ultimately gel. In order to achieve the desired stability, paper mills dilute the resin on receipt. At 25 °C, a 10 % solution will gel in about 8 days, whereas a 6 % solution will take about 65 days to gel at room temperature.

There is strong evidence that glyoxalated PAM imparts wet strength primarily through covalent bond formation between the resin and the fibers. It can be taken for granted that there is some intermolecular crosslinking within the resin but, in order to function, there needs to be at least some fiber-resin-fiber bonds within the fiber-fiber bonded area. The reaction of glyoxalated PAM with cellulose is rapid at neutral pH 6–8 and even more rapid at acidic pH 4–6, resulting in 80–100 % of the potential wet strength. Ageing or curing of the paper gives little or no additional wet strength. The reaction is reversible in the presence of water and a resin-treated paper gradually loses wet strength on prolonged soaking. This temporary wet strength can be sufficient for some paper grades, e. g. paper towels, and also during the paper manufacturing process when the the sheet is passing through a size press or coater. Glyoxalated PAM resins also contribute significantly to the dry strength of treated paper.

3.6.6.5 **Other Wet-Strength Resins**

- *Polyethylenimine* (*PEI*) was the first effective WSR used under neutral/alkaline pH conditions in papermaking without influencing the absorbency of the paper. The PEI manufacturing process is described in Section 3.7.1.1. The effective mechanism of PEI formation is somewhat different from the resins. PEI develops wet strength without curing the paper and the level of wet strength that can be attained is less than with the thermosetting resins. It has been proposed, that PEI functions by creating stronger interatomic bonding, rather than by forming homo- or co-crosslinked networks. The amine cationic groups responsible for wet strength have dissociation constants of around 12 and the retention and performance of PEI is best at pH 7–9. The reasons why PEI has not been used more extensively as a wet-strength resin are higher costs than with thermosetting resins and because it causes yellowing and loss of brightness in white printing and writing papers.
- *Polyvinylamines* are a relatively new group of wet-strength resins. These products are environmentally friendly, their use does not result in any negative ecological impact (see also Section 3.6.5 on Dry Strength Resins). Their cost-performance ratio is at present less favorable than the conventional WSR in most cases.
- *Polyisocyanate* is another new type of WSR, up to now with very little practical use.
- *Dialdehyde Starch* (*DAS*) also has the potential for crosslinking cellulosic hydroxy groups in paper to give temporary wet strength. DAS is essentially a highly modified starch in which the vicinal hydroxy groups (at the C-2 and C-3 carbons) are selectively attacked by periodic acid, severing the C-2 to C-3 bond to form dialdehyde starch. The aldehyde groups are not present to any extent as free aldehydes, but rather as hemiacetals or as hemialdals. Since the linkages in these compounds are weak, dialdehyde starch reacts as if the aldehydes were free, permitting its use as a reactive polyaldehyde capable of reaction through hydroxy amino or imino groups.

3.6.7
Additives for Recovered Fiber Processing [5, 12]

For economic and environmental reasons the use of recovered paper as raw material has already reached a high level and will grow further. For its preparation specific chemicals are required, depending on the quality of the recovered papers and the necessary properties of the produced paper grades.

3.6.7.1 **Additives for Repulping**

These chemicals are intended to facilitate the repulping of recovered papers, especially for mixed and brown grades e. g. packaging material, corrugated boxes. To get an easier and faster defibration the addition of nonfoaming wetting agents (e. g. nonionic surfactants) and dispersants is used. Wetting agents reduce the surface tension. These products are predominantly surface active, such as sulfonated oils, alkyl sulfates, alkyl sulfonates, alkyl aryl sulfonates, or ethoxylated products based on nonylphenol. Dispersants used for repulping are mainly condensation products of formaldehyde and a naphthalene sulfonic acid as the sodium salt, or the sodium salt of a polycarboxylic acid. These products have high dispersing capacity for pitch, waxes, bitumen, etc. which otherwise would adversely affect the whole repulping and papermaking process as well as the paper quality. The application of such products preferably takes place in the pulper in undiluted form with amounts of 0.1 to 0.5 %, calculated on oven dry paper stock.

Repulping of wet-strength paper always requires more energy than repulping normal unsized or sized paper. Depending on the type of wet-strength resin used, different methods and chemicals are employed. When UF (urea formaldehyde) resins or MF (melamine formaldehyde) resins have been used, repulping was effected in an acid medium with sulfuric acid and/or alum at elevated temperature above 60 °C in the pulper for 15–30 min. If the wet strength of the recovered paper is based on polyamine-type chemicals, defibering of this paper also requires high-energy pulping at an alkaline pH value >10 by addition of sodium hydroxide. Other useful additives are hypohalous acid and persulfate salts.

3.6.7.2 **Additives for Deinking**

Newspapers, weekly and monthly magazines, brochures and office papers are used as raw material to produce graphic papers, tissue or the top ply of white board. In the "deinking process" first the printing ink has to be detached from the paper surface then the released ink has to be removed from the pulp slurry, either by flotation or by washing or by a combination of the two. Whereas in Europe flotation is most commonly used and washing is only used for special deinked pulp (DIP) qualities, in North America washing is more common.

The removal of ink from recovered paper is determined by the type of ink binder and the chemicals used during pulping. For wood containing recovered paper grades the most important chemical is *sodium hydroxide* (NaOH) with addition rates of 0.5–2 % (calculated on oven dry paper stock) to adjust the pH to 10–11. NaOH eases the detachment of the ink particles from the fibers as saponifiable binders in the ink are saponified by NaOH and the fibers swell substantially in this environment. However, sodium hydroxide solution also causes yellowing of the fibers, particularly of mechanical pulp. In order to prevent this, *hydrogen peroxide* (H_2O_2) is used as a bleaching chemical, which also has a saponifying effect. In addition, 1–5 % *water glass* (*sodium silicate*) is added to stabilize the hydrogen peroxide and to prevent the ink particles from redepositing on the fiber.

Additionally 0.1–0.2 % of a nonfoaming *wetting agent* (e. g. nonionic alkyphenol polyethylene glycol ether) can support the removal of the ink particles from the printed recovered paper. Since hydrogen peroxide is more effective at higher concentrations, the pulping process is carried out at stock consistencies of 12–20 % (high consistency pulper or drum pulper). *Soaps* and *fatty acids* are used in addition rates of 0.5–1.2 % as dirt collectors and flotation agents. They form calcium soaps with hard water or with the calcium carbonate from the coating or filler of the recovered paper. *Calcium chloride* must be added if the water is not sufficiently hard. For higher quality papers, further bleaching with sodium dithionite and/or hydrogen peroxide may follow. Coated papers can be deinked more easily because the inks are fixed only on top of the coating layer.

For woodfree recovered paper grades the dosage of deinking chemicals (NaOH, soap, fatty acid, nonfoaming wetting agent) can usually be reduced substantially. Because deinked pulp (DIP) is very often used in paper grades of high brightness, bleaching with hydrogen peroxide, sodium dithionite and/or formamidine sulfinic acid (FAS) is more important and bleaching is often performed in two or more stages.

The effluent/white water quality has to be controlled very exactly. COD increases with increasing pH. For flotation deinking of recovered paper the total chemical costs have a relatively high proportion of 15–20% of the overall DIP production costs. Yield rates up to 93% for newsprint production are attainable.

In wash deinking after saponification the ink particles together with pigments and fillers of the recovered paper are removed by washing the pulp slurry through wire supported by the addition of 0.1–0.5% of a dispersing agent. Here large effluent streams are produced and solid losses are high, with yield rates of only 60 to 70% being not unusual. So flotation deinking, or a combined flotation-washing process, is also gaining a foothold in North America.

3.6.8
Additives for Specialty Papers [13, 14]

Specific functional chemicals are indispensable in the production of specialty paper grades. Such grades are expected to display a very heterogeneous range of properties. Specialty paper grades account for only ca. 4% of worldwide paper production, but the proportion of chemicals applied for their production is mostly significantly higher than for conventional papers. A number of specialty papers with their required properties and applied additives are described below .

3.6.8.1 Photographic Base Paper

Paper for photographs must carry a uniform emulsion coating, it must resist the development solution in the development bath, it must be perfectly clean for a clean image, and it cannot contain any inhibitors to the photochemical process like iron, copper, or sulfur. It must even be free of radioactive traces, which cause photographic reactions and spots in the image. The paper, which must have a stable white color, is made of clean bleached pulp. The necessary high dry and wet opacity will be obtained with titanium dioxide (TiO_2), chalk and low molecular weight polymers (e.g. polyacrylamides). In order to obtain resistance against the reagents and rinsing water, including edge and dimensional stability, the base paper needs a strong stock-sizing with behenyl diketene and high wet-strength with polyamine-polyamide-epichlorohydrin resin. Additional the paper web is dip sized with gelatin, polyvinyl alcohol (PVA), polyacryl amide (PAM), and modified starch before calendering. Most photographic papers for color prints are extrusion coated with an opaque plastic film (e. g. polyethylene) to improve the impermeability.

3.6.8.2 **Banknote Papers**

These papers have to avoid forgery, must be durable and resistant to wetting, folding and aging. Therefore they are produced under alkaline conditions with high wet and dry strength. To achieve these properties, polyamide-epichlorohydrin resins, polyacrylamides and/or aminoplast resins are used, together with strong stock sizing with AKD (alkyl keten dimer) and surface sizing with proteins plus crosslinking agent (glutaraldehyde). For security reasons these papers will be marked by mingle colored fibers with the paper stock and/or by using uncolored reactive dyes, which create a certain color when they react with an acid or an alkali.

3.6.8.3 **Laminate Papers: Décor Paper, Pre-impregnated Foils**

Décor paper is made for white or colored décor, often imitating wood finishes. It needs a high wet and dry opacity and very high lightfastness, which is obtained by using titanium dioxide (TiO_2) plus low molar mass polymers (polyamine-polyamide-epichlorohydrin resins, polyacrylamides). Also high wet strength without loss of absorbency is demanded and achieved by relatively high addition rates of polyamine-polyamide-epichlorohydrin resins. Colored décor papers with very high fastnesses are produced with inorganic and organic colored pigments.

Pre-impregnated foils are used where the surface requirements for resistance and closedness do not require more expensive high-density laminates. The impregnation will be made on the paper machine, using a modified size press. Typical resins for this application are UF (urea formaldehyde) or MF (melamine formaldehyde) resins with a very low content of free formaldehyde. To achieve good flexibility and printability of these foils, additional polymer dispersions (e. g. styrene acrylates) are used.

3.6.8.4 **Filter Papers**

There is a wide range of filter papers for various purposes. The use of porous paper for filtering and separation ranges from the use of filter cartridges for engine protection to dust pouches for vacuum cleaners and air conditioning, and from tea bags and coffee filters to reagent carriers and filter disks for laboratory use. Their common denominator is the requirement for a controlled, high porosity. Depending on the intended use, additional required characteristics are the resistance to different media and/or temperatures, stiffness, and cleanliness. Specific characteristics of filter papers are their resistance to flow, their filtration efficiency, and their dust-holding capacity.

The controlled porosity together with very high wet and dry strength is obtained by using polyamine-polyamide-epichlorohydrin resins together with a low molar mass polyacrylamide or polyethyleneimine, polyisocyanate, or polyvinylamine.

3.6.8.5 **Imitation Parchment (Food Packaging)**

Some of these papers have to be water-resistant and pore free, which is why microcrystalline wax, cationic styrene-acrylic emulsions, alkenyl succinic aldehyde (ASA) plus cationic starch, and styrene-maleic-anhydride (SMA) are used. To achieve resistance to oil and fat mainly perfluorinated alkyl acids, carboximethylcellulose (CMC), alginates and stearyl-melamines are applied.

3.6.8.6 **Aquarelle Board**

These boards must be resistant to fading, neutral, and stable. The finish varies from a coarse surface for painting to a very smooth surface for graphic work. High opacity and uniform surface structure will be achieved by using chalk (calcium carbonate) together with a low-molar-mass polymer e. g. modified polyethyleneimine, polyamine, polyvinylamine. Cationic styrene-acrylic emulsions plus carboxy methyl cellulose (CMC), starch and/or low molar mass polyacrylamides or polyvinyl formamides lead to controlled uptake of water and oil as well as high stiffness and rattle. For rub out resistance, surface sizing with starch and styrene-acrylic emulsion is applied.

3.6.8.7 **Carbonless Copying Paper**

The dominating principle for carbonless copy is that an emulsion of a specific oil e. g. diisopropylnaphthalene (DIPN) together with color formers (reactive dyes) is encapsulated in microcapsules (e. g. gelatine, aminoplast resins) applied as a coating on the backside of the copying paper (CB-coated back). Through the pressure of writing, the microcapsules are broken, and the color former solution flows to wet the front side coating of a receiving sheet (CF-coated front). The front side coating reacts with the color former, forming an image. The pressure sensitive coloring side (CB) has to be resistant to abrasion. Microcapsules from gelatine or polyurea or melamine-formaldehyde condensation products contain solvent e. g. diisopropylnaphthaline (DIPN), or isopropyl-butylbiphenyl, or phenylmethane-ethane plus reactive dyes (color former). Polymer dispersions of styrene-butadiene are used as binder for the surface application of the microcapsules. The coating formulation of the reactive receiving side (CF) consists of activated bentonite or phenolic resin or zinc salicylate plus styrene-butadiene binder.

3.6.8.8 **Ink-jet Papers**

Ink-jet is a noncontact printing method, since no part of the printing device other than ink contacts the paper at the moment of ink transfer. A sharp, detailed printed image (no wicking and bleeding), high color density and no strike-through will be obtained by a hydrophilic paper surface using a coating color with silica gel, polyvinylalcohol (PVA) and/or carboxy methyl cellulose (CMC) plus low-molar-mass cationic polymer e.g. modified polyethyleneimine, polyvinylamine, condensation product of organic amides with formaldehyde, polyacrylamide. The base paper should be hard-sized with alkyl ketene dimer (AKD), or alkenyl succinic aldehyde (ASA), or rosin size.

3.6.8.9 **Fire-resistant Papers**

Papers with fire-resistant properties are used for wallpaper, decoration paper, Chinese/Japanese lamps and partition walls. Flame retardants are added either at the wet end or by surface treatment in the paper production process. They either release incombustible gases on heating, which prevent the entry of atmospheric oxygen, or when heated produce a nonflammable melt that surrounds the paper. Chemicals for this purpose include calcium chloride, magnesium chloride, diammonium ethyl phosphate, and mixtures of zinc borates, antimony oxides, and organic haloid salts as well as inorganic bromides and oxybromides.

3.6.8.10 **Anticorrosion Papers**

These papers prevent the rusting of iron parts and the tarnishing of silver, aluminum, and copper. Generally they have to be produced in alkaline wet-end conditions in the absence of any acid and alum. Additionally the paper has to be impregnated or coated with chemicals that inhibit corrosion, e.g., sodium nitrite or sodium benzoate. The paper is coated by deposition of the chemicals from the vapor phase.

3.6.8.11 **Abrasive Base Papers**

Abrasive papers which are coated with an abrasive grit in a binder are used for belts in heavy grinding machines, as sheets for grinding by hand, in vibrating hand-held grinding machines, or disks in rotary machines. There are specific grades for wet grinding and for dry finishing by hand. The base paper must be strong enough to resist the forces in use, give a good anchoring of the grit, and suit the coating operation. High amounts of anionic and cationic starches, often together with carboxy methyl cellulose are used to obtain high strength properties. Additional polymer dispersions based on styrene acrylates or styrene butadiene are applied at the wet end of the paper machine and/or by on-machine or off-machine impregnation. With wet-end addition of these polymers effective fixation and retention in the paper stock with alum and/or cationic polymers e.g. polyethylenimines, polyamines, polyvinylamines are necessary.

3.6.8.12 **Papers with Barrier Properties**

Paper or board have almost no barrier properties against penetrants like moisture, water vapor, oxygen and other gases, aroma, grease and fat. To provide protection against outside influences as well as protection against loss of features from inside, a specific barrier coating is required. To make paper and board suitable as a barrier packaging material, the barrier layer has to be applied either by wax impregnation, lamination with films e.g. PE (polyethylene) or aluminum foil or the extrusion of molten polymers, The most favorable and economic method is the on- or off-machine coating of paper and board with an aqueous system, e.g. an aqueous polymer dispersion. According to the laws of Henry and Fick, polymers are needed whose chemical nature is quite the opposite of the penetrant. So the most hydrophobic polymers suit as a barrier against hydrophilic penetrants like moisture vapor whereas the most hydrophilic polymers protect against hydrophobic penetrants like oxygen or some solvents. Suitable polymer dispersions are based on vinylidene chloride, acrylic esters, styrene-butadiene, polyurethane, polyethylene-acrylic acid, or acrylic acid-acrylonitrile. A minimum of water vapor and oxygen transmission can be reached with polyvinylidene chloride. Acrylics offer an excellent barrier against aromas like terpenes and hydrocarbons as well as fat and a moderate oxygen barrier combined with good water resistance. As a barrier polymer, styrene-butadiene (S/B) offers moderate moisture and vapor protection as well as good water repellence. The aroma barrier to fruity esters is quite good. The S/B coatings are readily sealable with high sealing strength, correlating with the sealing temperature.

New in the market are hydrophobically modified styrene-butadiene dispersions which show an outstanding moisture vapor barrier, very similar to the moisture vapor barrier of a polyethylene film. The water resistance and the aroma barrier to esters are also very good · The sealability of the modified S/B coat is better than the unmodified one. Polyurethane (PUR) coatings have very high permeation resistance to moisture and vapor. For aroma, they offer a moderate or even good barrier against fruity esters and terpenes and an excellent barrier against hydrocarbons. The fat and oil resistance is good. PUR has extraordinary sealing properties and thermoactivability, which means, after thermal activation, the coating is cold sealable for about half a minute and afterwards no agglutination will occur. Polyethylene-acrylic acid is also a coating with excellent sealing properties and, in contrast to PUR, offers a very good moisture and vapor barrier and an excellent aroma barrier against fruity esters. The surface is highly water repellent. The aqueous polymer solution based on polycarboxylic acid derivative is an excellent oxygen barrier; it exceeds polvinyl dichloride (PVdC), but the coating is sensitive to water and moisture. The aroma barrier is also very good as long as the coating is dry.

Very high grease and oil resistance together with water and alcohol repellency are obtained by fluorinated acrylic copolymers which are completely miscible in water. These products can be applied either by surface or by internal application.

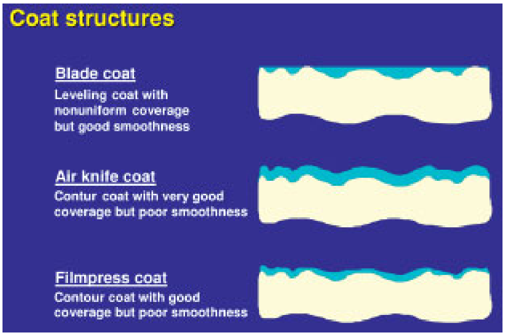


Fig. 3.11 Coat structures of different coating systems.

3.6.9
Additives for Paper and Board Coating [1–3, 15–21]

3.6.9.1 General Aspects

The paper coating process was first developed in the USA late in the 19th century, but did not find broader application until the middle of the 20th century. Since that time the European paper industry has become a leader in coating technology. Coated papers suit the highest requirements as regards printability. In paper and board coating an aqueous suspension, called coating color, is applied to one side of the sheet (mainly in the case of board) or to both sides (mainly for printing papers). After application of the required amount, the coating is dried and finished. In finishing, the coated paper and board achieve their smoothness and gloss potential. Coating is done either in the paper machine (on-machine coating) or in a separate step after the base paper production (off-machine coating). It is desirable that, besides filling the cavities, the coating also covers the highest lying fibers on the base paper surface (Fig. 3.11). There are methods that tend to favor filling of the cavities while higher spots remain covered by only thin or practically no coating (equalizing or leveling coat, e. g. with blade equipment). Some other methods give a coating of more or less uniform thickness, thus also covering the highest spots on the base paper surface, yet the cavities remain only partially filled (contour coat, e. g. roll applicators).

Coating colors consist of several components, white pigments (e. g. clay, calcium carbonate, talc, titanium dioxide) and so-called binders (e. g. starch, latexes) being the most important as regards volume and cost. Further specific additives influence and control the applicable solid content, the rheology, water retention and immobilization of the coating color during the coating process (e. g. dispersant, co-binders, thickeners), and others influence the physical and optical surface structure and properties of the coating layer (e. g. associative thickeners, lubricants, hardening agents, fluorescent whitening agents, defoamers, degassing agents). These components are described in more detail in Section 3.6.9.3.

Water is an essential component of a coating color making it possible to mix the components of a coating color, e. g., so that all the pigment particles are separated from each other, which is impossible in the dry state. Water also makes it possible to transport the color elsewhere and apply it onto the base paper so that the coating color remains uniformly dispersed. As water evaporates from the coating layer, the coating layer consolidates when the binder forms bridges between pigment particles and base paper. Coating colors should contain only as much water as the flow properties need, in order to save energy and costs for drying. The solid contents of the coating colors can be as high as about 70 wt. %.

The composition of coating colors resembles that of paints, containing similar components. Of course, there are differences in detail: the additives may be totally different, there are different kinds of binders, and paper coatings are white while most paints are colored so the pigments are different, etc. One major difference between paints and coating colors is the amount of binder: paints contain much more binder than do coating colors. This is partly due to their different objectives: The purpose of painting is to improve the looks of the surface to be painted, and also to create a protective layer. This latter function demands that the paint layer should be nonporous in most cases. This is achieved by using sufficient binder to completely fill the spaces between the pigment particles.

As for the coating colors, other than to improve the looks of the paper, the purpose of their application is to achieve the desired properties on the paper surface, the most important being the printing properties. The coating layer should be strong enough to resist the stresses of the printing process; the surface strength of the coating dictates the allowable minimum amount of binder. For example, offset printing inks are tacky, which requires a certain z-strength, or pick-strength, of the coating. On the other hand, increasing the amount of binder has a negative effect on several coating properties, and excess binder may cause quality concerns, e. g., low opacity and gloss, or glueability problems. Therefore adding more binder to the coating than the surface strength requires should be avoided; there is also a cost consideration. However, the coating process and base paper absorbency can make high binder levels necessary.

3.6.9.2 **Market Situation and Future Trends**

The worldwide consumption of paper and board will grow by approximately 2 to 2.5 % for the next two decades at least. The development and fast worldwide expansion of electronic media has led to a certain shift in paper qualities and challenged the development of new paper and board qualities. In particular, pigment coated grades have participated most in this new competition in the area of communication and packaging. Because of their significantly better printability, their more aesthetic attractiveness and their more valuable feel, the growth rate of coated paper and board will be twice as high as that of paper and board in general (Table 3.1).

Printed paper is a cost efficient medium with a high capacity for information, universally easily available and fully recyclable. Paper and board based packaging

Table 3.1 Further predicted overproportional growth of coated paper and board production worldwide.

Production (10^6 t)	**1994**	**2004**	**2014**	**Growth rate 1994–2004 p.a.**	**Growth rate 2004–2014 p.a.**
Paper and Board, World	280	350	430	2.3%	2.1%
Coated	42	60	90	3.6%	4.2%
Share of total	15%	17%	21%		

material is also cost efficient, aesthetically attractive and environmentally friendly. Most pigments are significantly cheaper than chemical pulps so increasing both the proportion of coated paper in general and the coating layer(s) compared to fibers (Fig. 3.12) is an important economic factor. In 2004 coated paper and board accounted for 17% of the total worldwide paper production of 350 × 10^6 t and will grow by 2014 to 21% of the then 430 × 10^6 t paper and board production. The proportion of coated paper to board is ca. 80% to 20% and the proportion of coating layer compared to the total area weight for paper is significantly higher (30–65%) than for board (5–20%). The future trends for coated papers will involve more specific paper products, further development of coating technology, ongoing progress in printing technology, environmental issues, development of coating color raw materials and the globalisation of paper companies.

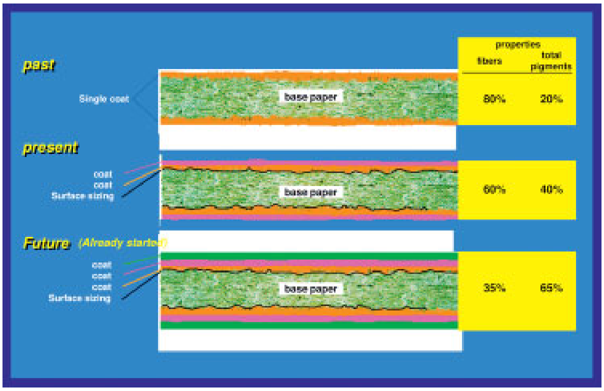


Fig. 3.12 Predicted increasing proportion of fillers and coatings vs. fibers/base paper.

3.6.9.3 Components of Coating Colors

3.6.9.3.1 Pigments

With respect to mass the most important component is the *pigment* with a total amount of almost 18×10^6 t per year dry material worldwide. There may be only one kind of pigment in a coating color, or more commonly a combination of several types e. g. clay, calcium carbonate, talc, titanium dioxide (more details see 2.2.2). The share of pigment in the dry coating is about 85–95 wt. %.

3.6.9.3.2 Dispersants

In the dry form, pigment particles form clusters, in which the parts of the clusters are more or less tightly attached to each other. More tightly attached ones are called "aggregates". Aggregates and primary particles together can also form clusters that are less tightly bound – so-called "agglomerates" or "flocs". The purpose of dispersing is to make a dispersion where neither agglomerates nor aggregates exist and only primary particles are present. Primary particles are evenly distributed in water, and the system stays stable for a certain time.

Disruption of aggregates, disaggregation, is typically an irreversible process, after which particles cannot be bound as tightly as they used to be. Instead of forming aggregates, disaggregated particles tend to form agglomerates. Disruption of agglomerates is called "deflocculation". Deflocculation is a reversible process. Agglomerates re-form when the force for deflocculation is removed.

The process of dispersion can be divided into three stages: wetting, disruption of particle clusters and stabilization. *Wetting* means that all the external surfaces of pigment particles must come into contact with water. Air must also be displaced from the internal surfaces between pigment particles in agglomerates and aggregates. Wetting is usually not a problem with paper pigments except for talc which is not spontaneously wet by water. When talc is dispersed, a separate surfactant is required to provide proper wetting. *Disruption of particle clusters*, disaggregation, is accomplished by mechanical energy. Disruption can be performed using crushing mills, kneading mixers, or high-speed mixers. Crushing mills are needed when the shear forces induced by mixers are not sufficient for disaggregation. Although dispersing can be performed in mixers, there is a certain difference between mixing and dispersing. Mixing does not change the size and surface area of particles, while dispersing changes both. *Stable* pigment dispersions with the highest solid content can be achieved only by using dispersants. When pigment clusters are broken down by dispersing, the surface area of pigment in the dispersion increases, there is more surface for particles to interact with each other, and the viscosity in the dispersion increases rapidly. Use of dispersants stabilizes deflocculated particles in the dispersion and hinders their interaction. The dispersant must be mixed with water at once, when the breakdown of pigment clusters starts. Only then can interaction and therefore reagglomeration of particles be avoided. For this reason, dispersant is added to water at the beginning of dispersing, even before the pigment is added.

Reagglomeration is avoided if particles are kept far enough from each other. Two general principles are considered as stabilization mechanisms: electrostatic stabilization and steric stabilization. When both occur simultaneously, it is called "electrosteric stabilization". In electrostatic stabilization, the charges of particle surfaces are made to be the same sign. Dispersant is adsorbed onto the particle surface, and thus the surface gets a highly localized charge with the same sign as that of the dispersant. A negative charge on the surface, when anionic dispersant is used, creates a cloud of positive counterions around the particle (the so-called "electric" or "ionic" double layer). The closer to the surface, the more localized are the counterions. At a greater distance from the particle, in a continuous water phase, negative and positive ions are in balance. The counterion cloud acts as a stabilizer, creating repulsive forces between particles. Electrostatic stabilization is the most commonly used stabilization method in paper pigment dispersions. To act as a good stabilizer, the dispersant must be highly charged. Examples of these kinds of dispersants are salts of polyacrylic acid and polyphosphates. In steric stabilization, particle surfaces are covered with uncharged polymer, the chain of which extends into the water. When two particles with polymers on them approach each other, they cannot approach too closely because the polymer chains would overlap, and this is not entropically favored. Thus polymers create a steric hindrance against particle interaction. Dispersants, which work as steric stabilizers, are also called "protective colloids". Examples of these are starches and polyvinylalcohols. A good example of a dispersant, which works as an electrosteric stabilizer, is carboxy methyl cellulose (CMC).

The viscosity minimum is the optimum dosage of dispersant. After the optimum the viscosity is slowly increased. Viscosity decreases when dispersant is added, due to the increased stability of the dispersion. The stability is a maximum at the viscosity minimum. The viscosity starts to increase after the optimum because additional dispersant can no longer be adsorbed onto the pigment surface, and thus stays in the water increasing its electrolyte concentration and decreasing the stability. Overdosing of dispersant therefore must be avoided. Pigment type, dispersant type, pH, and additional components all affect the dispersant dosage required. The smaller the particle size the larger the total surface area of pigment, and the more dispersant is needed for stabilization. Generally it can be said that the required dispersant dosage is in the range 0.1 to 0.5 % of dry pigment.

Today, the most commonly used pigment dispersants are *polyacrylate salts*. Usually they are low molecular weight polymerization products of acrylic acid, which have been neutralized with sodium or ammonium hydroxide. They are very resistant towards different types of attack like high pH, high temperature, or high shear forces. *Polyphosphates* were previously used as dispersants. They are effective, but lack hydrolytic stability during storage of the dispersion; they easily hydrolyze to orthophosphates, which have no deflocculation power. This causes an increase in the viscosity of the dispersion. The longer the polyphosphate chain, the more effective it is as a dispersant. Tetrasodium pyrophosphate, $Na_4P_2O_7$, is the simplest polyphosphate that can be used as a dispersant. Sodium tripolyphosphate, $Na_5P_3O_{10}$, is widely used as a dispersant and as a builder in detergents. Other anionic polymeric dispersants are lignin sulfonic acid salts and formaldehyde condensation products with aromatic sulfonic acids. Because of the nature of sulfonic acid, these types of dispersants bear the maximum anionicity over the whole pH range typically used in pigment dispersions. Lignin sulfonates are made from native lignin. Their effectiveness as a dispersant depends on their purity and degree of sulfonation. Lignin sulfonates can be used as a dispersant with hydrophobic surfaces. Their disadvantages are poor thermal stability, tendency to foam and they bring a high load of detrimental substances to the papermaking process. Formaldehyde condensation products with aromatic sulfonic acids have an aromatic backbone and are also effective dispersants with hydrophobic surfaces.

Nonionic polymers, which can be used as stabilizers are, e. g., starches, polyvinyl alcohols, and polyacrylamides. Nonionic polymers work as protective colloids; their mechanism of stabilization is steric stabilization. Carboxy methyl cellulose bears a small anionic charge along the chain. However, it is often considered to act as a protective colloid. Actually, carboxy methyl cellulose can be considered to use both its protective colloid properties and its charge in stabilizing, thus acting as an electrosteric stabilizer.

The charge of pigment dispersants is usually anionic but, in some applications, cationic dispersants are preferred. They are seldom needed in coating color pigments, but they are beneficial in pigment dispersions meant for filler applications or for specialty coating applications. Cationic dispersants are typically cationically charged polymeric compounds e. g. modified polyethylenimines, polyvinylamines. Usually they do not act as effectively as anionic dispersants.

3.6.9.3.3 **Binders**

Binders are the second most abundant component in the coating color after the pigments with a total amount of approximately 3×10^6 t of dry substances. Many different binder types are used (Fig. 3.13). The most important aims for the application of binders in coating colors are the binding of pigment particles to base paper, the binding of pigment particles to each other, partial filling of voids between pigment particles (porous coating structure) and affecting the viscosity and water retention of the coating color.

An ideal binder can be characterized by good binding power, good water retention properties, ease of mixing or dissolving in water, general ease of handling, good compatibility with other coating components, low or desired effect on the viscosity of the coating color, good mechanical and chemical durability, good optical and mechanical properties, nonodorous and harmless to health, low tendency to foaming, resistant to bacteria, constant quality properties, low price and good availability. Again, as with pigments, there is no single binder, which can meet all these requirements. Latexes meet many of them; however, they often need a co-binder or thickener to adjust the rheology and water retention to the desired level.

There are three kinds of binders in coating, the (main) binder, the co-binder and the sole-binder. A *sole-binder* is a single binder that alone can perform all the

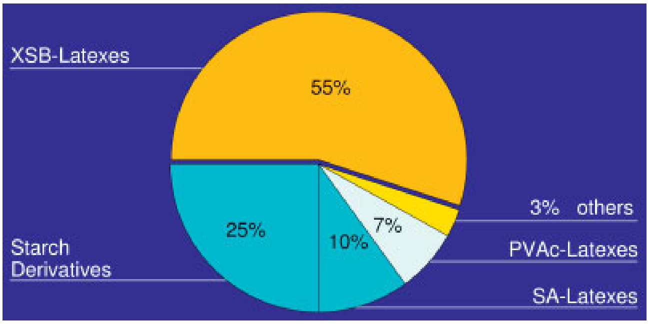


Fig. 3.13 Market shares of binders for paper and board coating in 2004 (total of ca. 3 × 10^6 t of dry materials worldwide). PVAc = polyvinyl acetate, SA = styrene acrylate, XSB = carboxylated styrene butadiene.

desired binder functions in a coating. Usually the binder systems consist of a combination of two binders, in which the (main) binder is responsible for the binding function. The co-binder is used to affect the rheology and water retention properties of the coating color. Its dosage is smaller than that of the main binder.

The binders can be classified by their origin and solubility in water:

- Soluble in water:
  - Starches
  - Proteins
  - Cellulose derivatives: ethers e.g. carboxy methyl cellulose
  - Polyvinyl alcohol (PVA, PVOH)
- Insoluble in water:
  - Carboxylated styrene butadiene latexes (XSB Latex)
  - Styrene acrylate latexes (SA Latex)
  - Polyvinyl acetate latexes (PVAc Latex)

Water-soluble binders give better water retention for the coating layer than latexes that are not soluble in water. They also affect the rheological properties of the coating colors, making them more viscous, and also shear thinning (pseudo-plastic) and thixotropic. Some synthetic co-binders have a similar effect. Carboxylation of SB-Latex means incorporation of small amounts of unsaturated carboxylic acids such as acrylic acid, methacrylic acid, maleic acid, to improve considerably the compatability of these highly hydrophobic polymers with the other coating components.

3.6.9.3.3.1 Derivatives of Natural Polymer Binders

In the initial phases of paper coating, i.e. the late 19th century till nearly the first half of the 20th Century, these binder types were used exclusively. All are hydrophilic. The most widely employed binders of this type are starch and its derivatives with a consumption of approximately 800 000 tpa worldwide at present. Additional natural binder types are cellulose ethers such as carboxymethyl cellulose, in the United States, hydroxyethyl cellulose, soybean protein, and, to a very small extent, casein and alginates. Natural binders act as protective colloids that prevent the flocculation of the pigments; they increase the viscosity and water retention of coating colors and give the coat a higher stiffness. Natural binders have a relatively low water resistance (wet pick). They are mainly used in combination with synthetic polymer binders and/or hardening agents (see Section 3.6.9.3.6).

Starch derivatives of various types are used in mixtures with other binders. For example, oxidized starches are usually employed together with polymer dispersions. Hydrolyzed starches exhibit high stability in solution, good binding power, and good flow behavior. Hydrolyzed, esterified starches exhibit good stability in solution, high binding power, and increased reactivity towards wet-strength additives (hardening agents) such as urea- or melamine- formaldehyde resins. Hydrolyzed, etherified starches exhibit the same properties as the esterified derivatives. However, in contrast to the esterified derivatives, they can be used at pH values above 8 without the risk of saponification. Starch derivatives that contain phosphate and amino groups are compatible with cationogenic substances such as satin white. The phosphate groups react with multivalent metal ions, such as aluminum ions, which leads to a certain degree of water resistance. The amino groups react with aldehydes, which enhances the activity of hardening agents.

Cellulose Derivatives: Pure carboxymethyl cellulose (CMC) coats of 0.5–3 g m^{-2} increase the grease resistance and printability of paper. Depending on the use, various mixtures of low- and high-viscosity CMC are employed. Pigment-containing CMC coats, which can be applied on the size press, contain up to 10% semi-technical, low-viscosity CMC or salt-free, purified CMC. CMC is usually processed together with other natural or synthetic binders. Above all, CMC increases the effectiveness of optical brighteners (see 3.6.9.3.5.5) and the water retention of the coating mixture. Water retention is so high that the addition of other binders that promote water retention in the coat is only necessary to a lesser extent. In general, the amounts of CMC employed are 0.3–1.5% based on the pigment, and very low viscosity types are preferred. This gives an adequate coating color viscosity, even if the solids content of the coating color is high. Types of CMC that are soluble in cold water are rapidly becoming established because they do not require dissolving at elevated temperature. The presence of satin white pigment can cause strongly interfering coagulations in the coating color.

Casein has been used as a central binder type in the past, but nowadays is of only marginal importance in cast coatings. For its application it must be present in the dissolved state. It is dissolved by the addition of alkali (e.g., ammonia, sodium hydroxide, borax, or sodium carbonate) either separately in a cooker (up to 70 °C) or with the pigment in a kneader. The casein concentration is limited to ca. 20% due to its high viscosity. The limit of processability is shifted to ca. 33% by the addition of urea or dicyanodiamide, which reduces the viscosity and increases the storage stability of casein solutions. The mixing of casein solutions with pigments, especially China Clay, can cause a "shock" phenomenon (a rapid increase of viscosity).

Soybean protein is a very important binder type, especially in North America. It has properties very similar to those of casein. Isolated soybean proteins are hydrolyzed, isoelectric proteins. They are used in the form of alpha and delta proteins with four different viscosities (extra low, low, medium, and high). The viscosity refers to the dissolved soybean protein, the solvent of choice being aqueous ammonia (26 Bé). Proteins dissolved in this way exhibit very low sensitivity to water after drying. Like casein, soybean protein is mostly used as a mixture with polymer dispersions. This combination permits the preparation of coating colors with high solids content and a relatively low viscosity. Solids contents of ca. 60 %, suitable for blade coaters, can be achieved.

3.6.9.3.3.2 **Synthetic Latex Binders**

The ongoing development of coating equipment and applicators in connection with the increasing production speed (actual process up to 2.000 m min^{-1}; pilot coaters up to 3.300 m min^{-1}) has forced the development of new binder types, which meet the changed requirements better. In Europe the first *styrene-butyl acrylate dispersion* (*SBA*) was polymerized by Badische Anilin- und Soda-Fabrik, today BASF, in 1929. In the following years a partial substitution of the natural polymer binders began and from the1950s onwards an extensive and continuous growth in market demand has been observed. The corresponding pioneer work in the USA took place in Dow Chemicals, where, from 1944 onwards, the production and market introduction of *carboxylated styrene-butadiene latexes* (*XSB*) started. *Polvinyl acetate latexes* (*PVAc*) as a coating binder were first researched and introduced to the market in 1955, also in the USA, where a higher proportion than in other world regions is still used. The actual worldwide market demand for these three main types of synthetic coating binders comes to approximately 2×10^6 t p. a. as dry material with approximately 75 % XSB-, 15 % SA-, 7 % PVAc- and 3 % other latexes. These synthetic latex binders made it possible for the first time to attain a high solid content at low viscosity, a prerequisite for modern high-speed coating machines. In addition, polymer dispersions give the coat a higher water resistance, better flexibility, higher gloss, and better printability. The products employed today are aqueous dispersions of polymers, usually stabilized with anionic emulsifiers. The solid content of the dispersions is generally ca. 50 %. Very often, the polymers are copolymers of several monomers, e. g., styrene, butadiene, acrylic esters, vinyl acetate, and acrylonitrile. Apart from these main monomers small amounts of auxiliary monomers, such as acrylamide, acrylic acid, maleic acid, and methacrylamine are also added to modify the dispersion properties.

Styrene-butadiene dispersions lead to varying film hardness, depending on the proportion of styrene used. Approximately equal proportions of styrene and butadiene result in binders which provide a relatively soft film and a very good pigment binding capacity. Disadvantages are the odor of the dispersion and the tendency of the films to yellow when exposed to light. Acrylate dispersions are specialties and of high importance for impressive prints. Butyl acrylate is mainly copolymerized with styrene or vinyl acetate. The ratio of the soft component (butyl acrylate) to the hard one (styrene or vinyl acetate) determines the application characteristics of the dispersion. In general, acrylate dispersions have an excellent brightness and ageing resistance and are less odorous. Apart from these two most important groups of polymer dispersions, vinyl acetate homo- or copolymers have gained acceptance in paper coating plants, especially in the USA. These products generally have a lower binding power, but provide very hard and porous coats, and have an excellent ageing resistance. Polymer dispersions based on methacrylates and copolymers of vinyl acetate and ethylene are less important in paper coating.

In recent years the requirements for coating binders have become more and more diverse. Changes in raw materials for paper production and/or production process conditions as well as new requirements for paper characteristics and printing technologies have forced the development of *tailor-made binders* with very specific property profiles. Such products are not generally different from XSB- or SBA-latexes, as regards the principles of physics and chemistry. But with the know-how of correlation and influence factors of monomers, functional monomers, process auxiliaries, functional additives, process parameters and the interactions with different pigments, together with a flexible polymerization unit, it is possible to optimize, very flexibly and quickly, a binder in respect of binding power, stiffness, print evenness, print gloss, blister resistance, low yellowing and coater runnabilty.

Apart from the two-component systems, binder + co-binder, synthetic *sole binders* which do not require a co-binder have been available since the early 1960s. Synthetic binders are low-viscosity aqueous dispersions which usually do not influence properties such as viscosity and water retention that are important for the flow behavior of the coating. For this reason, these "multipurpose dispersions" are used alone in only a few cases. They are usually mixed with co-binders, which are responsible for adjusting the flow properties of the coating color. On addition of alkali, these products develop the required viscosity and water retention, but retain their dispersion form. Special binders of this type have become popular, especially for illustration paper that is produced in large amounts and used in rotogravure or web offset printing. Table 3.2 lists the various binder systems, their influence on the production of coating colors, the rheological properties of the coating color, and the coating properties.

3.6.9.3.4 **Additives Influencing the Properties and Processing of the Coating Color**

It is desirable that coating colors have moderate pseudoplastic, shear thinning flow behavior. Too drastic shear thinning can cause excessive water penetration into the base paper and, accordingly, loss of binder. To adjust the rheological properties and water retention of a coating color, synthetic co-binders and thickeners are used. They have a profound effect on the runnability of a coating color, and hence of the coating machine, on account of their thickening action, their characteristic rheology at different shear rates, and their water retention. The mechanisms for dissolving, thickening, water retention, and rheology of synthetic co-binders are very

Table 3.2 Comparison of various Binder Systems

Binder system	Production	Rheological behavior	Coating properties
Polymer dispersion alone (rarely used)	simple mixing process	usually unfavorable	variable via type of dispersion; waterproof, glossy coat attainable; no activation of optical brighteners
Polymer dispersion + watersoluble cobinder, e. g., casein, starch, CMC (very frequent)	mixing and dissolving processes, sometimes separately with heating	largely controllable via cobinder	variable via single components; limited water resistance and gloss; full activation of optical brighteners
Polymer dispersion + synthetic cobinder (frequent)	integrated mixing/ dissolving processes, no heating	controllable via cobinder	limited variability; waterproof and glossy coat attainable; full activation of optical brighteners
Polymer dispersion + viscosity regulating additives (in special cases)	integrated mixing/ dissolving processes, no heating	limited controllability	variable only via type of dispersion; good water resistance and gloss, no activation of optical brighteners
Special dispersion (for publication papers)	integrated dissolving/ mixing processes, no heating	slight controllability	limited variability; improved water resistance with additives; good gloss attainable; optical brighteners can be activated only via auxiliary components

similar to those of synthetic thickeners. Co-binders and thickeners can be roughly divided into “natural” and “synthetic” products. Natural products are proteins (casein, soy protein) and polysaccharides (starch, alginates, cellulose ethers) and synthetic products are e. g. acrylic copolymers, polyvinyl alcohol, polyvinyl acetate and associative thickeners (Table 3.3).

3.6.9.3.4.1 **Co-binders**

These are primarily used to adjust the viscosity and water retention of coating colors to the required levels and to modify their rheology according to the demands of particular coating techniques. But they should also offer some additional advantages over the thickeners in order to justify the higher recipe costs, e. g. binding power, activation of optical brighteners (Table 3.4).

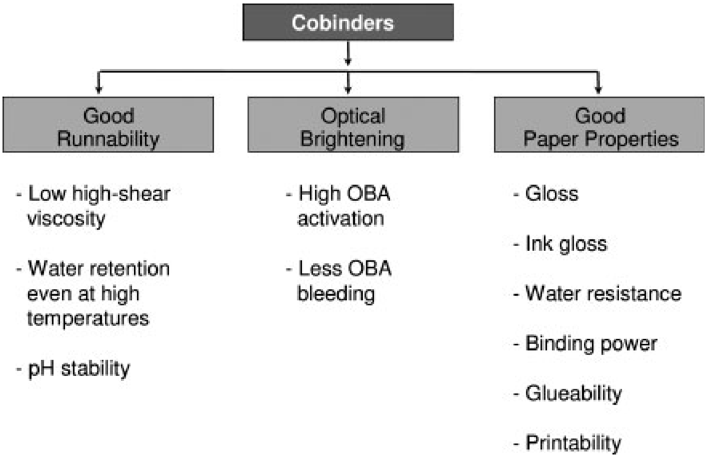
Natural products, like casein, starch, and soy protein used as main binders in the past, also impart the necessary viscosity and water retention to coating colors. However, they were unable to satisfy the increasing demands that were placed on runnability and coating quality, and they have gradually been superseded by syn-

Table 3.3 Co-binders and thickeners in paper and board coating (source: E. Lehtinen, Helsinki University of Technology.
CMC = carboxy methyl cellulose, HEC = hydroxyethyl cellulose, PVOH = polyvinyl alcohol, OBA = optical brightening agent.

	Product type	Delivery form	Pretreatment	Thickening effect	Comments
Natural Products	Starch	Powder	Cooking	+	Co-binders, low affinity for pigments, yellowing
	Soy Protein	Powder	Cooking	+	
	Casein	Powder	Cooking	++	Mainly for cast coating
	CMC	Powder, Solution	Added as supplied Dissolved	+++	All-round-product
	HEC	Powder, Solution	Added as supplied	+++	Low water retention, mainly used in USA
	Alginates	Powder	Added as supplied Dissolved	+++	High water retention, expensive, mainly used in USA
Synth. Prod.	PVOH	Powder	Cooking	+	Best activator for OBA
	Acrylic Polymers	Solution, Latex	Added as supplied	+++	Versatile, easy to handle
	Associative Thickeners	Latex	Added as supplied	++++	Good runnability, low water retention

+ low ++++ high

Table 3.4 Main requirements placed on co-binders (source: BASF). OBA = optical brightening agent.



thetic binders. So natural products, principally starch and soy protein, are nowadays only used as co-binders. Casein is only used in cast coating because it has some special features which make it difficult to replace with synthetic products. Alginates and hydroxyethyl cellulose (HEC) are mainly used in the United States and Japan, and have not been adopted to any significant extent in Europe.

Carboxymethyl cellulose (CMC) is a versatile product with an all-round range of properties, and is popular in many regions. CMC improves the water retention efficiently. By choosing the optimum grade, the water retention can be adjusted to the individual needs, which are dependent on the coating conditions and the coating color formulations. In formulations with kaolin clay, the differences in water retention between different CMC grades are much smaller than in colors based on calcium carbonate. One reason for this is that CMC quickly builds up a network structure with clay particles, which imparts extra water retention. With calcium carbonate pigment, the water retention is more dependent on the viscosity of the water phase. A higher molecular weight and higher viscosity type of CMC is needed to give good water retention for coarse calcium carbonate-based precoatings. Low molecular weight and low viscosity type CMC grades give good performance for fine clay-based coatings. Lower molecular weight and lower viscosity type CMC grades are closer to Newtonian5 type behavior, while higher molecular weight and higher viscosity type CMC grades are more pseudoplastic. CMC is mechanically stable in high shear conditions and compatible with all common types of coating raw materials.

Synthetic products comprise polyvinyl alcohol (PVOH), polyvinyl pyrrolidone (PVP) in combination with PVOH, acrylic copolymers, and associative thickeners. Due to the high degree of carboxylation of acrylate ester dispersions, they turn into colloidal dispersions upon addition of alkali. Thus the laborious and energy consuming dissolving and cooking processes involved in the use of natural binders are avoided. The binding power of PVOH exceeds that of all other binders used in paper coating, nevertheless it has gained only limited acceptance. This is mainly due to the fact that the application of large amounts of polyvinyl alcohol lead to rheological problems on the coating machine during processing. PVOH is a solid compound, which is composed of a hydrocarbon chain bearing hydroxy groups on every second carbon. Depending on the extent of the polyvinyl acetate hydrolysis, more or less acetyl groups remain attached to the chain. The stereochemical structure of polyvinyl alcohol, the direction in which the OH groups/acetyl groups point, is already fixed during vinyl acetate polymerization. Like most free radical induced reactions, the PVOH polymer shows an atactic structure. This means that the functional groups are randomly oriented. Their molecular weight (MW) and degree of hydrolysis primarily characterize polyvinyl alcohols. In practice, further features such as tacticity, branching, average length, and distribution of residual acetyl group sequences play a minor role only. Since PVOH is fully soluble in water, its viscosity under defined conditions is taken as a proportional measure of its molecular weight. Coating grades range from 3 mPa s (very low MW) to 6 mPa s (low MW). PVOHs with viscosities higher than approximately 6 mPa s should not be used on coating machines. The degree of hydrolysis is based on the measurement of the ester value and indicates how much mole percent of the basic polyvinyl acetate is "saponified" to PVOH. For coating purposes, a degree of hydrolysis is selected from a range of 88% (partially hydrolyzed) through 99% (fully hydrolyzed). At the same degree of hydrolysis, higher concentrations or lower temperatures lead to an increase in viscosity. Given the same MW, fully hydrolyzed grades display a higher viscosity than do partially hydrolyzed grades due to increased hydrogen bonding. Going from about 97 to 100 mol% hydrolysis, the crystallinity of the polymer increases considerably, which has an impact on the solid state in particular. One apparent change is the reduction in cold water solubility of the PVOH.

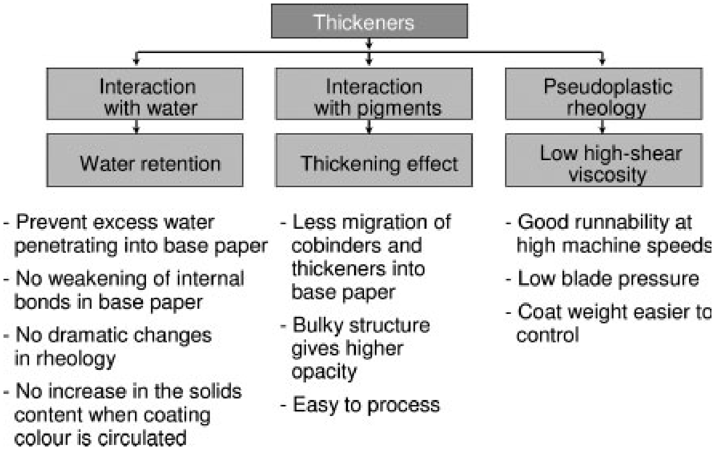
The choice of other monomers for synthetic co-binders is not restricted to acrylic acid, methacrylic acid, and esters such as methyl acrylate, ethyl acrylate, butyl acrylate, methyl methacrylate, and ethyl methacrylate. Other functional monomers such as acrylonitrile, acrylamide, and vinyl acetate can also be used, so there is a great scope for varying the chemical composition of synthetic co-binders. The proportion of carboxylic acids to the other monomers is usually lower, with the result that synthetic co-binders are less anionic and they adsorb more readily on the surfaces of clay pigments. Important differences of synthetic co-binders compared to the thickeners (see below) are their shorter chain length and their low proportion of acids. This explains the low thickening effect of synthetic co-binders and hence they can be added to coating colors in larger quantities. They are usually added at rates of 0.5–3 parts per 100 parts of pigment, expressed as solids. These relatively high levels of addition and the presence of functional monomers can have a substantial effect on the properties of the coating.

3.6.9.3.4.2 **Thickeners**

The main function of thickeners is to adjust the viscosity of the coating color to the desired level and to impart the necessary degree of water retention (Table 3.5). Thickeners must be able to interact strongly with water molecules if they are to increase the water retention of coating colors. They also need to interact with other ingredients of coating formulations, especially pigments, in order to display a thickening effect. The nature and strength of these interactions depend on the chemical composition of the polymer. Thickeners also need to display pronounced pseudoplastic flow. High runnability depends on a combination of these features. Most synthetic thickeners are supplied in the form of aqueous, acidic dispersions (which are often erroneously referred to as "emulsions" in the literature) or alkaline solutions of synthetic polymers. Some are supplied in the form of true water-in-oil emulsions, but they are much less common.

The main products used as thickeners are CMC, PVOH (both already described in Section 3.6.9.3.4.1), acrylic copolymers and associative thickeners. The acrylic copolymers are nonionic monomers and acrylic acid or methacrylic acid. The nonionic monomers are mainly esters of acrylic acid (principally methyl acrylate and ethyl acrylate) and methacrylic acid (principally methyl methacrylate), and acrylamide. The monomers that are selected need to be fairly hydrophilic and polar in

Table 3.5 Main requirements of thickeners (source: BASF).



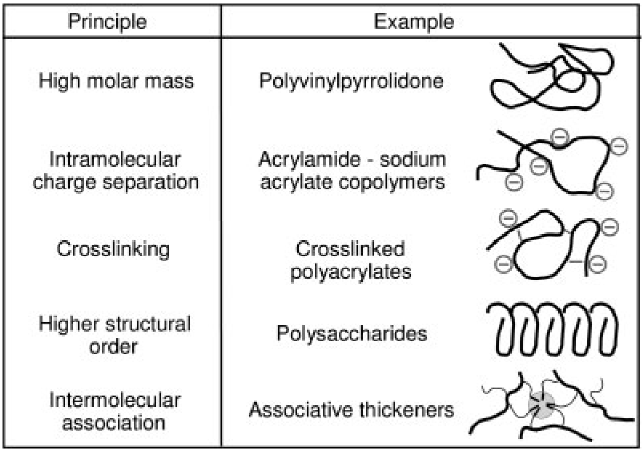
- Prevent excess water penetrating into base paper
- No weakening of internal bonds in base paper
- No dramatic changes in rheology
- No increase in the solids content when coating colour is circulated

- Less migration of cobinders and thickeners into base paper
- Bulky structure gives higher opacity
- Easy to process

- Good runnability at high machine speeds
- Low blade pressure
- Coat weight easier to control

order that the polymer is able to dissolve in aqueous coating colors and interact with other polar coating ingredients such as pigments. Strongly hydrophobic monomers such as styrene, butadiene, and ethylene are hardly ever used because they interfere with the interaction between the polymer and water molecules. Polyacrylic acid can also be used as a thickener in its dissociated form, i. e., as the sodium or ammonium salt, if its molar mass is high enough. Polymers have to be able to dissolve before they can exert a thickening effect. Most natural products have to be heated and converted to make them capable of being dissolved, whereas acrylic copolymers are soluble on account of the alkali ions contained in the coating color. When addition of alkali increases the pH of the dispersion, the carboxyl groups dissociate and donate a proton, which causes them to become anionic. The formation of anionic charges along the polymer chain causes it to stretch owing to mutual repulsion, and water molecules are attracted to the polymer chain and become attached to it. The dispersed thickener particles then dissolve, which allows them to unfold their effects. It only takes a few minutes to dissolve them completely. Nevertheless, it is important to ensure that sufficient alkali is available in the coating color because the thickener dispersion consumes alkali and the stability and viscosity of the coating color can suffer if the pH is allowed to drop. Another important point to be considered is the sensitivity of the dissolved polymer to electrolytes. Polyvalent cations such as Ca^{2+}, Mg^{2+}, Al^{3+}, and Fe^{3+} can have a detrimental effect on the performance of these products by occupying the sites of anionic charge on the polymer.

The interaction between the polymer and water has a pronounced effect on the viscosity of the aqueous phase as well as on the water retention of the coating color. Like all hydrocolloids, synthetic thickeners bind a large number of water molecules along their polymer chains, with the result that their diameter and volume increase and they occupy a greater space in the aqueous phase (Fig. 3.14). Apart from



Principle	Example
High molar mass	Polyvinylpyrrolidone
Intramolecular charge separation	Acrylamide - sodium acrylate copolymers
Crosslinking	Crosslinked polyacrylates
Higher structural order	Polysaccharides
Intermolecular association	Associative thickeners

Fig. 3.14 Thickening mechanisms in the aqueous phase (source: BASF).

this hydrodynamic mechanism, there are a number of other mechanisms by which the thickeners are able to restrict the mobility of the aqueous phase. The high molar mass and the high degree of structural order cause a large increase in the volume of the dissolved polymers under hydrodynamic forces. The anionic charges along the length of the polymer also have the effect of stiffening the polymer chain by causing it to unfurl and stretch out because the charges repel each other. The mobility of the aqueous phase is lower because of the stiffness and extension of individual polymer chains and the crosslinking between different polymer chains. The maximum degree of internal crosslinking is obtained as the result of the associative interaction between the hydrophobic side chains (see Section 3.6.9.3.4.3). The common feature of all these effects is that the mobility of the aqueous phase is reduced owing to intramolecular and intermolecular crosslinking and the viscosity is increased due to the increase in the volume of the polymer. The pronounced thickening effect of thickeners is the result of their interaction with pigment particles. Acrylic and cellulosic thickeners have a high affinity for pigments because the polar functional groups of the thickener molecule are attracted by the polar surfaces of the pigment. The polymer chains are adsorbed on the surface of the pigment particles and bind them together by means of a bridging mechanism, leading to a higher degree of crosslinking within the entire system. The thickening effect, i. e., the increase in viscosity at low shear, is principally the result of the thickener forming “bridges” by means of adsorption.

3.6.9.3.4.3 **Associative Thickeners**

These have a long history of use in paints. They consist of an essentially hydrophilic, water-soluble polymer with strongly hydrophobic terminal groups or side

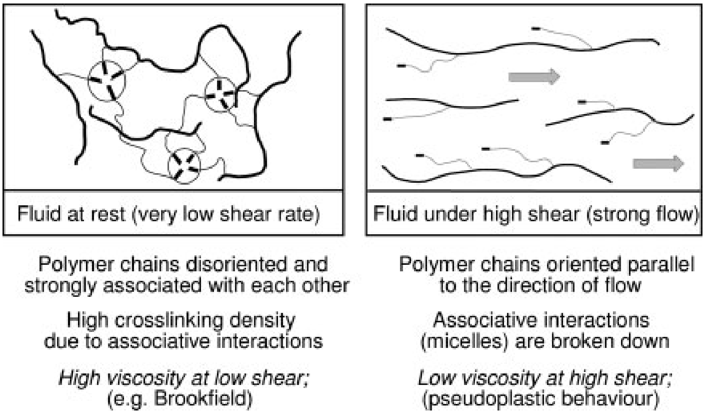


Fig. 3.15 Rheological behavior of coating colors influenced by an associative thickener (source: BASF).

chains. The hydrophobic terminal groups are aliphatic or aromatic hydrocarbons, and they are completely insoluble in water. They are joined to the main polymer backbone by means of a hydrophilic spacer, which ensures that they remain flexible. Their structure is similar to that of surfactants, and they also tend to join together in water to form micelles. This associative interaction between the hydrophobic side chains increases the degree of internal coordination of the whole system, with the result that the coating color has a very high viscosity at low shear (Fig. 3.15). The association between the hydrophobic groups is the result of van der Waals' forces, which are very weak and easily overcome. If the coating color is subjected to shear, they quickly lose their attraction for each other and no longer form a network. The micelles break down and the thickener molecules are oriented in the direction of flow, which causes a reduction in the viscosity of the coating color. However, because the hydrophobic constituents are no longer associated with each other, a consequence of the low viscosity of the coating color under high shear is that its water retention is much lower.

The associative thickeners can be divided into three different categories according to the chemical composition of the hydrophilic polymer backbone (Table 3.6).

1. HEUR (Hydrophobic Ethoxylated Urethanes): These thickeners consist of relatively short-chain, ethoxylated polyurethanes that have been terminated with hydrophobic substituents. The associative interaction between the hydrophobic chain ends causes them to join together to form long chains, and the viscosity increases accordingly. Another feature of these products is that they also interact with the dispersed polymer binder particles. There are variants in which the main polymer backbone consists of alternating hydrophilic and hydrophobic blocks. HEUR-type associative thickeners have long been used in the paints industry but they have been less successful in coating colors because of their lack of affinity for pigments.

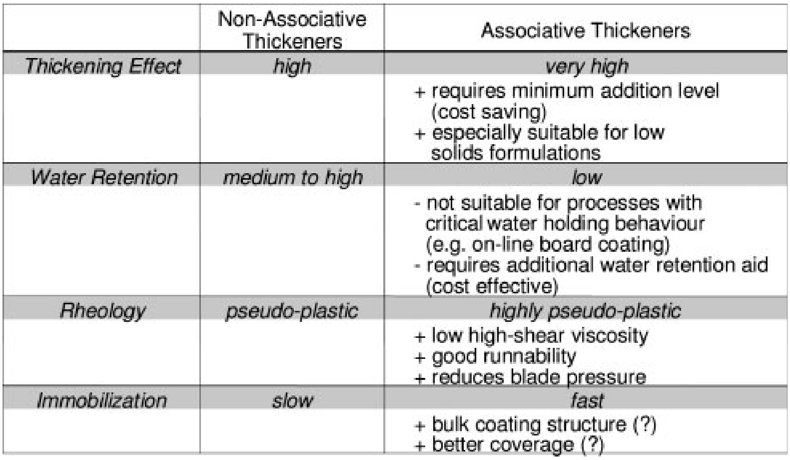
Table 3.6 Types and properties of associative thickeners used for coating (source: BASF).

HEUR	HASE	ACT
Hydrophobic ethoxylated urethanes	Hydrophobic, alkali-swellable emulsions	Associative cellulosic thickeners
- Fairly low molar mass	- Fairly high molar mass	- Hydrophobically modified hydroxyethyl cellulose
- Hydrophobic terminal groups; forms of long polymer chains due to association	- Hydrophobic side chains; intermolecular crosslinking due to formation of micelles	- Pronounced interaction with pigment and latex particles
- High level of interaction with latex particles	- High level of interaction with pigment particles	- Performance comparable to that of HASE
- Less suitable for paper coating colours	- Low viscosity at high shear, low blade pressure ensures good runnability	
	- Low level of water retention	

2. HASE (Hydrophobic Alkali-Swellable Emulsions): The hydrophilic polymer backbone consists of an alkali-soluble polyacrylate, and they do not differ from the other acrylic-based thickeners described above in this respect. The most commonly used monomers are ethyl acrylate, acrylic acid, and methacrylic acid. The hydrophobic side chains are attached to the polymer backbone by means of a polyethylene oxide spacer. The associative thickening effect can be controlled by varying the ratio of associative monomers to conventional monomers in the polymer backbone, the hydrophobicity of the polymer (i. e., the chain length of the aliphatic hydrocarbons), and the number of ethylene oxide units in the spacer. The intermolecular association between the hydrophobic side chains themselves and between the side chains and the dispersed binder particles is responsible for the very high viscosity that can be achieved. The relatively high molar mass of the acrylic polymer backbone and its high affinity for pigments mean that these products can be used in paper coating, but the water retention level is lower than with conventional thickeners.

3. ACT (Associative Cellulosic Thickeners): Products in this category consist of cellulose ethers with hydrophobic substituents. The most important product in this group is hydrophobic modified hydroxyethyl cellulose (HMHEC) which also has a high affinity for styrene-butadiene binders and clay pigments. The applications open to these products are comparable to those for HASE products. The low water retention can be compensated for by the speed with which the filter cake forms on the surface of the base paper. Associative thickeners bring about a very high increase in viscosity, and so they only need to be added in very small amounts. This is an economic advantage over conventional thickeners, but only if the water retention of the coating color is unimportant. Other products need to be added to boost the water retention of the coating color if, for instance, highly absorbent paper is coated with a precoat or if coarse $CaCO_3$ is used as the pigment.

Table 3.7 Comparison of conventional and associative thickeners (source: BASF).



	Non-Associative Thickeners	Associative Thickeners
Thickening Effect	*high*	*very high*
		+ requires minimum addition level (cost saving) + especially suitable for low solids formulations
Water Retention	*medium to high*	*low*
		- not suitable for processes with critical water holding behaviour (e.g. on-line board coating) - requires additional water retention aid (cost effective)
Rheology	*pseudo-plastic*	*highly pseudo-plastic*
		+ low high-shear viscosity + good runnability + reduces blade pressure
Immobilization	*slow*	*fast*
		+ bulk coating structure (?) + better coverage (?)

It has to be noted that the results obtained for water retention with static methods do not correlate with the water retention in practice under dynamic conditions. The great advantage of associative thickeners is that they are much more pseudoplastic than conventional products, and coating colors have a lower viscosity at high shear (Table 3.7). This gives better runnability, and less blade pressure need be applied in order to control the coat weight. Associative thickeners cause a large, immediate increase in viscosity when the shear applied to the coating is released, and this can lead to a more bulky coating being formed with a superior optical appearance.

3.6.9.3.4.4 **Lubricants**

Lubricants are used in the coatings of paper and board for a number of reasons. They improve the runnability of the coating color by reducing the friction between the machine and the coating color, and also by reducing the friction between the base paper and the coating unit. This can be seen for example as fewer scratches in the coating and longer lifetime of coater blades. They enhance the plastic deformation of the dry coating in the supercalender by preventing the cracking of the soluble binder film that leads to dusting. This also improves gloss. During calendering, lubricants migrate from the coating onto the hot calender rolls forming a monolayer on the rolls and thus preventing the sticking of the coating to the rolls that causes build-ups. Different kaolins have different dusting tendencies, and dusting can often be solved by using a lubricant. The most commonly used lubricant is *calcium stearate*. It is produced by reacting stearic acid with calcium hydroxide, followed by emulsification and processing to a 50% aqueous dispersion. The critical properties of the calcium stearate dispersion are mechanical impurities and free Ca^{2+}, a good dispersion contains a minimum amount of both. Particle size and shape are important for antidusting properties. The optimum size is 5–10 µm and the shape should be platy. The platy shape enables the stearate to gather on the pigment, plasticize the surface of the dry coating, and reduce the dusting at calenders and printing machines. *Wax emulsions* are mostly emulsions of paraffin waxes, microcrystalline waxes, or polyethylene waxes. These are the oldest group of lubricants in paper and board coating. These emulsions give good runnability but have less effect as antidusting agents than does stearate. Particle size is small and the dry solids content of the emulsion is usually 20%-30%. *Soy lecithin/oleic acid* blends are a new group of substances used as lubricants. *Polyethylene* and *polypropylene glycols* are used in blends with calcium stearate or alone as a lubricant. These lubricants are claimed to have influence on the rheology and flow properties of the coating color.

3.6.9.3.4.5 **Defoamers/Deaerators**

In the coating process, entrapped air or gas can give rise to production problems and quality loss. The major part of the air seems to get mixed into the coating color during the coating application and circulation. Such air is mostly dispersed as small bubbles that, due to the high viscosity of some coating colors, may remain in the color until drying. Higher coating speeds (2000–3000 m min^{-1}) and total solid content of coating formulations possibly contribute to more stable micro-foam. Formation of *foam* is a topic in many industrial processes including the coating of paper and board. Foam is formed through an interaction of mechanical forces and physical chemical properties of the chemicals. From a physical chemical point of view, foam can be defined as a dispersion of air or a certain gas in a liquid or fluid medium. The formation of foam always involves a substantial increase in surface area between the dispersed air or gas and the liquid. Foams in general are inherently unstable and are susceptible to decay with time. On the other hand, it is well known that under certain circumstances foams can be quite stable and may persist over long periods of time. Pure liquids and liquid mixtures, which do not contain a surface-active ingredient, are not able to produce stable foams. Surface-active ingredients or surfactants reduce the surface tension of the liquid and, in consequence, the surface energy renders the system more stable than without surfactants. Besides surface activity, other parameters like foam structure, lamellae thickness, foam drainage, surface rheology, and elasticity contribute to the stabilization or destabilization of foams. These parameters are dependent on time, pH, the presence of surfactants, polymers, proteins, and/or salts as well as the chemical composition and the physical properties of the liquid. Foam generation can occur at different levels of mechanical energy input to the liquid system. Different foam volumes can be generated using the same liquid composition but with different mechanics involved.

Foam reduction, defoaming or deaeration can be achieved by various means. Apart from pressure reduction or mechanical influences (e. g., skimmer or separation grids), special chemical additives are mainly applied to control the foam. In general, it can be stated that there is a need for formulations of specific defoamers for each specific foaming liquid system.

In those cases where surfactants are already a part of the chemical composition of the liquid medium, high-foaming surfactants may be replaced by low-foaming surfactants, e. g., methyl- or butyl-capped alkyl- or fatty alcohol ethoxylates or propoxylate or polymeric materials like polyoxyethylene or polyoxypropylene or both as block copolymers. In contrast to these water-soluble defoamers, usually insoluble hydrophobic additives are widely used as very efficient defoamers. Among these should be mentioned hydrocarbon/fatty acid/ester or wax blends, (poly) siloxanes, fluorocarbons, dispersions of solid particles (hydrophobic silica, organic microwaxes, etc.) in hydrocarbons or (poly)siloxanes. The chemical composition of the defoamer and the particle size distribution of the dispersed additive in the liquid medium determine the efficiency of these defoamers. In these defoamers, the fluid component serves as a dispersal aid for the solid, crystal-like particles. When added to the foam, the hydrophobic liquid component spreads out on one side of the foam lamella surface, producing a nonzero contact angle to the surrounding water phase. After further drainage of the foam lamella, the hydrophobic drop finally bridges the lamella and causes lamella breakdown due to the high contact angles and ongoing drainage. In this respect, the dispersed solid particles enhance these processes and improve the efficiency of the defoamer system to a great extent. Foam control agents are usually applied during coating preparation. In systems where the pigments, binder(s) and the other additives are made up simultaneously, the antifoam agent is added before the pigment and adhesive. Normal dosages lie in the range 0.05 to 0.2 % on dry coating solids. Defoamers are sometimes added pre-diluted and should be properly mixed into the system to ensure an even distribution throughout the volume. Spots in the finished coating layer, commonly referred to as fisheyes and birdeyes, can have a variety of causes. Such deficiencies can be related to the type of antifoam or to too high a dosage of antifoam, where the foam control agent counteracts the complete spreading or wetting of the paper surface at these positions.

3.6.9.3.5 Additives Influencing the Quality and Printability of the Paper Surface

3.6.9.3.5.1 Co-binders and Thickeners

The structure formed by the pigments plays an important part in determining the physical properties of the coating and, because co-binders and thickeners have a high affinity for pigments, they play an important part in influencing the structure of the coating by controlling dewatering. The physical properties of the coating that are affected most by the use of synthetic co-binders and thickeners are the smoothness and porosity and the brightness of coatings that contain fluorescent whitening agents. Careful attention needs to be paid to all these factors when the paper or board is to satisfy all the market demands made on its gloss and print gloss, ink uptake and holdout, glueability, brightness and opacity, water resistance, and absence of mottling. Synthetic co-binders also help to bind pigments to each other.

They largely contribute to the pick strength of the coating. The amount of binder employed in the coating can be reduced if large proportions of synthetic co-binder are employed. Generally speaking, two parts of co-binder can be used to replace one part of binder. They also increase the water resistance of coatings. Once they have formed a film, they become firmly integrated within the structure of the coating and are no longer soluble in water.

3.6.9.3.5.2 **Insolubilizers**

There are many chemically different types of insolubilizers or crosslinkers, but they all have the same function – to add water resistance to the coated paper surface. Water resistance is particularly important in offset printing, but also for wallpaper, label paper, poster paper and in the storage of board packages. In double-coated boards, crosslinkers are used in the precoating to impart water resistance against the topcoat. The water resistance can be measured as wet rub and wet pick or seen as less pick, print mottle, or binder migration. The water sensitivity of paper and board coating originates from the fact that water-soluble binders tend to lose their binding power in contact with water and dissolve. This water sensitivity of binders can be described as the amount of O-atoms in the molecule (in hydroxy and carboxyl groups). The water sensitivity can be decreased by crosslinking the soluble binders with insolubilizers or by building an insoluble net around the binders.

Traditional insolubilizers in paper and board coating are based on formaldehyde and its amino compounds (melamine, urea) or on glyoxal. Imidazoline derivatives are also used as crosslinkers. Next-generation insolubilizers are based on zirconium; the product most widely used is ammonium zirconium carbonate (AZC).

Glyoxal is the simplest aliphatic dialdehyde. It is an effective crosslinker of starch, and gives the coating an immediate curing. The crosslinking mechanism is a reaction with the hydroxy groups. Glyoxal first reacts with one starch molecule and then with another one, leading to crosslinking of two starch molecules. Glyoxal is a less effective crosslinking agent for synthetic water-soluble binders. Some of its derivatives, such as condensate products with urea or ethylene urea can be used here. Glyoxal is ineffective at pH >8.5. Difficulties have resulted with viscosity build-ups due to crosslinking in the wet form.

Melamine-formaldehyde (MF) and urea-formaldehyde (UF) resins have been used in paper coating since 1940. In the 1970s, methylated MF and UF resins for the most part replaced these resins. *Melamine-formaldehyde (MF) resins* and *urea-formaldehyde (UF) resins* have reactive imino- (>NH) and methylol ($>N{-}CH_2{-}OH$) groups. Methylated MF and UF resins have also some functional methoxymethyl groups ($>N{-}CH_2{-}O{-}CH_3$). These groups undergo reactions with paper coating binders: the hydroxy group of starch and polyvinyl alcohol, and the carboxyl groups of latexes. Both UF and MF resins can also self-condensate. The reaction of MF/UF and their derivatives is an acid catalyzed condensation reaction, which requires a certain temperature and pH. The curing reaction takes up to two weeks to complete.

Environmental pressures against formaldehyde-based resins, higher pH in coating formulation, and the need for faster curing are the reasons why *ammonium zirconium carbonate* (*AZC*) is more and more used in the paper industry. AZC reacts with carboxyl and hydroxy groups in the coating, hydroxy groups in starch and PVA, carboxyl groups in latexes, and oxidized starch. The reaction takes place when ammonia is evaporated and water is removed on drying. AZC forms covalent bonds with carboxyl groups and weaker hydrogen bonds with hydroxy groups. High pH does not affect the reaction. Other zirconium-based crosslinkers are *potassium zirconium carbonate* and *zirconium acetate*. The reaction mechanism is similar for all these products.

In coatings the amount and type of binder present determines the addition level of crosslinkers. It is recommended to use 5%-10% crosslinker based on total dry binder. In general, starch-based coatings require a higher amount than coatings based on synthetic binders. It is important to optimize the dosage of crosslinker. An excessive amount can result in cracking problems or even in increased, instead of decreased, solubility of water-soluble coating components. A crosslinker should be added to the coating color as the last ingredient.

3.6.9.3.5.3 **Tinting (Shading)**

In many cases, the yellowish color of the coating clay does not satisfy market requirements. Apart from the addition of pigments such as titanium dioxide, which increase brightness, blue-violet dyes (*shading dyes*) are often used at a concentration of about 2 g per 100 kg of pigment to attain a bluish white coating surface which appears brighter to the eye. Not only basic dyes, but also considerably more lightfast direct dyes and pigments may be used. If the brightness required is very high, optical brighteners are also added.

3.6.9.3.5.4 **Optical Brightening Agents (OBA)**

The brightness of paper and board has increased dramatically during recent years. The brightness of pulp, fillers and coating pigments is not high enough to reach these brightness targets. Therefore there is a need to use a coating additive called an optical brightener. These products are also known under the names optical whitening agents, optical bleaching agents, or fluorescent whitening agents (FWA).

Fluorescence is a phenomenon where the molecules of a fluorescent substance become electronically excited by absorbing light energy and then emit this energy at a higher wavelength. Fluorescence is usually restricted to compounds with large conjugated systems containing π-electrons. Most of the OBAs on the market are derivatives of bis(triazinylamino)stilbene. Only the trans-isomer exhibits strong fluorescence, the cis-isomer is nonfluorescent. The OBAs used in the paper industry are natrium salts and are thus water soluble. There are three types of optical brighteners used in the paper industry, all based on the stilbene molecule. The main difference is the number of solubilizing sulfonic groups. Disulfonated OBAs have two sulfonic groups; the two other substituents could be hydrophilic groups. This OBA has a very good affinity but limited solubility and is mostly used in the wet-end. The most commonly used OBAs are the tetrasulfonated types. Tetrasulfonated OBAs are versatile products because of their characteristics of medium affinity and good solubility. They can be used in most applications in the paper industry: wet-end, size-press, and coating. The hexasulfonated OBAs are specialties used mostly in coatings where high brightness is required.

OBAs absorb ultraviolet radiant energy at 300–360 nm and re-emit the energy in the visible range, mainly in the blue wavelength region. This increases the amount of light emitted, resulting in higher brightness or whiteness. Because the reflected light is bluish, the yellow shade of paper is compensated, contributing to making the paper look still whiter. Whiteness is defined as the measured reflectance of light across the visible spectrum including color components. Brightness again is defined as the reflectance of light at the wavelength 457 nm without color in the measurement. To measure the brightness or whiteness of paper and board containing OBAs requires an instrument having a known amount of UV in the illumination. The test method used increasingly is the CIE whiteness (SCAN method P66) instead of the traditional ISO brightness, which does not define the illuminant. An increase in OBAs at lower concentrations results in an increase in whiteness · As the concentration goes up to 1.5 parts of dry pigment there is no more gain in whiteness when adding more tetrasulfonated OBA. This is called the saturation point or the graying point. The hexasulfonated OBA actually has no graying point because of its high solubility.

3.6.9.3.5.5 **OBA Carrier**

Optical brighteners work only when they are fixed to a carrier. A good carrier is linear and contains OH- or other hydrophilic groups. Linearity increases the contact between the carrier and OBA so that physical bonds (such as hydrogen bonds and van der Waals forces) can be formed between the OBA and the hydrophilic groups of the carrier. Carriers in a coating color are, among others, starch, CMC, or PVA. By adding one of these products in coating color, higher brightness can be achieved.

UV exposure causes yellowing of brightened paper, but a good carrier increases the light stability. Furthermore the carrier has an influence on the migration of OBA; the more efficient the carrier, the better the resistance of OBA to the migration.

3.6.9.3.5.6 **Influencing Opacity**

The main contribution to opacity has to come from the pigments. Synthetic products are usually less opaque than natural products and this can be a problem, especially when coating ULWC (ultra light weight) grades of paper. Products with a very pronounced thickening effect are only added in small quantities, so they hardly have any effect on opacity.

3.6.9.3.5.7 Influencing Smoothness and Gloss

The gloss of paper largely depends on its smoothness. High gloss depends on the evenness of the topology of the paper surface. Like all hydrocolloids, co-binders and thickeners have an effect on the smoothness and the gloss of the paper. They are able to migrate in the wet coating, and migration can lead to them becoming unevenly distributed on the surface. They can also absorb water and swell, which also impairs the smoothness of the paper. Synthetic co-binders are usually less detrimental to gloss than natural products. One of the reasons for this is that natural products are able to absorb moisture and swell after they are dried, whereas acrylic polymers are much less sensitive to moisture once they have dried to form a film. Another reason is that acrylic polymers are highly thermoplastic, and respond very well to calendering. The films formed by natural products are thermosetting, and so they are not deformed as easily under heat and pressure in the calender nip.

3.6.9.3.5.8 Influencing Porosity, Print Gloss and Glueability

The gloss of the printed paper is determined by the smoothness of the paper surface and the ink holdout. In turn, the ink holdout is mainly determined by the porosity and the chemical and physical structure of the coated surface. Coatings need to be porous on a microscopic scale so that the soluble component of printing inks is able to penetrate the paper and dry more quickly. The intensity and brilliance of the printed image and the ink consumption depend on the pigments staying on the surface. The hydrophobicity of the coated surface and the surface tension both influence the ink uptake.

Coatings that contain synthetic thickeners and co-binders are more hydrophobic and take up more ink, but their porosity can have a detrimental effect on the print gloss. Synthetic co-binders give rise to an open-pored structure, which can increase the rate of ink absorption and give a lower print gloss. The task here is to find the best compromise between the pore size distribution and the hydrophobicity of the coated surface in order to obtain the highest possible print gloss without prolonging the drying time of the ink too much. An open-pored structure is often highly desirable in multiple coats applied to board because this guarantees high ink absorption.

Another important aspect governed by the porosity of the coating is the glueability of coated board. Here the affinity of the adhesive also plays an important role. High porosity can be obtained by using binders based on vinyl acetate, and it is for this reason that large quantities of vinyl acetate binders are used in the United States to coat folding boxboard, in spite of disadvantages such as low binding power, poor printability and build up of stickys in the wet-end of the paper or board machine. The approach taken in Europe is to use styrene-acrylic and styrene-butadiene binders, which give a more compact, less porous coating, and to add special co-binders that form a porous film and aid glueability. The porosity of the films formed by acrylic-based products and their compatibility with acrylic and acetate-based adhesives give very good glueability when they are applied to folding boxboard.

3.6.9.3.5.9 **Influencing Printability**

The evenness of the printed image is a very important criterion for quality. The acceptance of coated paper by printers depends on its runnability in the printing process and its printability in terms of an even image that is free of defects.

The printability of paper is principally determined by the surface of the coating, and its structure and topology, pore size and pore size distribution, chemical nature, and homogeneity all play an important part in influencing the interaction between paper and ink. The binder has the greatest influence on printability, but co-binders and thickeners also play a part and they have to be adapted to the printing process.

In offset litho, mottling is mainly caused by the uneven distribution of coating ingredients at the surface of the coating. There are different types of mottling depending on the causes and the way in which the mottling manifests itself. In gravure printing, missing dots can be avoided if the paper has a very smooth surface and a defined microscopic roughness.

In both printing processes, it can be assumed that co-binders and thickeners with very high water retention will have a detrimental effect on print quality. Very high water retention prolongs the drying time of the wet coating and the various different ingredients in the coating migrate at different rates, which causes the binder, co-binder, and thickener to become unevenly distributed. This patchiness gives rise to mottling in offset litho printing processes. Low web speeds and low drying capacity tend to exacerbate this problem. Excessively high water retention can also give rise to a rough, uneven coating which can cause missing dots in gravure printing.

There are no hard and fast rules with co-binders and thickeners when it comes to avoiding mottling. All natural and synthetic products can cause mottling under adverse conditions. Coatings that contain starch are known to have a high tendency to mottle, even if starch is only contained in the precoat. Soy protein behaves similarly. Synthetic products are not usually prone to mottling, although CMC can give rise to missing dots in gravure printing processes.

3.6.9.4 **Color Formulations**

Special coating methods and coating colors have been developed for different printing and converting processes. Manufacturers of coating chemicals, together with their customers, have developed a large number of new pigment and binder qualities plus additives to meet the highest quality requirements. Depending on the quantities and grades of chemicals of different coating colors, their direct product cost can vary within a wide range:

- Precoatings 300–400 € per t of coating (dry base)
- Top coatings 400–600 € per t
- LWC coating color 350–450 € per t
- Specialties 400–3000 € per t

Very generally, a coating recipe consists of the following components (dry materials):

100	parts of pigments (clay, calcium carbonate, talc, TiO_2)
0–0.3	parts of dispersant
5–12	parts of binders
0–1	parts of thickener
0–1	parts of lubricants (calcium stearate)
0–1	parts of optical brightening agent (OBA)
0.01–0.05	parts of shading dyes
0.01–0.1	parts of defoamer / deaerator

More details about coating color formulations depending on the specific paper and board grades are mentioned in Section 7.6.

3.7
Process Chemicals [1–3, 9–11, 21–24]

Process chemicals are all additives which are used to solve or prevent problems in the paper manufacturing process, to improve its efficiency and/or to provide ecological advantages. For example these additives allow reduction in the consumption of fresh water and energy, the prevention of foam and deposits, the improvement of drainage and/or reduction in fiber losses. Their proportion related to all chemical additives is only 10% (Fig. 3.3).

3.7.1
Retention and Drainage Aids (RDA)

The term retention refers to the holding back of the papermaking stock on the wire during sheet formation and dewatering. The fibers are retained on the wire better than the fillers and the fines, which may be washed through the wire and even through the fiber mat formed. The most common retention parameters can be defined as *first-pass retention* (FPR) and *overall retention*. First pass retention is the ratio of the amount of solid material that leaves the headbox slice to the amount of solid material that is contained in the paper web leaving the couch roll (typical values are 40–70%). Overall retention is the ratio of the amount of solid material that is sent to the wet-end of a paper machine to the amount that goes onto the reel at the dry end of the machine (typical values are 90–98%).

3.7.1.1 Retention Aids

These increase adsorption of pigments (fillers) and fine particles onto the fibers so that they are retained with the fibers. This adsorption must be able to resist the high shear forces which arise in pipes and different apparatuses of modern high-speed paper machines. In the early days of papermaking, common retention aids were based on alum, which neutralizes charges on the furnish components. Later, single polymers such as PEI (polyethylenimine) were introduced with patching as the dominant mechanism. In single polymer and dual polymer systems (e.g. PEI + PAM), high molecular weight polymers like PAM (polyacrylamides) cause bridging – which is considered to be the major mechanism. However, the latest developments, micro- and nanoparticle systems (e.g. PAM/bentonite, PEI/PAM/bentonite, silica gel/PAM), follow a complex flocculation mechanism. Since their introduction in the early 1980s, the latter systems have been successfully applied. Recently, organic microparticle systems have been introduced. Systems based on polyethylene oxide (PEO) and phenolic resin or polyvinylformamide (PVF) copolymers and polyvinglamine (PVAm) function according to the network flocculation mechanism or at least by hydrogen bond interactions.

Retention aids can be divided into three main product groups according to their chemical composition: inorganic salts such as aluminum sulfate and polyaluminum chloride (PAC), natural polymers such as cationic starch, and synthetic polymers, high-molar-mass polyelectrolytes (Fig. 3.16). The most important members of the last group are cationic, anionic or nonionic polyacrylamides and modified polyethylenimines. There are also many smaller groups of products such as various polyamines, poly-DADMAC and, most recently, polyvinylamines. The above mentioned microparticle systems need, as a further compound, inorganic particles like bentonite or silica gel. The worldwide consumption of RDAs is 2×10^6 tons p.a., expressed as solids. It may come as a surprise that the aluminum compounds occupy such a dominant position. However, it must be borne in mind that rosin

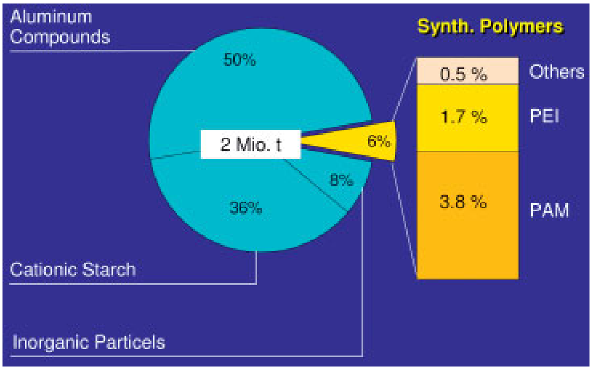


Fig. 3.16 Chemical classes of retention aids and their world consumption in 2004 (mass shares of solid substances). PEI = polyethylenimine, PAM = polyacrylamide.

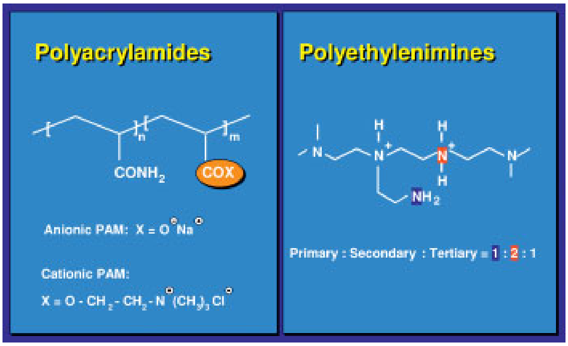


Fig. 3.17 Chemical structure of retention aids.

sizing, where alum is needed, still plays a very important role, leading to the market share for aluminium compounds being about 50 %. Cationic starch has a market share of 36 % or 720 000 tonnes p.a. Again, it must be remembered that cationic starch is also used to increase the dry strength of paper as well as to boost retention. The market share for synthetic polymers is 6 % or 120 000 tonnes p.a. This figure seems very low, but the high efficiency of these polymers means that they only need to be applied at rates as low as 100–500 g solids per tonne of paper. From the point of view of their chemistry, all retention aids are polymers, even aluminum sulfate and PAC are present in the form of polynuclear complexes, the structure of which depends on the pH. Polyacrylamide and polyethylenimine illustrate the common underlying chemical principle of all these products: a polar structure with hydrogen bonds and ionic bonds and a high molar mass (Fig. 3.17).

3.7.1.2 **Drainage Aids**

These are chemical additives that improve the dewatering of the paper web along the process, in forming, pressing and drying. The potential benefits include increased machine speed and higher production rate, improved formation, and lower dryer steam consumption. Improved drainage can lead to decreased headbox consistency. This, in turn, decreases fiber flocculation. In general, most of the agents that serve as retention aids and charge neutralizers can also be used as drainage aids, but their charge density (meq g^{-1}) and their molar mass (g mol^{-1}) in interaction with the other wet-end conditions influence their drainage efficiency significantly. Therefore drainage aids are mainly based on the same chemistry as retention aids and are expressed in the common term RDA. The specific benefits that can be obtained can be illustrated with reference to a modified polyethylenimine with a charge density of 6.5 meq g^{-1} and a molar mass of 2×10^6 g mol^{-1}. Besides the improvement of fiber, fines and filler retention on the wire, the drainage acceleration on the wire and especially the water release in the press and dryer section lead to an increase of 3 to 10% in productivity and a similar saving of specific energy.

RDAs also act in synergy with other chemical additives such as deaerators, which boosts the overall performance of other wet-end chemicals and reduces their consumption. With improved retention as well as with the fixation of colloidal dissolved substances much cleaner white-water is obtained with a COD reduction and over all less deposits are achieved. Consequently a higher degree of process water closure, less volume of waste water and an improved PM runnability can be obtained. The waste water is also more easily treated.

3.7.2
Fixing Agents

In the production and processing of chemical, semichemical and mechanical pulps and recovered paper, various inorganic and organic substances are accumulated in dissolved or colloidal dissolved form. Other water-soluble substances enter with the fresh water, fillers, recycled uncoated and coated paper broke and also by chemical additives. As the process water circuits are increasingly closed, the concentration of these water-soluble and colloidal substances and finely dispersed particles increases considerably and an additional contaminant load is thus imposed on the waste water. These substances interfere with the production process by increasing build-ups and deposits, they reduce the efficiency of the chemical additives, and impair the quality of the produced paper. Therefore these substances are also classed as detrimental substances (Fig. 3.18).

The use of highly cationic polymers is a common possibility to remove the load of dissolved anionic substances by complex formation, fixation to the fibers and subsequent discharge with the freshly produced paper. Besides the dissolved anionic substances there is a variety of nondissolved, hydrophobic substances (particles) mainly coming from the raw materials, e.g. wood extractives, coating additives, adhesives. By fixation of the particles to the fibers they can be removed from the system before they build uncontrolled reactions with the paper stock and

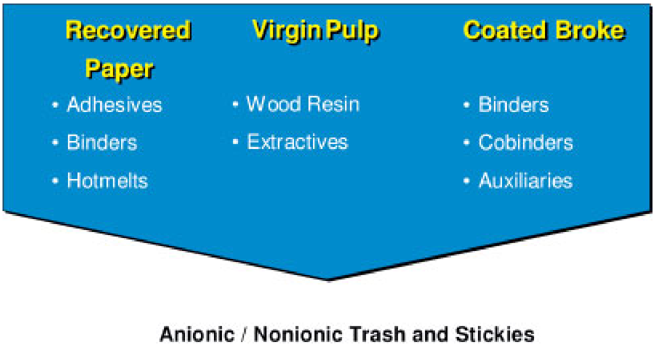


Fig. 3.18 Sources of detrimental substances.

Table 3.8 Fixing agents: categories, molecular weight and charge density (source: BASF).

Molecular weight [10^6 g mole^{-1}]	**Polymer**	**Charge density [meq g^{-1}]**
0.2–0.3	polyallyldimethylmethacrylate (polyDADMAC)	~ 6
< 0.05	dicyandiamide-formaldehyde-resins	1–2
3–5	cationic polyacrylamide (PAM)	1–5
0.05–0.2	polyamine (PAm)	6
0.8	modified polyethylenimine (PEI)	11[a]
0.1–5	polyvinylamine (PVAm)	0–15[a]

[a] Charge density per g of cationic polymer without counter ion measured at ph 7.0.

chemical additives or before they have a chance to form sticky agglomerates. The most commonly used fixing agents in the paper making process can be divided into six categories (Table 3.8). Apart from their chemical nature and molecular structure, these polymers mainly differ through their charge density and molecular weight. In general it can be stated that polymers with a combination of high cationic charge density and high molecular weight perform best in terms of eliminating dissolved anionic material from a contaminated system. However, the density of accessible anionic charge, located on the surface of white pitch particles, is usually much lower than the accessible anionic charge density of dissolved substances. Therefore a fixing reacting exclusively by a charge mechanism, is often not efficient in controlling the bonding strength between white pitch particles and fibers and minimizing the formation of white pitch agglomerates. Besides the charge density, there is another molecular parameter which can be used to control the bonding strength between fibers and particles. The modification of cationic polymers with nonpolar hydrophobic groups is likely to influence the interaction of the polymer with the hydrophobic particles. The modification of a partly hydrolysed PVAm (DH=30 %) and a PEI with hydrophobic functional groups is depicted schematically in Fig. 3.19. In many cases, the use of a fixing agent in a mill has to be seen in combination with other chemical additives e. g. retention aid, sizing agent, dry strength resin, where their effectiveness will be significantly improved by the fixative.

The most popular tests for quantifying the general contamination of a paper machine system are COD (chemical oxygen demand), cationic demand and conductivity. For specific insights regarding pitch contaminants there are other useful tests. Turbidity of stock filtrate can serve to quantify the presence of colloidal dissolved material. Soxhlet extraction with dichloromethane (DCM) is commonly used for quantitative pitch analysis of deposit and paper samples. The hemacytometer is frequently used to measure dispersed pitch. An optical laser counter can

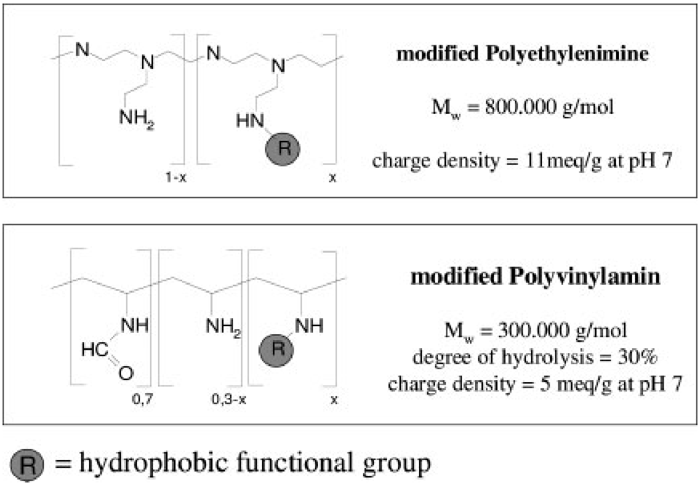


Fig. 3.19 Hydrophobic modification of polyethylenimine (PEI) and polyvinylamine (PVAm) (source: BASF).

be used to measure particle size and volume of hydrophobic particles. Information about the deposition tendency of hydrophobic particles, untreated and treated with fixing agents, can be evaluated by the impinging jet method in which the filtrate of a stock or white water sample is pumped at a certain speed through an impinging jet cell. The deposition of the particles will be measured by the surface coverage on the collector plate after a defined time period.

3.7.3
Additives for Pitch and Deposit Control

The very heterogeneous compounds of detrimental substances which can be present in the papermaking process, are the reason why only a part of the pitch and deposit problems can be solved by fixing agents. Besides the dissolved anionic substances there is a variety of nondissolved, hydrophobic substances (particles) coming from many different sources and determined by the raw materials used e. g.:

- rosin and wood extractives from high yield chemical and mechanical pulps (wood pitch)
- binders and coating additives from recycled coated broke (white pitch)
- adhesives and hot melts from recovered papers (stickys).

These substances affect paper machine runnability and paper quality. They can be found on paper machine wires, felts, vacuum boxes, dryer cans, calender rolls and in the finished paper. The consequences vary from early replacement of wire and felts, to web breaks, dirt and even holes in the finished paper. In order to understand the mechanism of fixation for particles within this size range, one has to

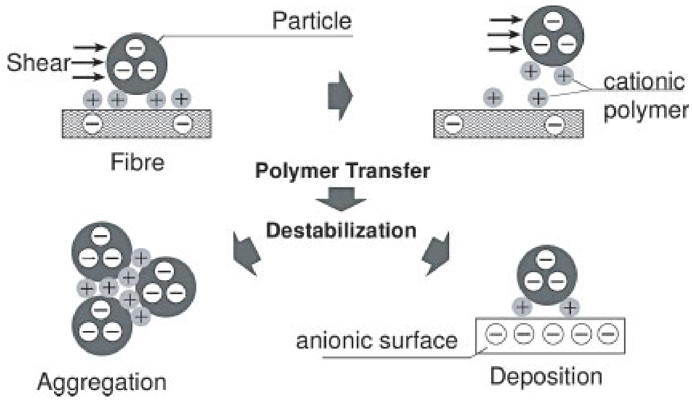


Fig. 3.20 Aggregation and deposition of hydrophobic particles (source: BASF).

understand the role of shear forces acting on particles fixed to the fiber. When a particle is fixed to a fiber, it can be detached by shear forces and pushed back into the system. Whether the particle is detached or not depends on the balance between the strength of the fixing bond and the shear force. For a given strength of fixing bond larger particles will be detached more easily then smaller particles. Taking into account the collision probabilities of particles and fibers under practical conditions, one can imagine that tear off and fixation take place numerous times before the particle finally gets fixed. For particles undergoing several successive fixation and tear-off cycles, a net transfer of cationic polymer from the fiber surface onto the particle surface will take place (Fig. 3.20). When the amount of transferred cationic polymer is high enough, this will lead to destabilisation. Eventually collisions between destabilised particles will occur and they will form even larger aggregates. As a result, poor fixing performance is observed when particle size increases. In practice large aggregates will be mechanically entrapped in the fiber mat causing sheet defects and machine deposits. In order to avoid the formation of aggregates and the deposition of destabilised particles, one has to avoid polymer transfer between fibers and hydrophobic particles. Therefore the bonding strength between fibers and particles, as well as their colloidal stability, has to be controlled by adapting the chemistry of the fixing agents to the chemical and physicochemical characteristics of the white pitch particles.

The vast majority of disturbing particles, by number and by volume, can be found in the critical size range between 0.2 and 5 μm, where mechanical separation techniques like pressure screens and cleaners are no longer effective. Chemical additives have different working mechanisms, and it is not always possible to predict which type of chemical is best suited to each case. Very often, it is worthwhile to carry out some laboratory tests before deciding to use a new chemical.

Anionic dispersants increase the colloidal stability by adsorption of anionic groups onto the particle surfaces. At the same time, the pitch particle dimensions are decreased and the possibility of building larger agglomerates decreases. Typical dispersants are polynaphthalene sulfonates and lignosulfonates. It should be noted that this mechanism is the opposite to the fixing of pitch onto the fibers. One consequence of using anionic dispersants is that, if fixing agents are used in a later stage, the amount of fixing agent to achieve the desired result has to be increased.

The use of *aluminum sulfate* (*alum*) is a classical way to solve pitch problems on paper machines. But only in an acid environment (pH 4.5–5.5) is alum a strongly cationic product that effects coagulation and fixation of dissolved and colloidal material onto the fiber. At higher pH (5.5–7), alum can be replaced by *poly-aluminum chloride*. Alum lowers the pH, hence, the use of alum in the presence of calcium carbonate should be considered very carefully.

In addition to the fully synthetic fixatives (Section 3.7.2.), *starch-based*, semi-synthetic strongly cationic polymers are available. Not only do these starch-based fixing agents have a better biodegradability, but they are also capable of forming hydrogen bonds from hydroxy groups in their anhydroglucose repeating units. In paper production, the hydroxy groups can form hydrogen bonds, not only with cellulose fibers but also with interfering low-molecular weight anionic carbohydrate compounds, thus decreasing the concentration of such substances in the water circuit .

To control pitch and other hydrophobic substances in the stock-water-system, *adsorbents* can also be used. These additives are pigments with a high specific surface area in water, like bentonites, micro crystalline talc or mica. The surface of the micro talc particles is hydrophobic and thus hydrophobic substances tend to adhere to it. The size of the particles to be adsorbed, however, must be smaller than that of the adsorbent used.

To prevent pitch or coating broke residues from adhering to felts, wires, or cylinders, it is possible to use some special *wire or cylinder protective agents*. These chemicals normally contain a cationic polymer and a surface active agent.

Use of the *enzyme lipase* has, in some cases, proved to be successful in the control of deposits. Lipase hydrolyzes triglycerides into fatty acid and glycerine, which are less hydrophobic and less inclined to build up tacky deposits. An addition of 3 ppm lipase calculated on pulp should be added to thick stock, e. g. groundwood, when about 70 % of the triglycerides will be hydrolyzed. The resultant fatty acids will be dispersed into the pulp and fixed onto the fibers with alum. Pitch deposits on the machine chest wall – which are very often a problem – will almost disappear and the amount of pitch deposits on wire, press, and dryer sections will decrease by 30 to 50 %.

Another possibility is to add a chemical for pitch removal in mechanical pulp production. Polyethyleneoxide (*PEO*) has been used for this purpose. PEO builds hydrogen bonds to pitch and has a natural affinity to pitch particles.

The first step of a pitch/deposit control program should be the evaluation of different treatment procedures in the laboratory with the test methods described in Section 3.7.2.

3.7.4
Slimicides and Biocides

Microbial problems in paper and board mills have significantly increased with the enclosure of white water systems to reduce the use of fresh water. Environmental constraints have also contributed to the need for reducing the amount of effluents. The recirculation of white waters has created serious slime problems because of the growth of microbes in the systems. Increased paper recycling levels increase the amount of nutrients in solid or dissolved form. It is noteworthy also that additives used in the production process themselves represent an ideal nutrient source (starch), or contain impurities with quite a lot of nutrient material (kaolin), for microbes. The slurries of fillers and coating pigments can contain considerable amounts of phosphorus and nitrogen, which along with the carbon source are the principal nutrients for most microbes. The incoming raw water can also contain considerable amounts of nutrients for microbes. The amount of nutrients present varies to a marked extent according to the season of the year. Moreover, the temperature in the process water circulation system has increased, thus providing a more suitable environment for the microbes.

The growth of microbes can cause many problems in the mills either in the paper product (spots, holes, spores, odor) or in the process (runnability, corrosion, deposits). Thus the microbiological state of the whole paper production process has to be under control. Problems caused by microbes can, to a large extent, be avoided by maintaining machine cleanliness and by taking notice of the microbe-favorable places in the local system as well as environmental factors. Equally important is the control of incoming raw materials and the purity of the chemicals used, and monitoring slurry preparation at the mill properly. Storage chests for coated broke require particular attention. The first steps to minimize microbial growth should be good housekeeping, prevention of deposit formation and an evaluation of the design and size of stock and water chests and pipes. The whole volume of stock suspension in the stock preparation and storage plant should be as small as possible and there should be no corner without flow.

Despite proper attention to the items described above, conditions recorded as slime problems (caused by microbial growth together with organic and inorganic contaminants) occur and are then offset by dosage with biocides. Biocides and products called slimicides or microbicides are chemicals used to prevent the growth of microbes. A number of biocides with different active ingredients are available. The efficiency of some biocides is based on destroying the cell membrane function, thereby inhibiting the metabolism and the growth of microbes. Other types of biocides penetrate the membrane and react with essential cell components (enzymes, proteins, etc.). The selection of the proper biocide for a particular use will depend on many factors, e. g., temperature, pH levels, and type and properties of the actual microbial fauna present which can even change from time to time. Typically, the major classes of biocides are organobromides, organosulfurs, isothiatzolinones, thiocyanates, thiocarbamates, metallics (substances containing copper and tin), chlorinated phenols, and phenates. Awareness of potentially dangerous effects upon the environment is important, and slime control programs must be planned accordingly. New types of biocides are being developed continuously to meet changing regulatory demands in regard to reduction of, e. g., toxicity and environmental impact. The main problems to note under practical conditions are environmental security, the manner of dosage (concentration, points of input in the system), and efficiency under process conditions. No one biocide will effectively kill all the bacteria present in the water system. This has led to the development of wide spectrum biocides.

Strategies used in biocidal control of microbiological slime problems include narrowing the spectrum of the bacterial population, thereby also reducing the formation of biofilms. To preclude the development of resistant microbe populations, a biocide should be periodically substituted by another one functioning by a different mechanism. The required dosage of biocides can be greatly reduced by determination and selection of the correct biocides for the particular species of microbes causing the problem. It should be kept in mind, however, that the required dosage can depend greatly upon pH. For example, thiocarbamates are effective in an acidic environment; however, as pH is raised toward neutral, the effect falls off dramatically due to the shorter half-life (about 18 h at pH 6 but less than 2 h at pH 7).

Knowledge of the composition of slime deposits and the formation mechanisms of biofilms has led to more selective slime control agents, in combination with the use of chemicals that are capable of either penetrating the biofilms or dispersing the deposits. So less toxic substances can be used in the system and keeping machine surfaces is easier.

In slime control without application of biocides, chemicals are avoided as far as possible. Some examples of elimination of slime without biocides are bacteriphage application, enzyme application and removal of nutrients. Slime-decomposing enzyme systems and specific viruses that kill specific bacteria have been developed. The Biochem method for example, uses modified lignosulfonate as a complex former. It neutralizes metabolites by electrostatic discharge, thereby making the nutrients nonusable by microbes. It also chelates essential trace elements present in the circuit system. Another product group to reduce deposit build-up, primarily microbiological slime, in the circuit system of a paper machine is the so-called "biological dispersing agents" or biodispersants. Principally, they are combinations of surfactants that have been optimized to dissolve pockets of slime, but they are usually also capable of breaking up other (primarily hydrophobic) deposits. These products, which are sometimes also used in combination with enzymes, are based on natural terpenes (oil of oranges), paraffin, lignosulfanates, or various detergents (tensides). Which product to use depends on the type of raw materials employed in the paper manufacturing process and the specific problem to be solved. If numerous microorganisms are introduced into the process (e. g. through the use of surface water), there is sometimes no alternative to the additional use of biocides. Biodispersants are effective in three ways. First they infiltrate the deposit (the so-called "creep effect"), then break it apart. Finally, they envelop the deposit in a chemical coating (surface passivation). These processes can be observed by measuring the surface coating of piezoelectric crystals, for example, or on metallic surfaces introduced into the paper machine as testing probes and examined using an electron microscope.

Biocide research today has to consider the toxicological and environmental impacts. The research therefore is focused on making biocides more effective at lower concentrations as well as on developing nontoxic and environmentally friendly products. In fact, many agents already known for years to be effective as biocides or as disinfectant chemicals, but considered to be costly, have been put into reuse. Examples are hydrogen peroxide, glutaraldehyde, ozone, and peracetic acid.

To control the microbiological situation, sometimes a full count of microbe species at different locations is required, rather than determination of the presence of certain microbial groups like slime-forming species, fungi, yeasts, anaerobic bacteria, etc. Conventional methods for identification of microbes include enumeration and screening of individual species isolated from count plates on selective media. Ready-made plates are available for the selection of different types of microbes. Commercial identification systems for industry and medical purposes, based on numerous biochemical tests or other characteristics, are available, including a database that covers practically all groups of bacteria.

3.7.5
Defoamers and Deaerators

Foam arises from dispersed gas in a liquid in a ratio such that the bulk density of the mixture approaches that of a gas rather than a liquid. When foam collects at the air/liquid interface, it is called *surface foam*. When foam is mixed into the liquid and is only slightly or not visible on the surface, it is usually called *entrained air*. Along the production processes of pulp, paper and board more or less foam is built up and gas is entrained. The violent motion of water during filtration and drainage and in the white water system, especially at high paper machine speeds, produces a stable foam, in the presence of surface active agents and colloidal surface active film formers with a negative charge, such as hemicelluloses, proteins, and polysaccharides. On the fiber surface there are always hydrophobic patches from wood resins, and positively charged patches, e. g. from alum, where the air/gas bubbles then accumulate (Fig. 3.21). The increased use of calcium carbonate as filler and coating pigment may lead to a further significant source of gas/foam by the decomposition of $CaCO_3$ to CO_2

High air/gas contents may be the source of severe problems in both paper manufacturing and paper coating and should be kept below 0.1 to 1.0 %, depending on the paper grade. Too high air/gas content in the headbox suspension has a negative effect on the retention of fibers, fines and fillers as well as on the paper formation and dewatering on the wire and press sections (Fig. 3.22). At high gas contents the number of pinholes (with their negative effect e. g. in coating and printing) and the average pore diameter of the paper sheet are increased, and also the surface roughness. For all pumping and suction processes more energy will be consumed. Paper

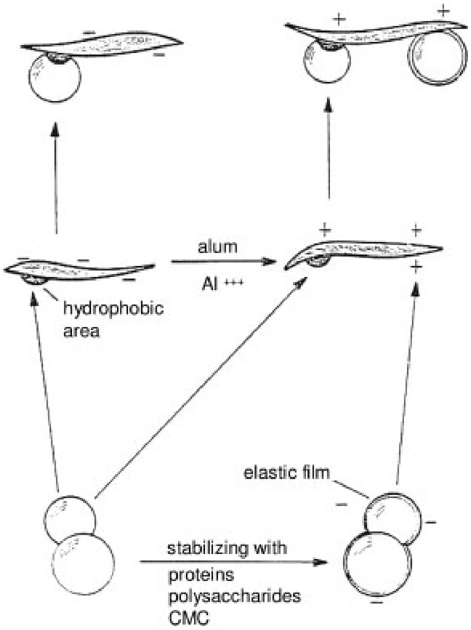


Fig. 3.21 Mechanism of gas bubble attachment to fibers. CMC = carboxy methyl cellulose.

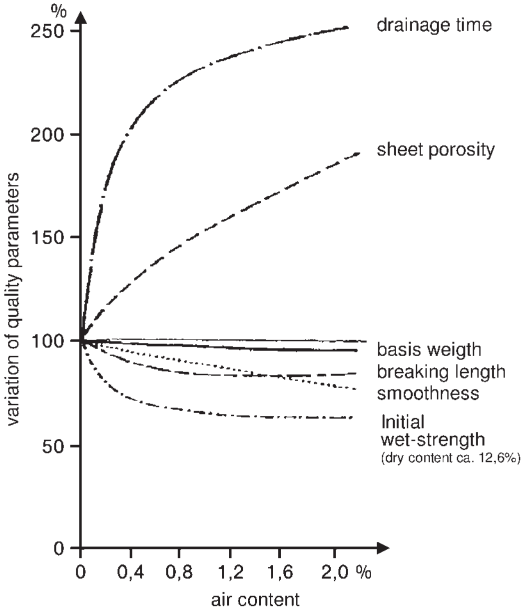


Fig. 3.22 Influence of air/gas content on stock properties and paper quality (source: dissertation U. Kirchner, TU Darmstadt, 1961).

machine runnability, and consequently productivity, may be lowered. Also, some process chemicals, such as reductive bleaching agents and retention aids, perform significantly worse in the presence of entrained air and gas. In coating, high gas contents of the color give rise to runnability problems and quality loss. Gas makes coating color foam in the machine circulation loop and leads to tank overflow and to an irregular pump/metering performance. The most evident negative phenomenon is, however, the uncoated spots on the paper surface caused by the entrapped air. Together with an insufficient amount of applied color, gas bubbles are the main cause of such a coating defect called skipping. In paper coating, high gas contents are closely linked with the color formulation, color preparation and circulation system, the applicator system and the coater speed (see Sections 3.6.9.3.4.5 and 7.7.6). Problems of excessive gas contents also originate from the use of hydrophobic substances (talc) and stabilizer chemicals for synthetic binders as well as from certain chemical reactions e.g. decomposition of calcium carbonate at reduced pH. Deaeration by thermomechanical means only does not provide the desired persistency of gas-free stock.

Chemical deaerators permit steady and prolonged deaeration by triggering bubble coalescence. This is achieved by means of hydrophilic emulsion particles, which penetrate the contaminated gas bubble surfaces, thereby facilitating their coalescence (Fig. 3.23). The difference in mechanism between deaeration by both thermomechanical and chemical means give the best results. The suitability of a defoamer and deaerator for certain mill conditions depends first on the hydrophobicity or hydrophilicity of its components. This means that a very hydrophobic product is a good "foam killer" and a more hydrophilic one is an efficient deaerator.

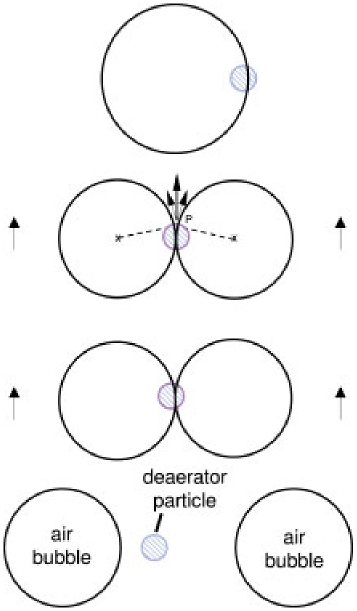


Fig. 3.23 Accumulation, bursting and growth of air/gas bubbles by deaerator application.

Table 3.9 Chemical composition of deaerators and defoamers.

Aqueous Emulsions
approx. 25 % Higher Fatty Alcohols ($< C_{16}$)
approx. 1–2 % Emulsifiers
approx. 73 % Water

Synthetic Oils
100 % Alkylalkoxylate e. g.: $R{-}O{-}(CH_2{-}O)_n{-}H$
or
100 % Acylalkoxylate e. g.: $R{-}COO{-}(CH_2{-}CH_2{-}O)_n{-}H$

Mineral Oils
Blend of alipathic, cycloaliphatic and aromatic hydrocarbons

Defoamers and deaerators are derived from hydrocarbons that contain substituted polar groups. The active substances contained in products supplied in the form of 25–30 % aqueous emulsions are mainly higher fatty alcohols, fatty acids, and fatty acid esters and their ethoxylates (Table 3.9). They may contain anionic or nonionic emulsifiers. The active substances contained in so-called *oil-type defoamers* are mainly fatty alcohol ethoxylates, fatty acid ethoxylates or mixtures of fatty alcohols. They can also contain emulsifiers in order to aid dispersion. It is important to note that the term oil-type defoamer refers to the oily consistency of this group of products, and has nothing to do with the use of mineral oil as an active substance. *Emulsion-type* defoamers account for half of the worldwide consumption of defoamers and deaerators, expressed as solids. *Synthetic oils* represent 40 % and mineral oils 10 %. It seems that mineral oils are no longer in use in Europe.

Controlled deaeration of stock suspensions and coating colors requires regular measurement of the air/gas content. The mainly used methods are based on the compressibility of air/gas (e. g. Brecht-Kirchner equipment, EGT, Celleco). The measurement measures the change in the gas volume by the change in the applied pressure using a vacuum (expansion method) or using pressure (compression method). A continuous in-line measurement based on ultrasonics is also possible. In water dispersed little gas bubbles are excellent scatterers of sound. The on-line apparatus measures the ultrasonic damping.

3.7.6
Cleaning Agents

Again, with increased usage of recovered paper, solid board and corrugated box board, enclosure of mill water systems, and use of plastic wires and felts, many new challenges have arisen for keeping the surfaces of chest walls, pipes, rolls, filters and drying cylinders and different paper machine clothings clean for optimum production. As is shown in Fig. 3.24 there are different necessities for cleaning. The major cleaning application, 41 %, is so-called system cleaning e. g. boiling out the whole stock and white water system which is directly connected to the wire

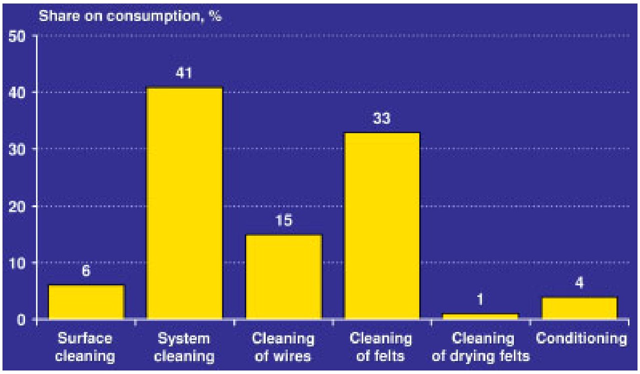


Fig. 3.24 Application of cleaning agents (average of all paper grades) (source: U. Hamm, PMV, TU Darmstadt).

part of the paper machine. One third of the cleaner consumption is used for felt cleaning and 15% for wire cleaning.

To prevent deposition or to remove deposits from wires and felts, so-called conditioners are continuously applied. The following dirt and deposits occur:

- inorganic substances e.g. lime and calcium sulfate
- organic substances e.g. resin/pitch, adhesives
- residues of chemical additives e.g. dyes, coating binders, starches, wet strength resins
- microbiological substances, fines from paper stock
- compounds of fresh process water e.g. humic acid, iron, manganese

Cleaning agents are characterised by a great number of commodities which can differ considerably in their chemical composition as well as in their cleaning efficiency. In principal, the cleaning agents belonging to the group of process chemicals can be subdivided into inorganic and organic products. As inorganic cleaning agents, sodium hydroxide as an alkaline agent and hydrochloric, sulfuric and phosphoric acids as acid agents, are mostly used. The number of organic cleaning agents available on the market is much higher. Simple formulations in most cases consist of tensides and sodium hydroxide or inorganic acids respectively. In more complex mixtures dispersing agents, chelating agents and solvents can be found. Solvent cleaning agents mostly consist of aliphatic and aromatic hydrocarbons, in certain cases as mixtures with tensides.

In the German paper industry in 1999, an average of 0.35 kg of cleaners per ton of paper was consumed. The proportion of organic cleaning agents was around 60%. Cleaning agents are applied continuously and, more frequently, discontinuously. Referring to the mass balances of discontinuous cleaning of paper machine clothings with tenside containing acid and alkaline cleaning agents, the process water load resulting from the application in the production of corrugating papers bears no risk for anaerobic or for aerobic waste water treatment plants when the cleaning agents are used in an appropriate manner and the washing liquor is buffered sufficiently.

3.7.7
Flocculants and Coagulants for Clarification of Different Water Sources

In the production of pulp, paper and board a large amount of water is generally necessary. Therefore different quantities and portions of *fresh water* (taken from river/lake nearby or from fountains), and *recycled process water* have to be used. For high production efficiency and good paper quality, clean water is required. On the other hand the *effluent* has to be environmentally friendly and has to meet the official legislation.

Therefore all three water sources (fresh water, recycled process water, effluent) have to be treated and clarified, mechanical treatment (filtration, sedimentation, flotation) always having first priority over chemical treatment. In practice, in most cases, a combination of mechanical and chemical treatment leads to an efficient solution.

3.7.7.1 Fresh or Raw Water

This can be colored, as turbid surface water may contain humus as well as iron and manganese, either in the oxidized form or bound to organic matter. Water of this type is treated by aeration + coagulation + addition of alkali + clarification + sand filtration. The removal of color and organic compounds usually requires a method based on chemical precipitation. Some reduction in organic matter content, of course, can be achieved by simple filtration. The removal of iron and manganese, on the other hand, usually requires:

1. Oxidation of iron (II) and manganese (II) to oxidation state III e.g. by chlorine or permanganate
2. Hydrolysis of the trivalent cation to produce the hydrated hydroxide
3. Coagulation of the hydrated hydroxide
4. Removal of the coagulate.

The next step is usually chemically-induced coagulation and flocculation. The sequence of events is addition of chemical, rapid mixing, and finally gentle stirring. Here *aluminum sulfate* is one of the commonly used chemicals. A suitable rate of addition can be calculated from zeta potential measurements. Aluminum sulfate reacts with the alkaline compounds naturally present in the water and also with any added lime or sodium carbonate. Another commonly used coagulant is *sodium aluminate*. This is normally employed as a supplementary coagulant to ensure proper treatment of cold waters or to coagulate residual aluminum sulfate. Supplementary coagulants are used in cases where floc formation would otherwise be unsatisfactory. Here the most common agents are *activated silicic acid*, certain natural organic compounds and synthetic polyelectrolytes, mainly modified *polyacrylamides* with high molecular mass. Their ionogenic character depends on the individual mill conditions. Other chemicals used, mainly for pH adjustment, include certain calcium and sodium compounds. The addition rates of aluminum compounds are in the range 10 to 100 g m^{-3} fresh water and those of polymers ca. 0.1 to 1 g m^{-3}.

3.7.7.2 **Recycled Process Water**

Recycled process water allows one to reduce fresh water demand and to reduce the effluent loadings from paper and board manufacture. In papermaking water consumption has been reduced dramatically in the last decades. Printing papers, for example, are manufactured at a specific fresh water consumption of about 8–10 $m^3\ t^{-1}$, packaging papers at about 3 to 5 $m^3\ t^{-1}$. Hereby, at least for graphic papers, solids and dissolved organic matter are removed. If lowering water consumption down to 2–4 $m^3\ t^{-1}$ salt concentrations have to be managed. In packaging paper production e. g. for testliner and corrugated medium, in more and more cases fresh water consumption is down to the evaporated water in the dryer section of the paper machine. This means a specific fresh water consumption of 1–1.5 $m^3\ t^{-1}$ and no more waste water to the effluent. These results can only be obtained by a very efficient mechanical and chemical treatment of the recirculated process water. To separate and remove solids and dissolved substances from this water, nonsalt building flocculants, e. g. *polyethylenimine, polyamine* and/or *polyacrylamides,* have to be used. The addition of these polyelectrolytes (solid) is in the range 10 to 100 g m^{-3} recycled process water.

In completely closed water circuits biological treatment (anaerobic-aerobic) remove dissolved organic matter even more efficiently. However, recycling the biologically treated water can be restricted by the resulting reduction in product brightness, which does not matter for packaging papers. With nano- and ultrafiltration very small solid particles and some dissolved high molecular mass material are removed. For good results the surface chemistry during the manufacturing process has to be thoroughly watched. Internal process measures reduce loadings at source, and direct savings can be made in raw material costs (fiber, fillers, additives) and also in energy consumption.

3.7.7.3 **Effluents**

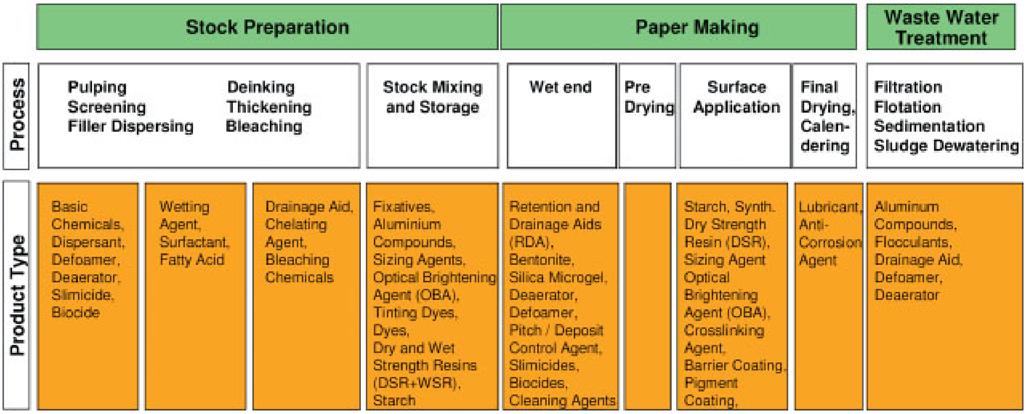
Effluents from pulp, paper and board mills contain wood materials in solid, colloidal and dissolved form. The effluents also contain some chemicals used in the production process, either in their original or modified form. The principal mechanical methods used to remove these compounds are filtration (including membrane and nanotechnology), sedimentation and/or flotation. All these methods require very good flocculation and coagulation of these undesirable substances in the effluent. Only then can they be separated from the clear water. The main chemicals used for coagulation are *aluminum salts* (e. g. $Al_2(SO_4)_3$), iron salts (e. g. $FeCl_3$ or $Fe_2(SO_4)_3$ or $FeSO_4$) and lime with addition rates of 100–500 g m^{-3} effluent. To achieve optimum flocculation results, it is often necessary to feed a suitable polymer, e.g. modified *polyacrylamide* with high molecular mass and a certain charge density during slow mixing. Addition rates of the polyelectrolyte (solid) are 1–50 g m^{-3} effluent. The primary purpose of chemical coagulation is to neutralize the electrical charges on the particles and hence prevent repulsion. This means adding metal cations because the suspended organic material is nearly always negatively charged. In most cases, the coagulant itself also precipitates (for example, as the hydroxide), making the treatment more effective. For this reason, pH control is important. Organic polyelectrolytes, on the other hand, normally bind together dirt particles and in this way promote floc formation. Typical charge measurements are anionicity determination, zeta potential measurement, and calculation of particle sizes. In effluent treatment, chemical coagulation is applied mainly to the separate treatment of concentrated effluent fractions (e.g., those from pulp bleaching, deinking of recovered printing papers, coating color preparation, and broke). The flocs formed are removed from the water by sedimentation, flotation, or filtration. The sludge produced is either fed back to stock preparation or after dewatering by polyelectrolyte addition and specific presses goes to incineration, depending on the paper grade produced.

Biological treatment of the effluent is particularly useful for removal of low molecular mass organic matter. The process is based on the ability of microbes to live and reproduce in effluents. In doing so, microbes break down dissolved and colloidal substances by using them as nutrients. In this way, waste is converted partly into biomass and partly into carbon dioxide and water. For effective biological treatment pretreatment of the effluent may be necessary. In particular, temperature, pH, and oxygen and nutrient contents must be suitable for microbial growth. For biological effluent treatment many different kinds of microbes, ranging from the simplest bacteria to protozoa and even worms, can be simultaneously used. Quite a large number of pulp, paper and board mills already use biological treatment, very often an aerobic one, and, depending on the specific conditions, also a combination of anaerobic and aerobic treatments.

3.8
General Remarks on the Application of Chemical Additives

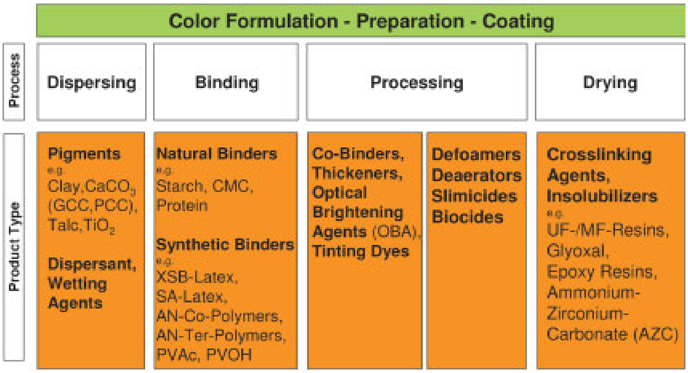
A range of chemical additives are used along the process chain of paper and board manufacturing and paper coating to provide technological, economical and ecological advantages (Tables 3.10 and 3.11). They allow the reduction of fresh water and energy consumption, as well as enabling the paper industry to increase the recycling rate in paper and board production. Furthermore, savings in raw material can be achieved by reducing the basis weight of paper without losing certain quality properties. The use of new chemical additives allows one to produce paper at neutral pH/slightly alkaline conditions instead of in an acid environment which was mainly in use until the 1970s. This results in less corrosion of machinery parts and also in improved paper properties, e.g. higher paper strength as well as much better permanence of the paper. Papermaking chemicals allow large sums of capi-

Table 3.10 Chemical additives and their different places of addition in the paper and board manufacturing process.



	Stock Preparation				Paper Making				Waste Water Treatment
Process	Pulping Screening Filler Dispersing Deinking Thickening Bleaching			Stock Mixing and Storage	Wet end	Pre Drying	Surface Application	Final Drying, Calendering	Filtration Flotation Sedimentation Sludge Dewatering
Product Type	Basic Chemicals, Dispersant, Defoamer, Deaerator, Slimicide, Biocide	Wetting Agent, Surfactant, Fatty Acid	Drainage Aid, Chelating Agent, Bleaching Chemicals	Fixatives, Aluminium Compounds, Sizing Agents, Optical Brightening Agent (OBA), Tinting Dyes, Dyes, Dry and Wet Strength Resins (DSR+WSR), Starch	Retention and Drainage Aids (RDA), Bentonite, Silica Microgel, Deaerator, Defoamer, Pitch / Deposit Control Agent, Slimicides, Biocides, Cleaning Agents		Starch, Synth. Dry Strength Resin (DSR), Sizing Agent Optical Brightening Agent (OBA), Crosslinking Agent, Barrier Coating, Pigment Coating,	Lubricant, Anti-Corrosion Agent	Aluminum Compounds, Flocculants, Drainage Aid, Defoamer, Deaerator

Table 3.11 Chemical additives and their different places of addition in the paper and board coating process.



	Color Formulation - Preparation - Coating				
Process	Dispersing	Binding	Processing		Drying
Product Type	**Pigments** e.g. Clay, $CaCO_3$ (GCC, PCC), Talc, TiO_2 **Dispersant, Wetting Agents**	**Natural Binders** e.g. Starch, CMC, Protein **Synthetic Binders** e.g. XSB-Latex, SA-Latex, AN-Co-Polymers, AN-Ter-Polymers, PVAc, PVOH	**Co-Binders, Thickeners, Optical Brightening Agents** (OBA), **Tinting Dyes**	**Defoamers Deaerators Slimicides Biocides**	**Crosslinking Agents, Insolubilizers** e.g. UF-/MF-Resins, Glyoxal, Epoxy Resins, Ammonium-Zirconium-Carbonate (AZC)

tal tied up in plant and equipment to be utilized more efficiently, and they can boost productivity by reducing downtime and increasing production rates. The productivity of subsequent coating and converting processes can also be improved by selecting chemical additives according to their specific properties.

Whether by chance or design, many papermaking chemicals have some useful side-effects in addition to the effects for which they have been primarily developed (Fig. 3.25). The intelligent combination of different chemical additives can improve quality, economy and ecology. On the other hand they can also interact in a negative way so the potential interactions of all chemicals applied have to be considered (Fig. 3.26). Some integrated systems have already been established according to the “lock and key” principle, such as combinations of fixing agents/retention aids/drainage aids, fixing agents/retention aids/internal sizing agents and combi-

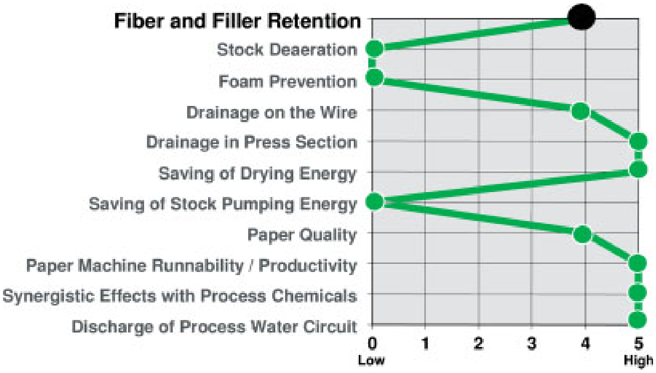


Fig. 3.25 Beneficial side effects of (PEI) as a retention aid.

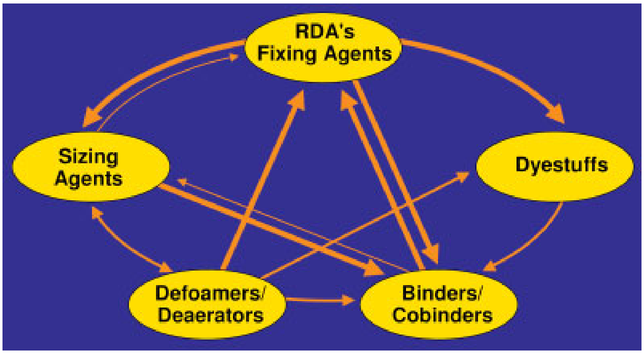


Fig. 3.26 Interactions of chemical additives – positive and negative effects are possible. (RDA = retention drainage aids.)

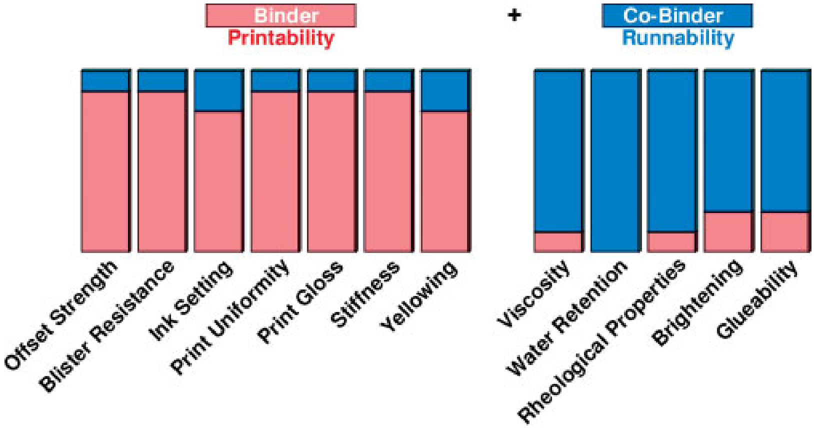


Fig. 3.27 Impact of binder/co-binder combination on the properties of coating color and paper quality (source: BASF).

Table 3.12 Measuring, monitoring and control of wet-end conditions and effectiveness of chemical additives.

- Chemical/Physical Status of Wet-end Condition
  - first-pass retention of total stock and filler (white water consistency/headbox consistency)
  - overall retention (paper production/total stock input)
  - turbidity of white water and clarified water
  - ph, COD, cationic demand, zeta-potential, conductivity
- Retention and Drainage Aids
  - headbox and white water concentration
  - cationic demand, zeta-potential,
  - freeness, dewatering time of stock suspension, turbidity
- Fixing Agents
  - catonic demand
  - pitch particle count (number, size, distribution, deposition)
- Deaerators
  - gas content (ultra sonic, compression, spec. gravity)
- Sizing Agents
  - indirectly via fiber/filler retention
  - directly: off-machine paper tests (Cobb. HST, BAT, Emco, DAT)
- Dry-Strength/Wet-Strength Agents
  - indirectly via zeta-potential
  - directly: off-machine paper tests (tensile after dry and wet conditioning)
- Dyestuffs
  - chromaticity co-ordinates
  - fastness of light and bleed
  - resistance of rub, acid, solvent and heat
- Biocides, Slimicides
  - total plate count (TPC), anaerobic and aerobic
  - mould and fungus count
  - sulfate reducing bacteria
  - oxidative demand, catalase control

nations of sizing agents/coating binders. Figure 3.27 shows a combination of a binder and a co-binder in a coating formulation, which results in improved machine runnability and better printability of the paper.

Attention has to be paid to the chemical and physical conditions of the white water circuit and to the measurement and control of the effectiveness of various chemical additives (Table 3.12). On-line measurements and integrated process control give the best and constant performance of multifunctional chemical combinations. Of similar importance are the methods and positions for metering chemical additives to the paper production system as well as the sequence of their addition (Fig. 3.28).

Nowadays, chemical additives are an integral part of advanced papermaking technology. Maximum performance can be achieved by tailoring their properties in

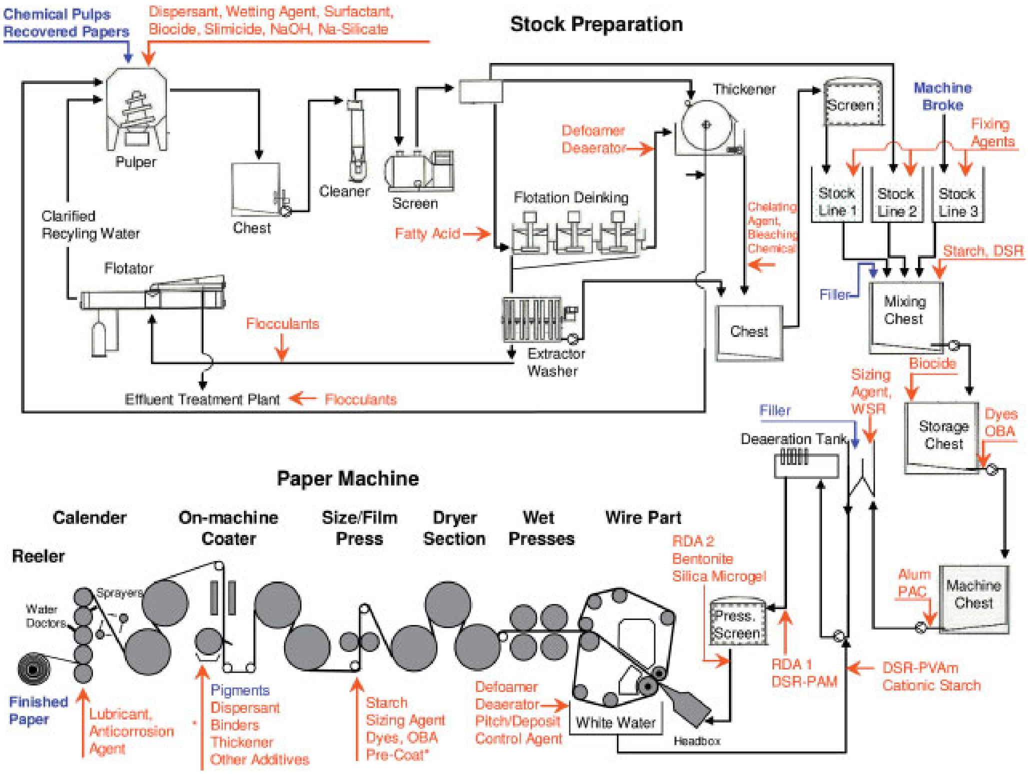


Fig. 3.28 Flowsheet of paper production process with integrated metering points and addition sequences of various chemical additives. (DSR = dry strength resin, DSR-PAM = dry strength resin – polacrylamide, OBA = optical brightening agent, PAC = polyaluminum chloride, RDA = retention drainage aid, WSR = wet strength resin.)

order to obtain the desired effects and by adapting products to local manufacturing conditions. The development of innovative chemicals and intelligent formulations and combinations of chemicals will play an even more important role in the future in responding to the challenges facing the paper industry in terms of higher productivity, improved and/or new quality properties and minimal environmental impact. This depends on taking an integrated approach to paper manufacturing, coating and converting and strengthening the cooperation between the paper industry, machinery manufacturers, the chemical industry and the paper converters and printers.

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4
Stock Preparation

4.1
Overview
Herbert Holik

The objective of fiber stock preparation systems is to modify the different ingoing raw materials in such a way that the finished stock finally supplied to the paper machine suits the requirements of the paper machine and of the quality demands put on the produced paper or board. The raw stocks used are the various types of virgin pulps as well as recovered paper grades. They are available in the form of bales, loose material or, in the case of integrated mills, as suspensions. The finished stock is a suspension of defined quality as far as the mixture and characteristics of the fibers, additives, and impurities are concerned. This quality essentially determines paper machine runnability and is the basis for the final paper and board quality.

A stock preparation system consists of several unit processes that are adapted to one another. Their individual efficiency and the reliability of processing machinery depend on suspension properties such as consistency and flake and debris content, on the chemicals entrained and added as well as on the process design itself. So some of the unit processes can be used several times in a preparation process line, others just once. Most of the machines used for performing the individual unit processes have not only one effect but also side effects that may or may not be desirable. The systems differ considerably depending on the raw material used and on the quality of the finished stock required. For instance, fiber design by refining is of central importance in the preparation of chemical pulp. For recovered paper processing the cleanliness of both the individual fibers and the suspension are the main objectives and so the removal of interfering materials is most important.

A stock preparation system comprises essentially three levels (Fig. 4.1):

- Production level, the direct line from raw material input to the finished stock which may include unit processes with some or all of the following objectives: To break down the raw material into individual fibers, to separate fibers and contaminants, to separate fibers/solids and water, to treat the fibers, and to treat the residual contaminants.
- Recovery level where fibers and other solids, and water are recovered from the

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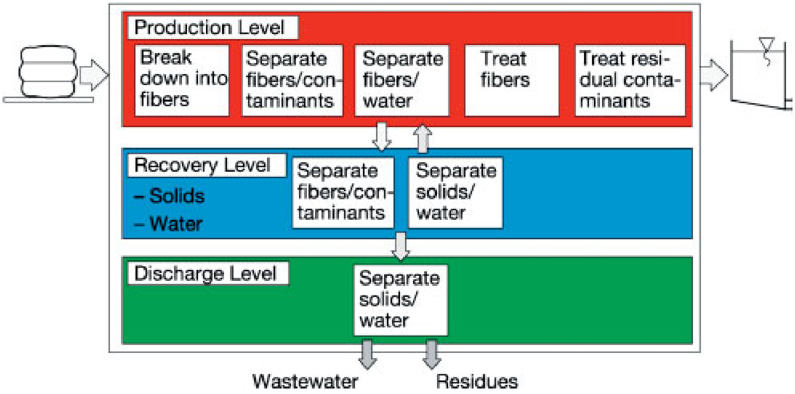

Figure 4.1 Process levels in fiber stock preparation and their functions.

rejects of the separation processes applied in the production level. Again fibers and contaminants as well as solids and water have to be separated.

- Discharge level, for ecological and economic reasons the final rejects are separated into wastewater and residues with high dry content.

The unit processes in fiber preparation and their objectives are:

- Slushing and deflaking: To break down the fiber raw material into a suspension of individual fibers. Slushing should at least result in a pumpable suspension enabling coarse separation and deflaking if required. In the case of recovered paper, ink particles and other nonpaper particles should be detached from the fibers.
- Screening: To separate particles from the suspension which differ in size, shape and deformability from the fibers.
- Fractionation: To separate fiber fractions from each other according to defined criteria such as size or deformability of the fibers.
- Centrifugal cleaning: To separate particles from the suspension which differ in specific gravity, size and shape from the fibers.
- Refining: To modify the morphology and surface characteristics of the fibers.
- Selective flotation: To separate particles from the suspension which differ in surface properties (hydrophobicity) from the fibers.
- Nonselective flotation: To separate fine and dissolved solids from water.
- Bleaching: To endow yellowed or brown fibers with the required brightness and luminance.
- Washing: To separate fine solid particles from suspension (solid/solid separation).
- Dewatering: To separate water and solids.
- Dispersing: To reduce the size of dirt specks and stickies (visibility, floatability), to detach ink particles from fibers.

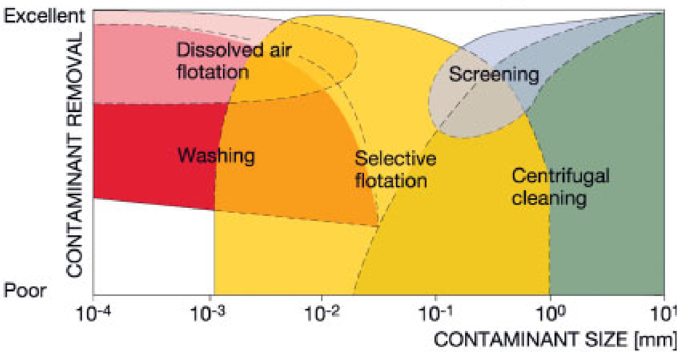

Fig. 4.2 Efficiency ranges of unit processes for contaminant removal in recovered paper processing.

- Mixing and storing: To generate a uniform blend of suspension components, and to prevent suspension components from de-mixing.

Separation processes are of high importance in recovered paper processing as this material contains

- Additives used in the previous paper production process, such as fillers and dyes, coating components and functional and process chemicals
- Substances added according to the application such as printing inks, varnishes, coatings, foil laminations, adhesives and waxes
- Materials mixed with the paper during its life cycle, subsequent collection, and handling in the mill including wires and strings, glass, sand and stones, or paper clips and folders.

Solid particles comprise a wide range of materials with a wide range of properties. Particle characteristics used as separation criteria must clearly differ from fiber characteristics. These include particle size, shape and deformability, density, and surface properties (hydrophobicity). Table 4.1 shows as an example the characteristics “specific gravity and size” for various types of contaminants. Most of these contaminants have to be removed for quality and machine runnability reasons, fillers may be tolerated to a certain degree. Figure 4.2 shows the efficiency scatter of the separation processes vs. particle size. Nonselective flotation (dissolved air flotation) separates small particles very efficiently from water. Washing removes small particles, the efficiency depending on the amount of extracted water. Selective flotation effectively removes particles over a wide size range, but only hydrophobic ones. Screening is most successful in removing larger and cubic particles. For small, flat or deformable particles the separation efficiency is lower. Cleaners have high efficiency in the removal of large particles with densities differing from water and wetted fibers.

Table 4.1 Density and particle size of contaminants in recovered paper processing.

Type of contaminant	Density, g cm^{-3}	Particle size range, μm
metal	2.7–9	> 1 000
sand	1.8–2.2	>1–>1000
fillers/coating particles	1.8–2.6	<1–1000
ink particles	1.2–1.6	<1–>1000
stickies	0.9–1.1	<1–>1000
wax	0.9–1.0	<1–10
styrofoam	0.3–0.5	>100–>1000
plastics	0.9–1.1	>100–>1000

The main unit processes, their principles and the machinery applied will be described in the next sections followed by a description of fiber stock preparation systems for different kinds of fiber raw material and final application of the finished stock.

4.2
Main Unit Processes and Equipment

4.2.1
Fiber Materials Feeding

The objective of fiber material feeding is to supply a predetermined and measured amount of fiber stock to the repulping unit. The feed is either continuous or batchwise. The fiber material is delivered to the paper mill in the form of bales (virgin pulp, recovered paper) or as loose material (recovered paper). Only in the so-called integrated mills (pulp mill and paper mill integrated in one location) is the fiber material supplied to stock preparation by pumping the stock suspension directly from the pulp mill to the paper mill. An extra feeding system and repulping is only necessary for shutdown periods of the pulp mill.

Virgin pulp is delivered in bales (mostly sheeted material), which are bound together by wires into stack units of six or eight bales. The first step is to dewire the units by cutting the centrally arranged binding wires, to remove them automatically and to wind them to coils for easy disposal. The next step is to de-stack the unit into single bales thus preparing the bales for dewiring, i. e. to cut and remove the wires and wind them to coils as above. A metal detector may follow to detect any uncut wires which would then be cut and removed by hand. The wire removal efficiency is better than 96% depending on the unit and bale quality. A further

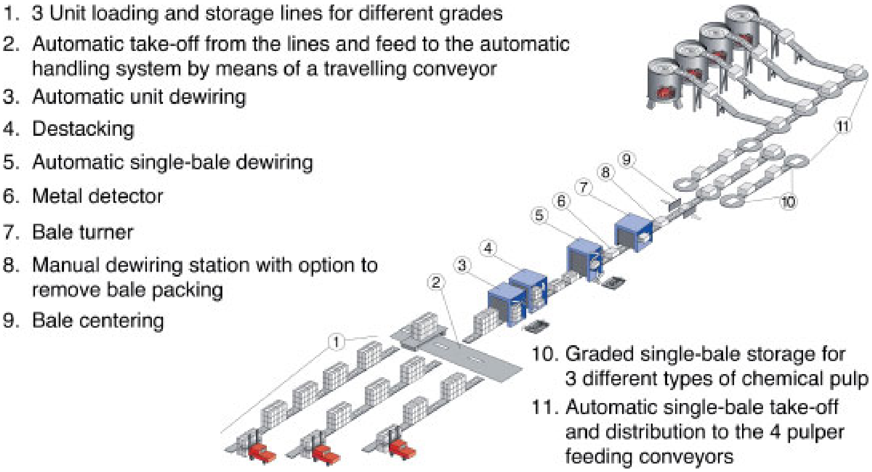

Fig. 4.3 Overview of a handling system for virgin pulp units and bales (source: B+G Fördertechnik).

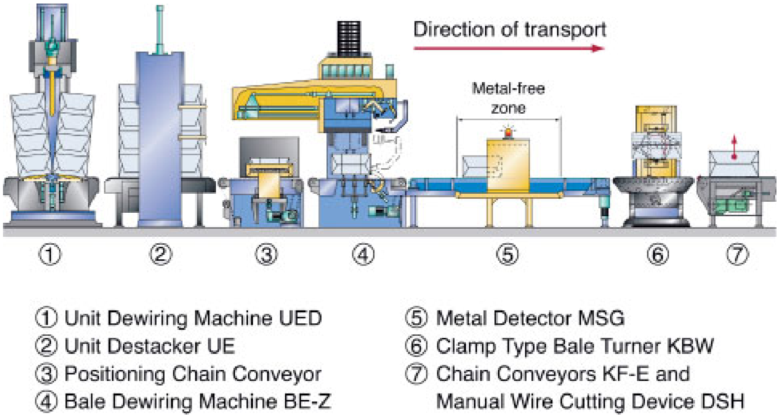

Fig. 4.4 View of a dewiring station for units and bales of virgin pulp (source: B+G Fördertechnik).

handling device may turn the bales through 180° for removal of the bottom packaging material. The bales are then fed to the repulping unit. In batch-wise working systems a weighing system will be installed. The capacity of such a virgin fiber material feeding line is up to 180 bales per hour. Figure 4.3 gives an overview of a handling system for virgin pulp units and bales. Figure 4.4 shows a closer view of a dewiring station for units and bales of virgin pulp.

Recovered paper is supplied to the mill in (individual) bales or as loose material. Often a mill has to handle both types. Automatic dewiring of recovered paper bales is more demanding than that of virgin pulp bales since these bales may vary in

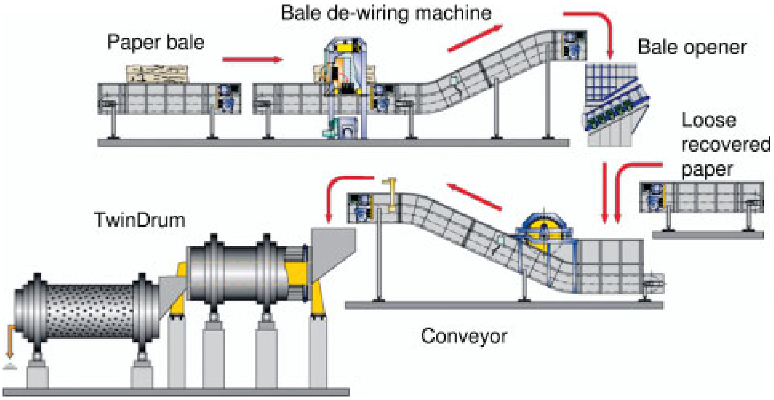

Fig. 4.5 Feeding system for baled and loose recovered paper (source: B+G Fördertechnik).

shape, size and kind of wiring. As in virgin fiber feeding systems the wires are cut and usually removed, the probability of bales not being dewired is less than 4%, depending on the bale quality. Only in cases when raggers are installed in low consistency pulpers (mainly in board and packaging paper lines), are wires needed to build up the tail and to entangle plastic foils, strings, and textiles. On automatic cutting of the wires the bales open up extensively. After wire removal the bale structure is opened into loose material by a bale opener. Now the flow-stream of loose paper is equalized to the required height by a levelling drum. The levelled loose material on the conveyor belt is weighed by a radiometric weighing system. In combination with a conveyor speed control this gives a constant mass flow of fiber material into the repulping unit. The capacity of such a fiber material feeding line for recovered paper bales is up to 120 bales per hour depending on the quality of the recovered paper. In Figure 4.5 the schematic of a complete feeding system for baled and loose recovered paper is shown.

4.2.2
Disintegration

4.2.2.1 Repulping/Slushing

The purpose of repulping or slushing is to break down the dried primary fiber pulp or recovered paper into individual fibers or, at least, to form a suspension which can be pumped. In the latter case the remaining flakes have to be broken down in subsequent deflaking machinery. Repulping is needed not only at the beginning of the stock preparation system but also for the wet or dry broke from the paper machine.

During pulping the applied disintegrating forces have to be greater than the raw material strength. Wetting reduces the strength by breaking the fiber-to-fiber hydrogen bonds. Strength reduction by wetting is about 85–98% for primary fiber pulp and nonwet strength recovered paper, and < 60–80% for wet strength recovered paper. Recovered wet strength paper grades which are difficult to repulp may be slushed at elevated temperatures of more than 75 °C. Addition of chemicals – acidic or alkaline, depending on the wet strength agent – further assists wet strength reduction.

The relevant forces in repulping seem to result from viscosity, acceleration and mechanical clinging. Viscosity is mainly a matter of suspension consistency, together with velocity difference it creates shear stress. Acceleration of a particle results in inertia forces. Clinging of a flake e. g. around the rotor may induce viscosity, acceleration, or mechanical forces.

The steps in repulping are:

- To feed the system with a predetermined rate of raw material and water
- To wet the fibrous raw material rapidly and completely
- To apply sufficient force to break the material down into individual fibers
- To discharge the suspension.

In the case of recovered paper repulping further steps may be necessary:

- To remove solid contaminants such as foils, stickies, and printing ink from the fibers
- To remove solid contaminants from the process at an early stage before they are broken down into too small particles which are difficult to remove in subsequent machinery
- To mix process chemicals (such as deinking and bleaching agents) into the suspension

Depending on the raw material, the amount of production and the contaminants content, repulping is done in different types of pulpers or drums at consistencies between < 6 % and < 28 %. Slushing time is between about 5 and 40 min. Pulpers are usually stainless steel vats with a vertical axis. A concentric impeller is the slushing tool, vertical elements at the cylindrical wall and guide elements at the bottom redirect the rotating suspension flow to the vat center.

Low consistency (LC) pulpers (Fig. 4.6) comprise a flat impeller with circumferential speed of about 15–20 m s^{-1}. They operate at consistencies of up to about 6 %. At the bottom they have a screening sieve with hole sizes of 6–20 mm for suspension extraction. Operation is either continuous for slushing of recovered paper (fluting and liner, high wet strength grades) and most of the primary fiber materials, or periodic for certain primary fiber applications. In recovered paper processing ongoing removal of trash has to be ensured in order to prevent excessive trash concentration which would reduce the production and quality and might even stop the pulper rotor. Figure 4.7 shows a LC pulper trash removal system. Part of the suspension in the pulper is extracted and fed to a junk separator to remove heavy contaminants. The following disk screen has two functions. It acts as a deflaker to reduce the number and size of the flakes and as a coarse screen for removal of remaining trash and oversized flakes. The reject is sorted in a drum screen, its accept being recirculated to the pulper and rejects being disposed. Often raggers are used for additional trash removal such as for bale wires, plastic, foils, and textiles.

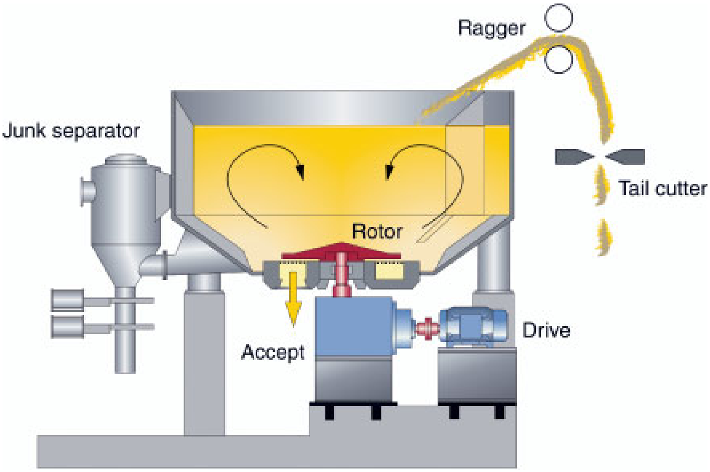

Fig. 4.6 LC (low consistency) pulper (source: Voith).

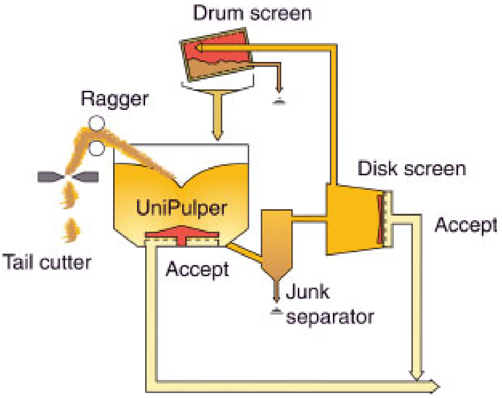

Fig. 4.7 LC pulper trash removal system (source: Voith).

Stock consistencies at medium consistency (MC) pulpers are up to about 12%, those at high consistency (HC) pulpers up to about 19%. Both pulper types have a helical rotor and usually no screen plate. Circumferential speed is about 12–17 m s^{-1}. They generally operate intermittently and are used in processing recovered paper such as newspapers and magazines. Figure 4.8 shows an HC pulper and Fig. 4.9 an HC pulping system for recovered paper processing including dumping and dilution water feed system. For each batch unwired baled or loose raw material and water are fed to the pulper. After its reduction to the desired flake content and size at high consistency – and detachment of ink to a certain degree – dilution water is added. The suspension is then fed to a disk screen with deflaking and coarse screening functions. Its reject goes via a buffer tank to a drum screen,

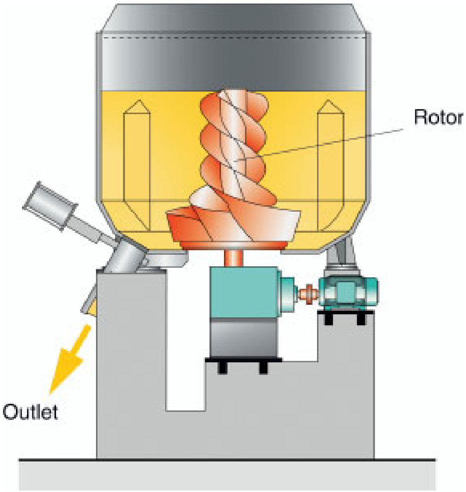

Fig. 4.8 HC (high consistency) pulper (source: Voith).

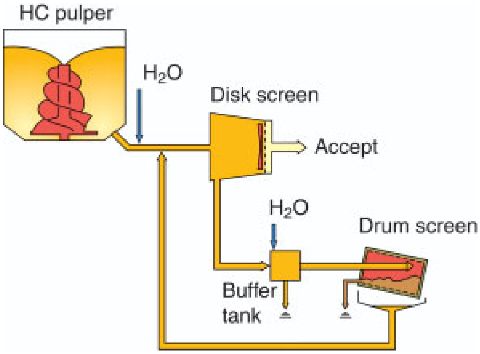

Fig. 4.9 HC pulping and detrashing system (source: Voith).

its accept to a dump chest. The reject of the drum screen leaves the system via a dewatering screw, the accept is recirculated.

Drum pulpers operate at consistencies of about 14%-28%. The drum is driven on the periphery, the axis is declined to the drum end. Drum pulpers are used in repulping of recovered paper of lower wet strength such as newspapers and magazines, fluting and liner as well as liquid packaging board. Due to the lower forces the size reduction of sensible contaminants such as stickies or thin foils is limited. Drum pulper systems combine the functions of slushing and coarse screening. There are two types on the market. One (Fig. 4.10) has a single drum body with a first zone for slushing and a second zone for coarse screening. The rotation speed is about 100–120 m min^{-1}, the drum diameter 2.5–4 m, length up to 30–40 m, the slushing zone being about two thirds of the length. Slushing consistency is about 14–20%, accept consistency of coarse screening (hole diameters about 6–9 mm) is about 3–5%. As the drum rotates the raw material is lifted with the help of lifting

Fig. 4.10 Drum pulper with a single drum body incorporating slushing and coarse screening (source: Andritz).

baffles mounted in the axial direction. Disintegration occurs mainly by two principles: (i) During lifting part of the material rolls and slides back thus generating shear forces and (ii) the remaining part of the material lifted to higher position falls back to the pond. The resulting impact exerts effective slushing.

The second type distributes the two functions of slushing and of coarse screening between two individual drums, each operating at different circumferential speeds and consistencies adopted to the different functions (Fig. 4.11). Furthermore the slushing drum is equipped with a D-shaped "displacement core". Both displacement core and drum are equipped with bars in the axial direction. The length of the slushing drum is about 7–15 m, that of the coarse screening drum 7–17 m. The rotation speed of the slushing drum is about 1.5 m s^{-1}, that of the coarse screening drum about 2.5 m s^{-1}. Consistency in the slushing part is about

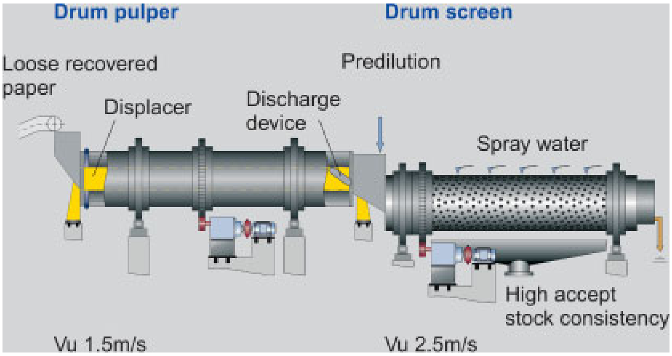

Fig. 4.11 Drum pulper system with separate drums for slushing and coarse screening (source: Voith).

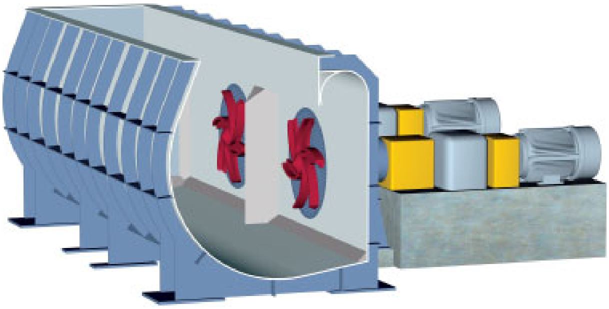

Fig. 4.12 Broke pulper beneath the paper machine (source: Voith).

23–28 %, that in the accept of coarse screening 3–5 %. The filling level of the slushing drum is adjusted to the actual production and is about 30–60 % of the drum volume. As the drum rotates the stock is exposed to shear forces in the upgoing channel between the drum and the fixed displacement core. The impact of the stock falling down from the top further supports effective slushing.

Broke pulpers beneath the paper machine are found at the end of the wire section and the press section where the web is wet and easy to slush. Slushing in broke pulpers in the dryer section, at the size press or in coating stations needs more energy and time, as the web is dry. (Broke from other places outside the paper machine are treated in pulpers as described earlier.) Broke pulpers extend across the whole width of the paper machine and have to treat the full production. In the case of a web break, the broke pulper located upstream of the break position has to start its full operation almost immediately. Water showers direct the web into the pulper and provide the necessary amount of dilution water. A consistency of 3–5 % together with an optimized system of vat geometry and rotor ensure good stock circulation and slushing in the pulper. Circulation energy and defibering forces are exerted either by agitators with a horizontal axis and propellers mounted on these or by impellers such as found in pulpers in stock preparation. The disintegrated part of the pulper content is extracted from the pulper through a screen plate. Figure 4.12 shows an example of a broke pulper.

4.2.2.2 **Deflaking**

The objective of deflaking is to break down small pieces (flakes) of undisintegrated paper or pulp sheets into individual fibers. The residual flake content after the deflaker should be zero, in special cases at least below 5 %. Deflaking helps to avoid paper quality problems, to save fiber raw material and to ensure improved operating conditions for the succeeding machines in the process e. g. screening or cleaning. Deflaking is carried out in deflakers after slushing in a pulper or a drum, in the preparation of recovered paper, virgin pulp or broke. A remarkable deflaking effect also occurs in disk screens. Cylindrical screens or pumps have a lesser effect.

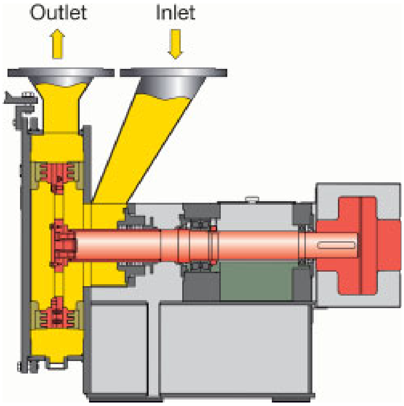

Fig. 4.13 Schematic of a deflaker (source: Voith).

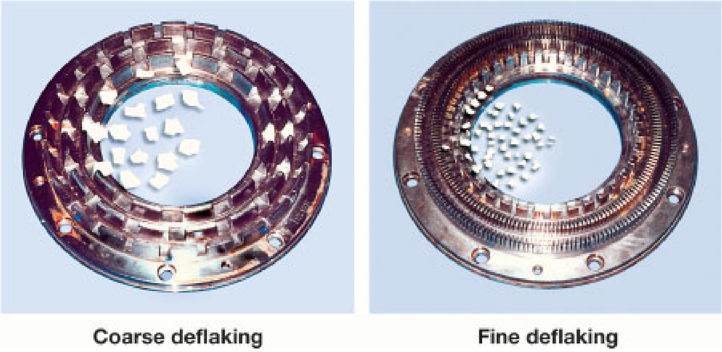

Fig. 4.14 Coarse and fine fillings for deflaking (source: Voith).

Deflaking is done at stock consistencies of about 3 to 5%. The shear forces necessary for disintegration are applied to the fiber bundles and flakes when they pass radially through the fillings slots of the intermeshing teeth of the rotor and the stator (Fig. 4.13). The peripheral speed of the rotor fillings is 25 to 40 $\mathrm{m\ s^{-1}}$. Depending on the entering flake size, flake content, and trash content, coarser or finer fillings for the deflaker are selected (Fig. 4.14).

For stocks with low deflaking resistance the specific energy demand is 20 to 40 $\mathrm{kWh\ t^{-1}}$. Deflaking is mostly done in a single pass. Two or more passes may be required for stocks which are more difficult to deflake. Flakes with high wet strength must be disintegrated in a disperser which can apply higher shear rates.

4.2.3
Screening and Fractionation

4.2.3.1 Screening

The objective of screening is the removal of interfering solid substances from the suspension that differ from the fibers in size, shape and deformability. These can be solid nonpaper particles like plastics or paper flakes and fiber bundles. The suspension passes a screen with holes or slotted openings which are larger than the fibers but smaller than most of the particles to be removed. The latter are intended to be retained by the screen and extracted at the reject outlet together with a certain amount of fiber suspension. Clearing devices rotate at a small distance over the screen surface generating pressure pulses and thus prevent the sieve from plugging. These rotors should be not too aggressive in order to maintain lower strength nonpaper particles in a screenable size. The pressure difference across the screen may force deformable particles through the screen openings. Cleanliness efficiency for soft stickies, for instance, is therefore lower than for hard stickies of the same size. Increasing the pressure difference results in further loss of efficiency for soft stickies removal compared to that for hard stickies.

Screening is used in both primary and secondary fiber preparation. In the latter, screening is done at several positions in the system with different kinds of machines with different kinds and sizes of openings. Pre-screening (first coarse screening step) is integrated in the slushing systems followed by a (second) coarse screening step and fine screening so more and more trash is removed step by step, first the coarse and then the finer material. Thus the subsequent screening step can operate safely and with low abrasion, even at the high demands of fine screening.

Fiber loss from the reject of a screen is reduced by re-screening the first stage reject in a second, third or even fourth stage. The reject of the last screen (tailing screen) determines the fiber loss. A higher reject rate increases the cleanliness efficiency of a screening system but increases the fiber loss. (Cleanliness efficiency is the ratio of effective separation to the maximum separation theoretically possible). More stages in one screening system result in lower fiber loss but higher investment costs. So screening is always a compromise between machinery outlay, cleanliness efficiency, fiber loss, throughput and operating reliability.

4.2.3.1.1 Coarse Screening

In coarse screening both disk and cylindrical screens are used. As shown in Fig. 4.15 a disk screen consists of a conical housing, a screen plate, a vaned rotor, and baffle bars. Screen hole diameters are about 2–4-mm, the peripheral rotor speed is about 20–30 m s–1. Disk screens operate at consistencies below 6 %. Due to their effectiveness in flake defibering, disk screens are also used in the second screening stage of a system with a cylindrical screen in the first stage to reduce loss of paper flakes consisting of valuable fibers. Without deflaking the subsequent

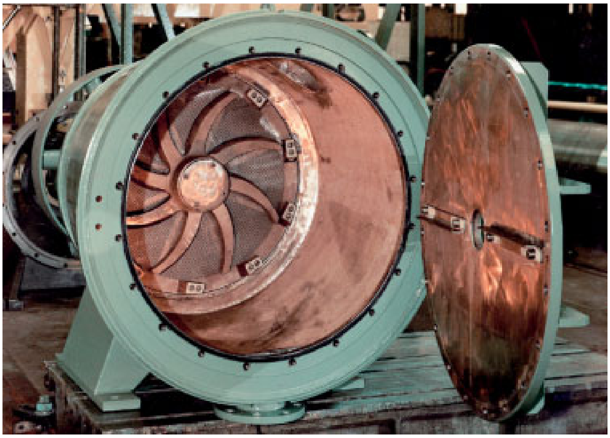

Fig. 4.15 Opened disk screen (source: Voith).

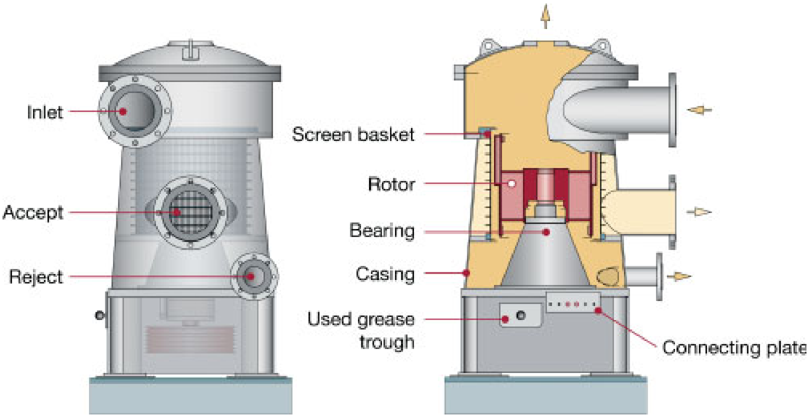

Fig. 4.16 Cylindrical screen with conical housing (source: Voith).

stages could not be operated reliably due to the enormous increase in flake content from stage to stage.

The design principle of cylindrical screens in coarse screening is usually identical or similar to that of fine screens. The exception is a machine type with rotating screen where the pulsing blades are stationary. This type of machine is only used in coarse screening. Cylindrical screens consist of a housing, a rotor with clearing devices and a cylindrical sieve (Fig. 4.16). Depending on the trash content of the suspension different types of rotors may be applied, one of is shown in Fig. 4.17. The defibering effect of cylindrical screens is lower than that of disk screens and

Fig. 4.17 Rotor for coarse screening application (source: Voith).

depends on the rotor type. Cylindrical screens are used for suspensions with low flake content and operate at consistencies below about 5%.

Final stage coarse screening machines must handle high trash content. On the other hand low fiber loss and high cleanliness efficiency are required. The machine in Fig. 4.18 is not pressurized and operates at a consistency of about 1–4% in the accept. Screen hole sizes are about 2 to 4 mm. Rotors fitted with vanes keep the screen clear and transport the debris such as plastics to the outlet. During the pass through the machine water sprays support the separation of fibers and debris resulting in a low fiber content in the reject. Another type of tail screen (Fig. 4.19)

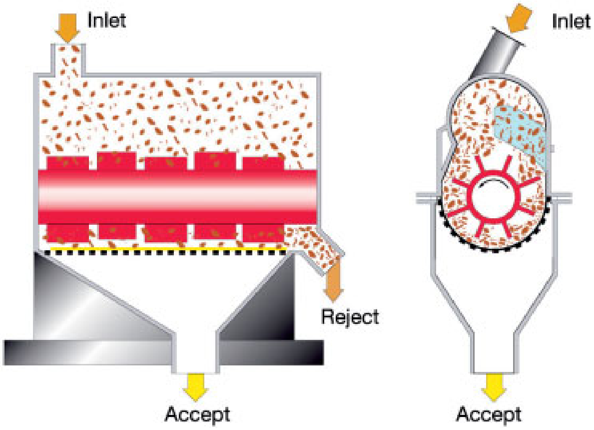

Fig. 4.18 Final stage screen operating at ambient pressure (source: Voith).

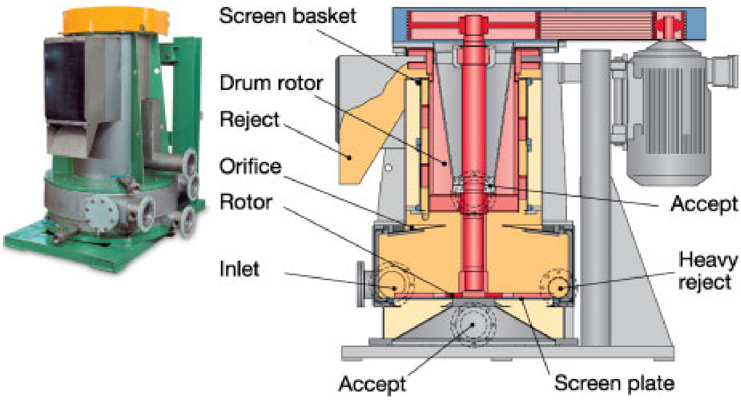

Fig. 4.19 Final stage screen with pressurized flat screen and non-pressurized cylindrical screen (source: Voith).

uses in its lower section a pressurized disk screen whereas the upper part is a nonpressurized cylindrical screen, both usually equipped with holes. Pressurized cylindrical screens are also used in the last stage to give lower flake and debris content.

4.2.3.1.2 **Fine Screening**

For fine screening different types of cylindrical screens are used. They may differ in the geometry of the housing (for uniform basket throughflow), the rotor shape (influencing the pulse characteristics), the rotor position (at the entrance side of the suspension into the screen or at the backside) and its circumferential speed, the flow direction through the screen (centrifugal or centripetal), the kind and size of slots, and the calculated suspension velocity through the screen orifices as well as any special configuration to influence the suspension stream lines in the vicinity of the apertures. Fine screening is done at low stock consistency of below 1.5 %. The rotor is adjusted to the requirements of LC screening (Fig. 4.20), its circumferential speed is 10–30 m s^{-1}.

The screen baskets are slotted with widths of 0.1–0.4 mm. Some baskets are milled, where the milling tool defines the slot width and the uniformity of width across the whole basket. Others are bar-type baskets (Fig. 4.21) where individual bars are affixed to mountings by welding, brazing or clamping. The distance between the bars is the slot width. The shape of the bars and the kind of mounting define a profile angle at the slot entrance. Both profile angle and slot width strongly affect the screening result: The smaller the slots and the lower the profile angle, the better the cleanliness effect, and vice versa. On the other hand finer slots and lower profile angle result in lower throughput and more thickening and fractionation. To maintain the slot geometry as long as possible during operation, abrasive particles should be removed from the suspension before screening. For

Fig. 4.20 Foil rotor used in fine screening (source: Voith).

that reason recovered paper processing systems mostly comprise LC cleaning ahead of LC screening.

Final stage screens in fine screening have slotted screen baskets due to quality requirements. Operation can be continuous or batch. Continuous operation of such a screen results in higher cleanliness but also higher fiber loss compared to batch operation. In batch operation flushing water washes out most of the fibers, but a larger amount of debris passes the screen during the wash cycle. Figure 4.22 shows a final stage screen where part of the reject is recirculated in order to prevent too high a thickening of the reject towards the outlet.

Each fine screening system comprises several stages, including a final stage screen. The individual screen accepts and rejects in the various stages are interconnected, depending on the requirements. Figure 4.23 shows feed forward, full or

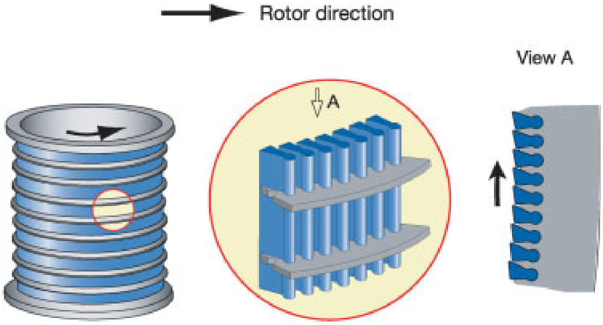

Fig. 4.21 Schematic of a bar-type screen basket (source: Voith).

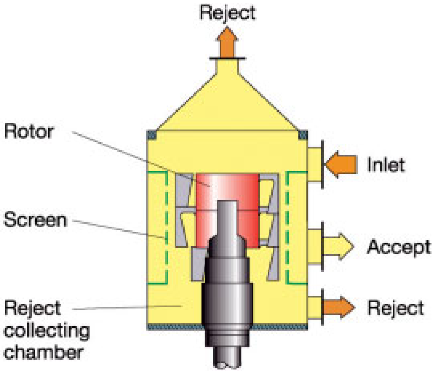

Fig. 4.22 Final stage screen in LC screening systems with slotted basket for batch or continuous operation (source: Voith).

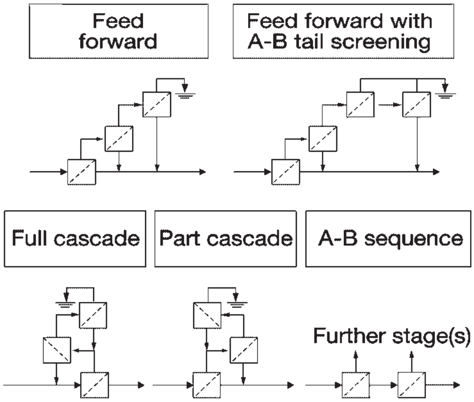

Fig. 4.23 Screening systems for recycled fiber processing.

partial cascade operation schematics. In cascade systems a higher separation probability is given. Feed forward may be advantageous when debris particles tend to be easily comminuted in screens or pumps during cascading. An arrangement in series (A–B sequence) provides optimal cleanliness at low fiber loss. This sequence can be applied in the primary, intermediate or final stage.

4.2.3.2 **Fractionation**

Screening is defined as the separation of debris from the fibers in a suspension. As a principle the fiber fractions in the accept and reject should be the same as in the inlet. In contrast to that, fractionation aims to separating certain fractions of fibers, for instance long fibers from short fibers. The mass flow split in screening is about 5–25 %, in fractionation higher, 30–40 %, due to the production requirements.

Fractionation is done both in flat screens and in cylindrical screens as used for screening, with some differences as regards operating conditions and machine parts. The resulting separation of long and short fibers is far from complete, many long fibers are found in the short fiber fraction and vice versa, only a certain enrichment of long or short fibers is possible. Operating and machinery parameters that improve the fractionating effect are e. g. smaller openings (holes or slots), lower or zero profile angle of slotted screens, and higher consistency. For improved overall effect in some cases additional fractionation is done in cleaners.

With fractionation in screens the main debris flow goes with the stream enriched with long fibers. Here the debris has to be removed in a separate screening step.

4.2.4
Centrifugal Cleaning

The objective of centrifugal cleaning is to remove from the suspension particles that negatively affect paper quality or cause either excessive wear or plugging in subsequent processing machines. For their efficient removal the particle density must differ from that of water, and their size and shape from those of the desired suspension components. Centrifugal cleaning complements other separation methods like screening due to its different physical separation principle. In contrast to screening, hydrocyclone cleaning does not tend to deform softer particles.

Hydrocyclones are used in stock preparation of virgin pulp and of recovered paper where they are even more important. Different hydrocyclone types exist for operation at various consistencies depending on the location in the process, at high consistency HC (2–5 %) after slushing of the stock, or along the process line at medium consistency MC (up to 2 %) and at low consistency LC (0.5–1.5 %) at the end of stock preparation and in the approach flow system. HW (heavy weight) cleaners may remove metal, glass, sand of particle sizes of about 10–100 µm up to 8–20 mm depending on the type, whereas LW (light weight) cleaners are effective for light particle removal such as wax or plastic foam of similar size range.

The separation takes place in the centrifugal field of so-called hydrocyclones (Fig. 4.24) that is generated by the velocity of the entering suspension. Here the heavy particles are forced to the outer wall (HW cleaners) whereas the light ones are driven to the center (LW cleaners). The flow streams where the heavy or light particles are accumulated are separated from the cleaned stock stream. The flow in a hydrocyclone is a three-dimensional two-phase flow. The circumferential component generates the centrifugal force, the axial component moves the solid particles towards the cleaner outlet and the radial component of the suspension flow proceeds from the outside towards the center and vice versa.

Hydrocylone efficiency generally increases with

- Increased centrifugal acceleration, obtained by high tangential velocity and the small diameter of the hydrocyclone. The velocity is dependent on the pressure differential between inlet and accept.

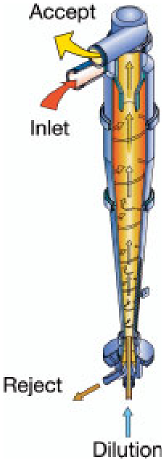

Fig. 4.24 Low consistency heavy weight (LC HW) cleaner (source: Voith).

- Lower stock consistency, as the fiber network may restrict particle motion at elevated consistencies.
- Appropriate reject removal without remixing of reject and accept streams.
- Particles with
  - large density difference compared with water
  - large size at comparable density
  - favorable hydrodynamic shape ($c_w \cdot A$) at comparable density and size.

According to the flow directions of the reject and accept relative to the inlet hydrocyclones are called either counterflow or unidirectional flow cleaners (Fig. 4.25). In counterflow inlet and accept or reject are at the top and reject or accept at the bottom. Unidirectional flow is defined by the reject and accept connections being opposite to the inlet.

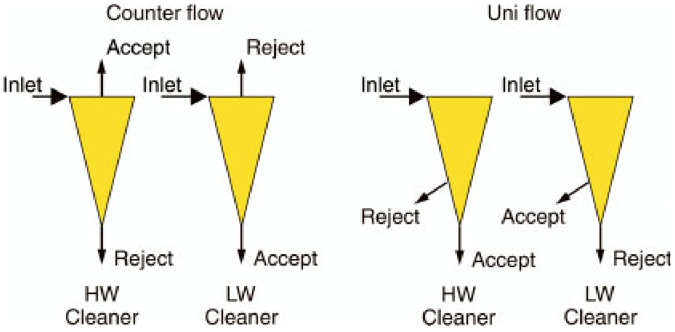

Fig. 4.25 Counterflow and unidirectional flow hydrocyclones for heavy weight (HW) and light weight (LW) particles removal.

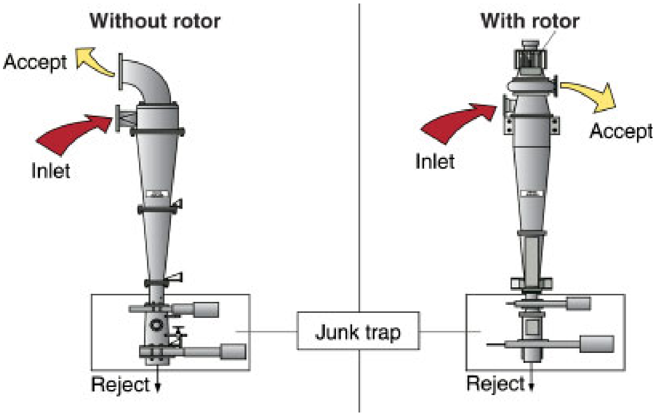

Fig. 4.26 High consistency (HC) cleaners with and without rotor, both with junk trap for intermittent operation (source: Voith).

Usually hydrocyclones have three connections (3-way with inlet, accept, reject of heavy or light weight particles). Some LC cleaners operate as 4-way cleaners (inlet, accept, reject of heavy and reject of lightweight particles) or even 5-way cleaners with an additional air outlet.

4.2.4.1 High Consistency (HC) Cleaners and Systems

HC cleaners are positioned after slushing and operate at consistencies of about 2–5%, sometimes up to 6%. They are the largest cyclones used in the paper industry. They have use for pre-cleaning to remove heavy particles of more than 1 mm in size. Their density has to be significantly higher than $1\ \mathrm{g\ m^{-3}}$. These particles may plug, wear or damage subsequent machinery and therefore they have to be removed. HC cleaners are built with or without a rotor and are mostly based on the counter flow principle. Reject discharge is batch-wise (mostly without a final stage) or continuous with a final stage reject discharge (Fig. 4.26). In the latter case the HC cleaner reject is diluted and then finally cleaned. This system is shown in Fig. 4.27.

4.2.4.2 Medium Consistency (MC) Cleaners

MC cleaners usually operate at consistencies of up to 2%, they are medium sized and single stage cleaners with a junk trap. By removing glass, sand particles and paper clips the subsequent machinery is protected from wear and reliable operation is ensured.

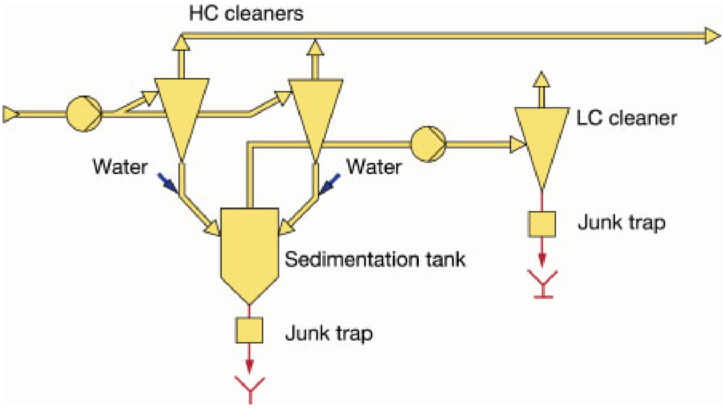

Fig. 4.27 System with primary HC cleaning and second stage low consistency (LC) cleaning (source: Voith).

4.2.4.3 Low Consistency (LC) Cleaners and Systems

LC cleaners operate at consistencies of 0.5 to 1.5% and they are smaller than the HC or MC cleaners. HC cleaners are usually of the 3-way type. Due to the low consistency and high centrifugal forces (small diameter and high circumferential velocity) the removal effect is highest. On the other hand the energy demand per ton of stock is high due to the above operating parameters. Reject outlet is continuous.

By removing fine sand particles heavy weight cleaners protect the fine slotted baskets of the screens from wear and sand accumulation. During cleaning the suspension thickens and is highest near the wall. Here the heavy particles are also accumulated. To prevent the reject outlet from plugging and to reduce fiber content in the reject, dilution water is added at this position. The cleaner design must ensure flow conditions in the reject outlet area where the dilution water does not remix the separated heavy particles with the cleaned stock. Figure 4.28 shows details of the reject area of a HW LC cleaner.

Light weight LC cleaners today are recommended mainly for wax and plastic foam removal. They can also be advantageous when particles such as soft stickies may be deformed or reduced in size in a screen. A precondition is that their density should be lower than that of water.

A cleaner system consists of as many as four stages. The reject of the first stage is diluted and cleaned in the second stage, the accept is fed back to the inlet of stage one, the reject is diluted and cleaned in the third stage etc. This type of system configuration is called a cleaner cascade system (Fig. 4.29). Individual cleaners of one stage are connected to form cleaner batteries with a common distributor feeding the inlets of all cleaners of the stage. Their accepts and rejects flow to collector pipes (Fig. 4.30).

A special type of equipment is a centrifugal cleaner with rotating housing. Due to high centrifugal acceleration and the flow conditions, the cleaner can remove light particles with a density close to that of water.

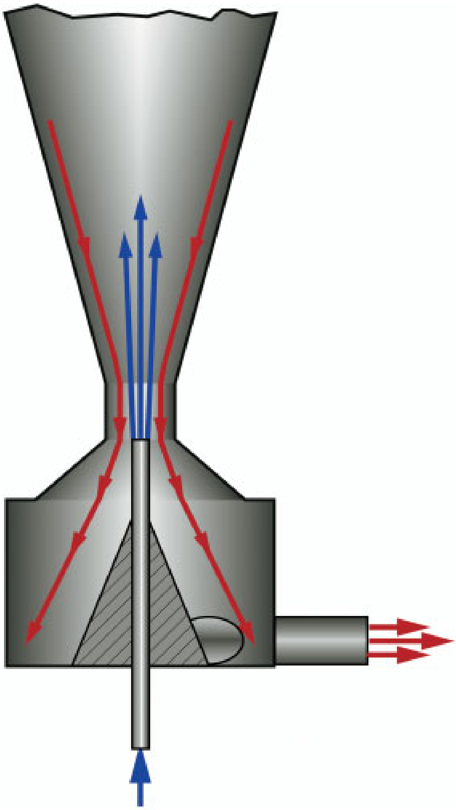

Fig. 4.28 Heavy weight LC cleaner with optimized flow design in the reject outlet area (source: Voith).

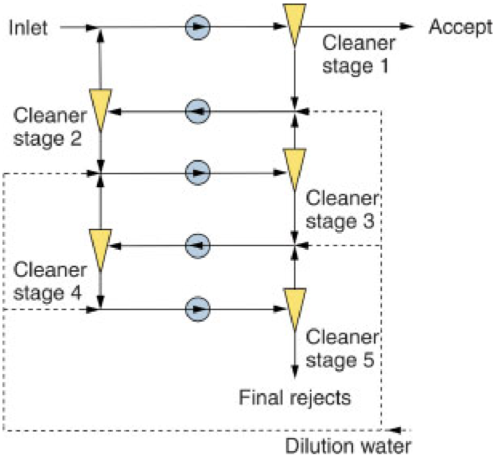

Fig. 4.29 Cleaner cascade system.

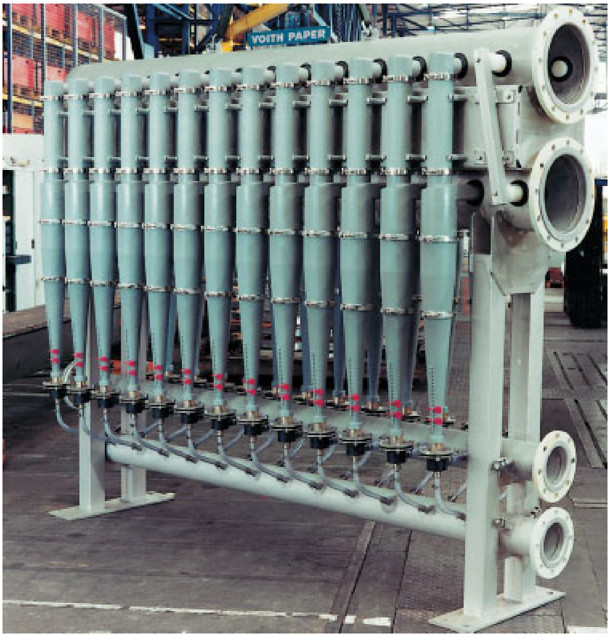

Fig. 4.30 Two rows cleaner battery (source: Voith).

4.2.5
Refining

The objective of refining or beating is to "design" the fibers to match the requirements of

- the paper making process
- the desired properties of the finished paper.

For example good dewatering characteristics of the stock are desired in the forming and press sections as well as a high potential for good formation quality in the forming section. Sufficient web strength is required for safe web transfer in the press and dryer sections when the paper web is still wet. Desirable paper properties may include certain strength properties (tensile, tear, burst, fold, Young's modulus), bulk, air permeability, opacity or printability. During refining all stock and paper characteristics are more or less affected so optimization of the refining parameters has to ensure a sound compromise of the resulting stock and paper properties.

Refining is very important in the stock preparation process for virgin chemical pulp. For mechanical and recycled fibers refining has lower importance. The refining of recycled fibers usually aims for strength increase and shive elimination or reduction.

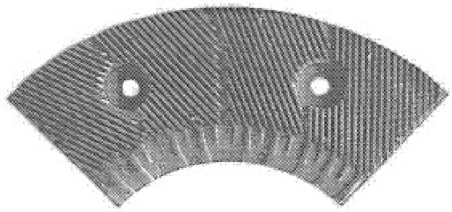

Fig. 4.31 Filling of a double disk refiner for low consistency refining (source: Voith).

By refining, the shape of the fibers is changed. They may be shortened, split lengthwise, collapsed or fibrillated. Refining is done either at low consistency (virgin fibers, secondary fibers) of about 3–6% or at high consistency (mainly secondary fibers) of about 30% and more.

In refining the fibers pass between the bars of the fillings of the stator and rotor of a refiner. The operating parameters influencing the result in low consistency refining are

- geometry (and material) of the fillings
- net refining energy
- specific edge load

In Fig. 4.31 a segment of a filling is shown. The angle between the bars of the rotor and the stator (cutting angle), the bar width and bar edge sharpness are the main influencing parameters of the fillings. As the bars are subjected to wear during operation the bar edges develop a shape that depends on the bar material and the load applied. The net refining energy is the amount of energy transferred to a specific amount of stock. It is the difference between total power consumption for the refining process and the "no-load" power when a defined volume flow of water or stock is pumped through the refiner at large spacing between the fillings. The refining energy transferred is controlled by the force pressing the stator and rotor together. The specific edge load is calculated from the net refining energy divided by the cutting edge length per second. The cutting edge length refers to the length formed per second by the edges of the bars as they move past each other.

Compared with fibrillation, cutting reduces the fiber length far more which results, for instance, in easier dewatering and helps to improve formation quality. On the other hand with cutting the strength potential of the fibers – especially tear – will not be fully developed. Shortening of the fibers is more pronounced using fillings with a small cutting angle, small bar width and sharp bar edges. Furthermore, refining should be done under high specific edge load. Less energy is needed to increase the SR value of a stock.

In contrast, for fibrillation of the fibers the bars of the rotor and the stator should have a large angle, and the specific edge load should be low. The result is for instance better utilization of the strength potential of the furnish, but there is a negative influence on formation quality and dewatering. Fibrillating refining needs more energy to increase the SR value of a stock.

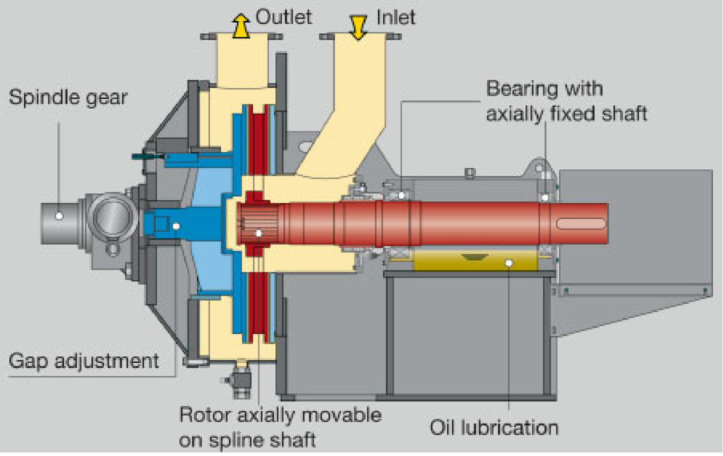

Fig. 4.32 Double disk refiner (source: Voith).

Today's refiners for low consistency refining are double disk refiners, or refiners with conical or cylindrical geometry of the rotor/stator unit. Figure 4.32 shows a double disk refiner. Both sides of the rotor are equipped with fillings acting against the stator fillings of the front side (with loading device) and the backside (with drive). The front stator is moved by the loading device, the rotor can slide along the center shaft when loaded or unloaded. The peripheral speed of the rotor is about 25 m s^{-1}.

In Fig. 4.33 a refiner with cylindrical rotor/stator geometry is shown. The stock enters the center of the machine via the hollow center shaft and is refined during its helical horizontal path to the two stock outlet pipes. The refining energy is controlled by the gap between the rotor and the stator which is adjusted by cone-shaped means.

High consistency (30% and more) refining is mainly based on the shear force effect between the fibers. This is why high consistency of the stock is required, which in turn necessitates its dewatering. To save costs HC refining is best placed

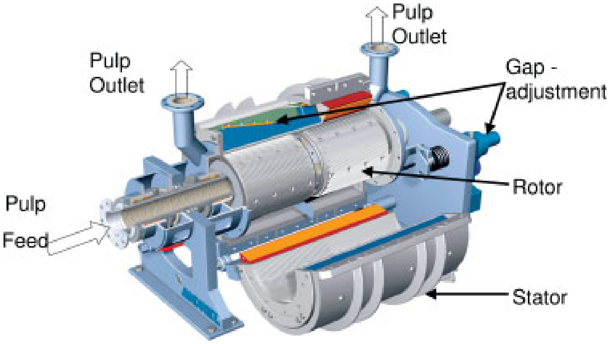

Fig. 4.33 Refiner with cylindrical rotor/stator geometry (source: Andritz).

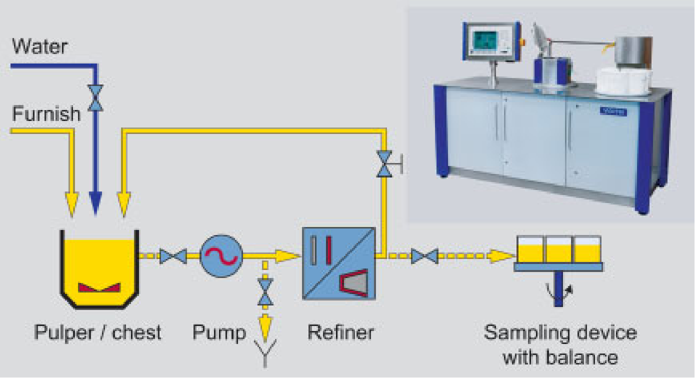

Fig. 4.34 System and photograph of a laboratory refiner (source: Voith).

in a system position where the stock is already dewatered for other purposes e. g. in order to separate the water loops (see Section 4.3).

HC refining preserves fiber length to a high degree, resulting in high dynamic strength properties, high elongation and porosity. HC refining is done either in special HC refiners or with disk dispergers such as described in Section 4.2.9. In this application the disk disperger is operated without steam heating.

Freeness (Canadian Standard Freeness CSF) or Schopper Riegler (SR value) are often used to check the effect of refining. Unfortunately this value can only partly characterize the actual properties of a stock. The properties of papers made from the same original stock but with a different kind of refining may vary in a wide range in spite of the same measured value of CSF or SR value. The same is true for the behavior of the stock in the paper machine. It needs additional measurements such as fiber length distribution, specific surface or flexibility of the fibers to obtain a better picture of a stock or refining process.

The refining energy required to increase the SR value is about 0.5 to 2 kWh t^{-1} °SR^{-1}. This value is influenced by the type of stock processed, the SR value and the refining conditions, as explained before. Some paper mills use a laboratory refiner (Fig. 4.34) to check the incoming fiber materials and to elaborate optimum refining conditions for their individual furnishes.

4.2.6
Flotation

4.2.6.1 Selective Flotation

Selective flotation is used in stock preparation systems for recovered paper processing. The objective is to remove contaminants from the suspension such as printing ink, stickies, fillers, coating pigments, and binders. In selective flotation air is injected into the suspension generating bubbles that are mixed with the suspension. Such an air bubble may catch one or more particles. The particles remain attached to the bubble and are carried to the surface of the suspension. The resulting foam containing the dirt particles is then withdrawn from the suspension. The selection criterion in flotation is the different surface wettability of the fibers to be retained and the particles to be removed. The surface of these particles is or has been rendered hydrophobic (water repellent). The size of the particles that can be removed at least reasonably effectively by selective flotation is limited to a range of about a minimum of 5 to10 µm up to a maximum of 250 to 500 µm.

"Deinking" of the stock is the main purpose of flotation in recovered paper processing: Removing ink particles increases brightness, removing dirt specks enhances cleanliness. Particles larger than 50 µm are usually called dirt specks and are visible with the naked eye. Depending on the recovered paper mixture and on the product demands, up to three flotation lines are installed in a system at different positions. The deinkability of the paper mixtures is different and depends e. g. on the paper grades, the printing process and the time after printing or on the water hardness in the mill. To optimize the mill's operating parameters a laboratory flotation cell or a pilot flotation cell is often used. It is important that these test cells work on the same flotation principle as the actual system in the mill.

The main prerequisites for a good deinking result are

- The particles have to move freely in the suspension: they have to be detached from the fibers.
- The particles must have a floatable size and shape: larger particles have to be reduced in size, too small particles have to be agglomerated into larger ones, flat particles should be reshaped to cubic ones.
- The particles should have sufficient hydrophobicity: if not given by nature to a sufficient extent this can be accentuated by applying surfactants to the suspension.
- The air bubbles have to move freely: the consistency should not be too high
- A sufficient number of air bubbles of convenient size (in the 1 mm range) should be uniformly distributed in the suspension: effective bubble generation and mixing of bubbles and suspension have to be ensured.

In the past a large variety of flotation cell designs were used. All cells have to ensure bubble generation, collision of the ink particles with the bubbles, transport of the ink-bubble aggregate to the suspension surface, and foam removal.

- Bubble generation:

  A simple way to generate bubbles is to press air through a permeable body such as perforated metal sheeting or ceramics. Here the bubble size depends mainly on the surface tension of the suspension, the air injection volume, the air injection openings and the suspension velocity at the openings. Dynamic mixers have rotating impellers with air outlets fed by compressed air. Static mixers make use of natural aspiration for air supply and of the kinetic energy for mixing. In this case bubble size is determined by the suspension properties and the energy involved. The relative air load (total air volume flow to total suspension volume flow) is mostly about 300 %, in some cases up to 1000 %.

- Collision of the dirt particles with the bubbles:
  Collision is a matter of probability and can only happen by relative movement of bubble and particle. Using a permeable body for bubble generation needs a longer residual time – and thus ascending path length – of the bubbles in the suspension to increase collision probability. With dynamic mixers collision of bubbles and particles is intensified in the vicinity of the rotating mixing body. In static mixers the complete streams of both suspension and air pass through the mixing element and undergo an intensive mixing with high collision probability.
- Transport of particle-bubble aggregate to the suspension surface:
  As soon as a particle has been attached to the bubble its detachment has to be avoided. Detachment may occur by too high shear forces due to turbulence, buoyancy and gravity. This suggests that one should make the ascending path length as short as possible. On the other hand a certain height of the suspension level is also advantageous: Collision probability is increased, especially important in designs where the collision probability at the moment of bubble generation is lower. It also often helps to still the suspension surface to enable effective foam removal and to avoid remixing of the foam with the suspension.
- Foam removal:
  Foam discharge is done e. g. by free overflow over a weir, where a scraper may support the removal. In other designs the foam is discharged through sucking pipes by pressure difference, either by vacuum outside or pressure inside the cell.
- Cell body:
  The cell body can be open but nowadays the cells are usually closed for environmental reasons. The closed cells can be pressurized or operate under a slight vacuum to avoid exhausts. One flotation line usually consists of several flotation steps where the accept stream of the preceding step is the inlet flow of the following one. The arrangement of these steps can also be different: individual cells for each flotation step connected by pipes to a complete line, individual cell compartments which are aligned in a horizontal or vertical direction in one overall cell body, and column-like cells with internal recirculation are all found. A special case is a vertical cyclone-shaped cell where the ascent of the bubbles is mainly due to the centrifugal forces and is directed to the center.

Figures 4.35–4.40 show schematic arrangements and photographs of three of the numerous different cell designs which also differ in the arrangements of the individual flotation steps. The circular cell in Fig. 4.35 and 4.36 is closed and pressurized. It is divided into 3–5 superimposed elementary cells. The suspension flows from top to bottom and is aerated after each elementary cell before being fed to the next lower one. Aeration is achieved by static mixers with self aspiration. The bubbles injected in each elementary cell ascend through the upper cells to the foam layer at the top. The foam is removed through pipes by pressure difference to the ambient. A reject valve allows control of the reject rate and composition in order to omit a secondary stage. Figures 4.37 and 4.38 show a flotation line with

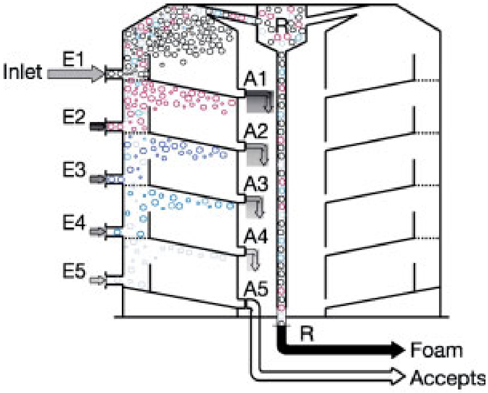

Fig. 4.35 Schematic arrangement of the KADANT LAMORT MAC flotation cell (source: KADANT LAMORT).

Fig. 4.36 KADANT LAMORT MAC flotation cell installation (source: KADANT LAMORT).

individual cells arranged in a horizontal circle. An air-dispersion rotor is used for aeration and mixing of air and suspension. The pressure difference between the inner aeration sector and the outer separation sector in the cell initiates the flow of the suspension from one cell to the next. The foam is removed over a weir to a common reject channel. The cell in Fig. 4.39 and 4.40 consists of an elliptical tube which contains individual cells arranged in line. In each cell the suspension is aerated by a self-aspirating static mixer working on the step diffuser principle. The foam flows over a weir and is collected in a common channel.

The foam from the flotation line contains – besides the particles to be removed – some fiber material, mainly short fibers and fines as well as fillers. This loss in valuable raw material has to be minimized. Reducing the amount of reject foam is limited as this negatively influences brightness and cleanliness. For quality and economic reasons a secondary flotation stage where the reject of the primary stage is floated to recover fibers, fines and some fillers, is in common use. The reject of

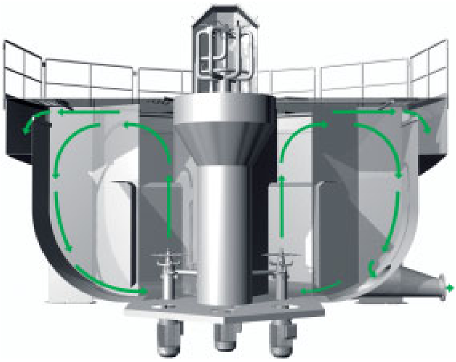

Fig. 4.37 Schematic arrangement of the Metso OptiBright™ MC flotation cell (source: Metso Paper).

Fig. 4.38 Metso OptiBright™ MC flotation cell installation (source: Metso Paper).

the primary cells contains large quantities of air. Deaeration of the reject is often necessary to ensure stable operation of the secondary cells. This can be done e.g. in a deaeration cyclone including a mechanical foam breaker.

Typically, flotation lines operate at stock consistencies of 0.8–1.5% and temperatures of 40–70 °C, neutral to slightly caustic suspension conditions (pH 7–9) and water hardness 5–30 °dH.

4.2.6.2 **Nonselective Flotation (Dissolved Air Flotation DAF)**

Nonselective flotation is used for process water clarification in the water loops (see Chapter 5). The objective is to dispose of all the undesired water components which cannot be removed by mechanical separation, such as anionic trash, fines, or microstickies. These components would negatively affect the production process and/or the product quality. As flotation is based on bubbles generated by de-

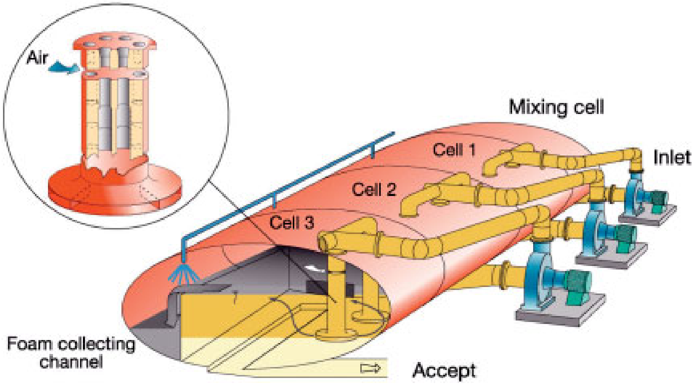

Fig. 4.39 Schematic arrangement of the Voith EcoCell (source: Voith).

Fig. 4.40 Voith EcoCell installation (source: Voith).

pressurizing air-saturated water this unit process is called dissolved air flotation (DAF).

The different steps in nonselective flotation are:

- Generating flocs: Flocculants (cationic polymers) are added and mixed with the water to be clarified. As a result the fine particles agglomerate to flocs. In addition coagulants can be used to transfer colloidal material ("anionic trash") into microflocs in order to make it accessible to flocculants.
- Bubble generation: First a side stream of the untreated water (sometimes also clarified water) is air-saturated in a tank at about 7 bar. The amount of air dissolved in the water is proportional to the pressure. With increasing temperature the amount of dissolved air is less. All remaining nondissolved air is removed as

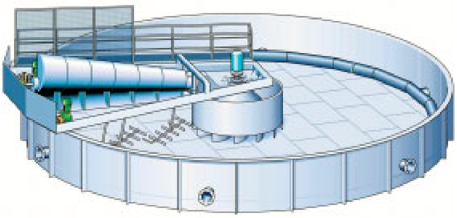

Fig. 4.41 Schematic of a tank for dissolved air flotation (source: meri Entsorgungstechnik).

Fig. 4.42 Air flotation tank (source: meri Entsorgungstechnik).

these bigger bubbles would negatively affect the further process. By depressurizing the water small air bubbles with a narrow size range are generated, finely distributed in the water.

- Flotation: The side stream of the aerated water is mixed with the main stream of unclarified water and fed into a flotation tank. The fine air bubbles adhere to the flocs and rise to the surface where they form a stable layer of sludge. For good flotation results flow turbulences in the tank have to be kept to a minimum.
- Sludge removal, clarified water outlet: The formed stable sludge is removed from the water surface and discharged. The clarified water exits from the bottom of the tank.

The largest equipment in dissolved air flotation is the clarification tank. It can be circular, rectangular, with or without built-in elements for flow guiding, and made from metal or concrete. The design depends e.g. on the requirements placed on the quality of the clarified water, the position in the process and the quantity of water to be clarified. Figures 4.41 and 4.42 show a schematic and a photograph of a circular tank for dissolved air flotation. They show the central feed of the mixed streams of aerated and unclarified water, the sludge removal by a paddle, the discharge to the tank center by a feeding screw, and the extraction of the clarified water near the bottom at the periphery. The tanks can have diameters up to 25 m and throughputs of up to 2500 $m^3 h^{-1}$.

4.2.7
Bleaching of Secondary fibers

With bleaching in stock preparation systems the optical properties of secondary fibers are improved: the brightness of the stock is increased and a possible color shade is reduced.

There are two different bleaching principles (see Section 3.3):

- Oxidative bleaching, mainly with peroxide as the bleaching agent, for brightness increase by fiber lightening.
- Reductive bleaching, with either (sodium) dithionite or FAS (formamidine sulfinic acid) as the bleaching agent, for color value correction and brightness increase by color stripping and fiber lightening.

The main parameters influencing the bleaching result are the type of chemical, its dosage, pH value, temperature, and retention time.

Depending on the requirements of the finished stock either one or both bleaching types are integrated in a stock preparation system (see Section 4.3). The amount and type of bleaching agents have to be adjusted to the fiber composition of the stock and to the desired properties of the finished stock.

Peroxide bleaching is carried out in the presence of NaOH, sodium silicate, and sometimes chelating agents at elevated temperatures. The optimum dosage ratio of NaOH and peroxide prevents yellowing and makes best use of the peroxide. This ensures the best possible bleaching effect at the lowest chemical costs. This kind of bleaching is most effective at high stock consistencies of about 30%. Hence a combination with the dispersion system which operates at high consistencies and temperatures is advisable, using the Disperger to admix the bleaching agents to the stock. Dosage of peroxide is about 1 to 2% of 100% active peroxide on oven dry pulp. The stock is then fed into a bleaching tower (downflow) to ensure sufficient retention time, about 30 to 60 min for wood-containing and 30 to 90 min for woodfree stock, at elevated temperatures of about 60 to 90 °C and a pH of 10 to 11. The brightness gain is about 4 to 11 %ISO for woodfree stocks and 2 to 5 %ISO for wood-containing stocks. These values depend strongly on the kind of raw material and the bleaching conditions. A system for peroxide bleaching is shown in Fig. 4.43.

Economic reductive bleaching of secondary fibers requires an oxygen-free stock as dithionite is sensitive to the oxygen contained in the air. Therefore the stock has to be deaerated which can be done sufficiently at a medium consistency of about 10 to 15%. FAS is less sensitive, thus operating consistency can be as high as 30% and a Disperger may be used for admixing of FAS. Best results are obtained when

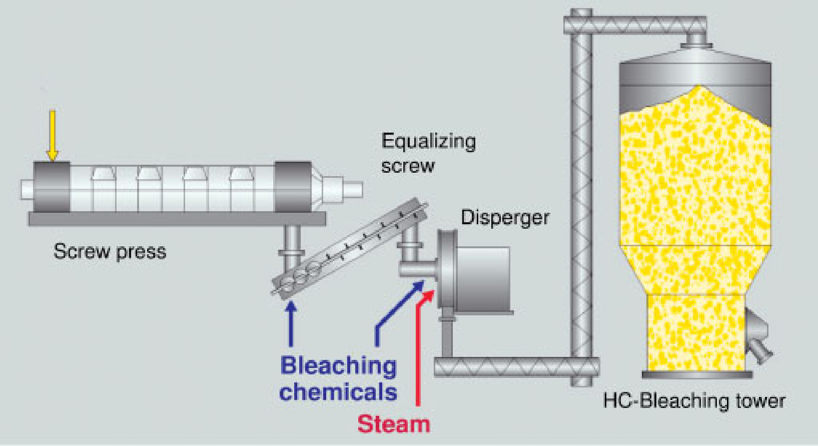

Fig. 4.43 Peroxide bleaching system (source: Voith).

operating the Disperger under pressure and at temperatures up to 120 °C. Both agents are usually fed to the inlet of a medium consistency pump and admixed to the stock in the pump. Dosage is 0.4 to 1.0% (dithionite) and 0.2 to 0.6% (FAS). The chemical reaction is much faster than with oxidative bleaching and hence reductive bleaching can be carried out in a bleaching pipe or smaller tower (upflow) with a retention time of 15 to 60 min. The temperature is 60 °C (minimum) to 95 °C, pH 6.5 to 7.5 (dithionite) and 10.0 to 10.5 (FAS). A system for reductive bleaching is shown in Fig. 4.44.

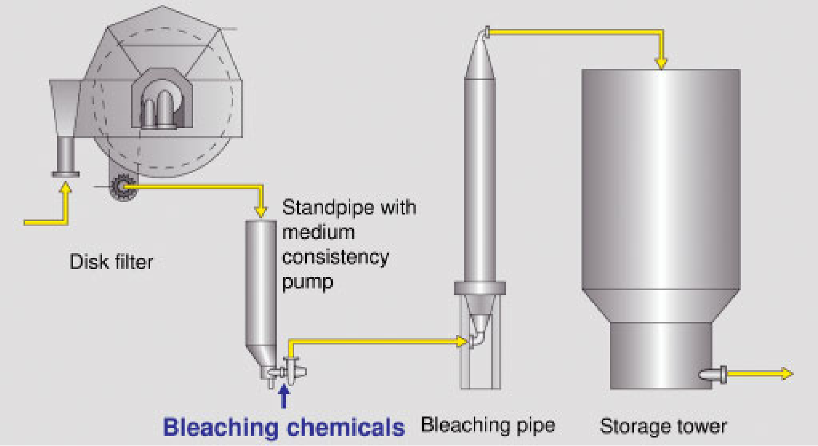

Fig. 4.44 Reductive bleaching system (source: Voith).

4.2.8
Washing

Washing is applied in stock preparation systems for recovered paper processing. Here the objective of washing is to remove from the fiber suspension solid and/or dissolved substances which may negatively affect the papermaking process or the finished product quality. Dissolved and colloidal contaminants include e. g. organic and inorganic substances contributing to COD and anionic trash. Solid particles comprise fillers, coating and ink particles, microstickies and fines. Removal of ink particles by washing (wash deinking) has been quite usual in the United States. Washing is a filtrating-thickening process. To be washed out the particles have to be smaller than about 30 μm. The washing effect is the greater the smaller the particles, the lower the consistency at the washer entrance and the higher the outlet consistency of the thickened suspension mat. The maximum theoretical washing effect is given by the ratio filtrate flow/inlet flow. This theoretical number cannot be obtained in practice as more particles are retained in the fiber mat than corresponds to the above ratio due to a certain filtering effect.

The application of a washing unit and the kind and amount of substances to be washed out depends on the raw material, the other unit processes applied in the stock preparation system and the finished product requirements (see Section 4.3). A washing stage in a system requires effective cleaning of the filtrate, usually by nonselective flotation (see Section 4.2.6.2). This in turn means high solid loss from the system. If desired the washing effect and thus the solid loss can be adjusted e. g. by cleaning only part of the filtrate or adjusting the washer itself if possible.

The machinery used for washing consists mainly of disk thickeners and high speed belt filters. Static filters such as inclined and curved screens, spray filters and pressure screen type washers are also found. Disk thickeners are described in Section 4.2.9. An example of a high speed belt filter is shown in Fig. 4.45. Each unit of this twin machine consists of an inlet feeding the suspension into the gap formed by the center roll and the wire. The filtrate is collected and the washed stock discharged. These machines operate at speeds of about 350 to 1000 m min^{-1}. The suspension is dewatered under the pressure exerted by the wire tension, leaving the roll with a consistency of about 5 to 10 %. Inlet consistency is about 0.7 to 1.5 %. The washing effect can be adjusted over a wide range by the fiber mat thickness i.e by its basis weight. The higher the basis weight the lower the washing effect. The proportion of ash and fines in the filtrate also depends on the basis weight as larger particles (as fines are, on average, compared to fillers) are better retained than fillers when changing e. g. from very low basis weights of 20 to 40 or 50 g m^{-2}.

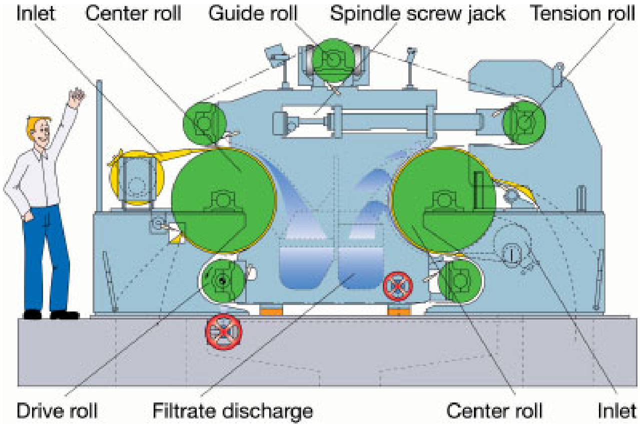

Fig. 4.45 High speed belt filter (Variosplit) with two dewatering units (source: Voith).

4.2.9
Dewatering

The objective of dewatering a fiber suspension in stock preparation is to separate the solids in the suspension from the water and dissolved ingredients. The reasons for dewatering the suspension are technological and economic. They are mainly

- to separate the water loops as regards chemical and contaminant load as well as temperature
- to adjust stock consistency to a defined level required by specific unit operations such as dispersing or bleaching
- to recover fibers from the white or waste water
- to increase consistency to the highest possible level when making wet laps or at discharge of the rejects.

Dewatering is a filtration process where a suspension stream of consistency c_i is divided by a filter into a thickened part with a consistency of c_t and a filtrate stream of consistency c_f. At the start of filtering the retention of the solids on the filter is lowest. With time mat thickness increases, as does retention, which means that the solids content in the filtrate decreases. Dewatering usually aims for zero consistency in the filtrate, which in practice is not reached as retention is never 100%. In contrast, washing takes advantage of this effect for solid/solid separation.

Various types of machines are used for dewatering in stock preparation: Drum filters, belt filters, twin wire presses, disk filters, and screw presses, as well as static filters such as inclined and curved screens. They can differ in several aspects such as

- the driving forces for dewatering e. g. gravity, vacuum, wire tension over a curved surface, mechanical pressing in a nip

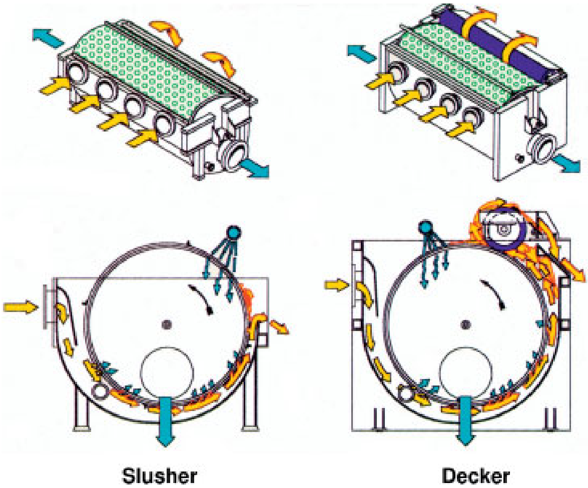

Fig. 4.46 Schematics of drum thickeners (source: Voith).

- the allowed inlet consistencies for ensuring safe operation, from 0.5% up to more than 3.5%.
- the obtained outlet consistencies of a minimum 3% up to more than 30%
- the filtrate consistency which may vary between ppm and % numbers.

Machinery selection is done according to technological and economic requirements.

4.2.9.1 **Drum Thickeners**

Drum thickeners (or slushers/deckers) comprise an open roll covered with a filter wire, rotating in a vat filled with suspension (Fig. 4.46). The feed consistency may vary between about 0.5 and 2.5%. A slusher is used when the required discharge consistency is not more than about 3–4%. For higher outlet consistencies of about 5–6% a decker, which comprises an additional roll to press and further dewater the filter mat before discharge, is used. As the cylinder rotates a mat is built up on the outside of the filter drum. Here dewatering is governed by the differential head between the suspension level in the vat and the filtrate level inside the drum. In the case of a slusher the thickened stock overflows into a chute, in the case of a decker the mat is removed from the couch roll by a doctor blade. The filtrate in the drum is extracted from the inside through a hollow shaft.

4.2.9.2 **Belt Filters, Twin Wire Presses**

Here, in principle, the suspension is fed onto a horizontal moving wire and dewatered by gravity or additionally by a vacuum placed under the wire. Dewatering

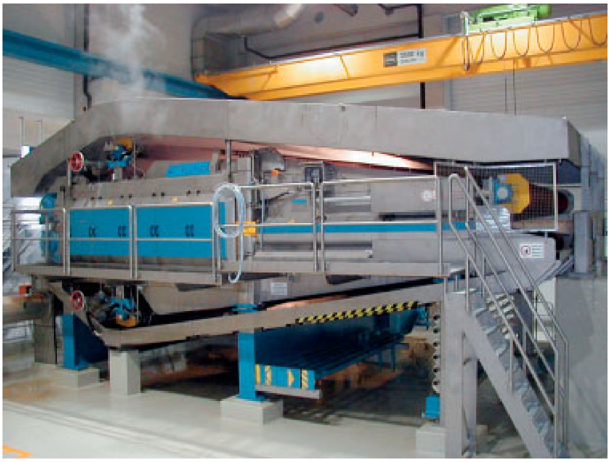

Fig. 4.47 Twin wire press (source: Andritz).

capacity can be further increased by a second wire covering the suspension and the bottom wire. By guiding this sandwich over roll(s) of different diameter(s) D under a tension S of the outer wire a dewatering pressure p is exerted: $p = 2\ S/D$. The highest dry content of the thickened stock is obtained when additional dewatering is done in one or several press nips. Twin wire presses (Fig. 4.47) make use of all three principles and obtain high consistencies of about 25 to 50 %.

4.2.9.3 **Disk Thickener**

The filtering elements in disk thickeners are hollow disks covered on both sides with wires. Numerous disks are mounted closely and equally spaced on a hollow shaft. The length of the machine is up to about 12 m with 3.0–5.5 m disk diameter. The filter disks are immersed about halfway in the suspension in a trough. The driving force for dewatering is the head differential between the suspension height in the trough and the filtrate level. As the filter disks rotate (at 5–20 m min^{-1} at the circumference) a fiber mat builds up which continuously falls back to the trough due to gravity and flow forces. Thus the trough consistency increases and the thickened suspension exits over a weir. The filtrate is removed through the hollow shaft. Its consistency is high as the fiber mat is continuously removed resulting in low retention.

4.2.9.4 **Disk Filters**

Compared to disk thickeners disk filters (Fig. 4.48) additionally apply vacuum to further increase the consistency, production, and retention. They are used for white water cleaning in the paper machine water circuit (save-all) and for dewatering of pulp suspensions in pulping. Typical consistencies are 0.5–1.3 % at the inlet

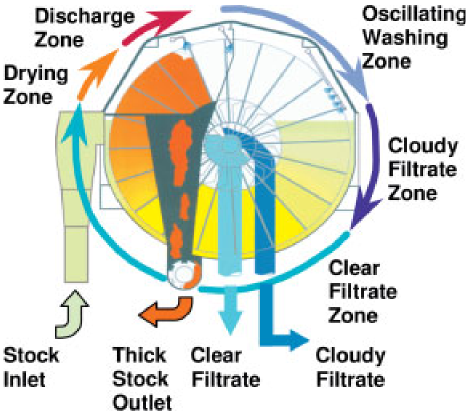

Fig. 4.48 Disk filter (source: Voith).

and up to 12–18% at discharge. The filter disks are similar in design to those in disk thickeners. A filter mat builds up during rotation at the filter disk surface supported by the vacuum generated by a "barometric leg" governed by the differential head of filtrate level in the filter and the outlet to the ambiance. Due to the vacuum the mat remains fixed to the filter disks and is further dewatered after having emerged from the suspension ("drying zone"). The thickened stock is removed from the disks in the upper quadrant by knock-off showers and collected in a conveyor via chutes between the disks. The disks are then cleaned by oscillating cleaning showers before the filter area is re-immersed into the suspension, and filtration starts again. In the beginning filtration takes place by gravity and the filtrate consistency is high (cloudy filtrate) due to the thin fiber mat. Consistency decreases with increasing filter mat thickness (clear filtrate) when a vacuum is applied. The filtrate is divided into two streams by separating means in the filtrate zone, the cleaner one being used for shower water. Sometimes a third stream (superclear filtrate) is drawn off.

4.2.9.5 **Screw Presses**

Screw presses comprise a housing, perforated (round holes or slots) screens, and a rotating screw (Fig. 4.49). The stock is transported by the screw to the outlet, being dewatered en route. The free volume between the screw body and the housing, available during the transport, decreases in the axial direction by the increase in the dewatering pressure. Reduction in the free volume can be achieved by decreasing the screw pitch angle or screw rotor diameter and increasing the screw rotor shaft diameter. Since the filter mat is continuously removed from the screen cylinder a high consistency and dewatering capacity is possible. On the other hand the filtrate consistency is highest compared to all other dewatering methods. Screw presses are also for dewatering in reject handling systems.

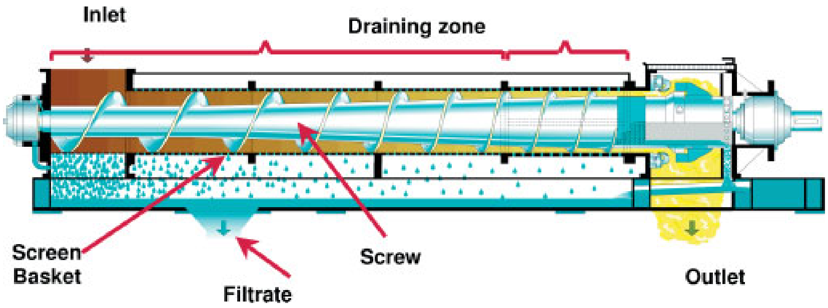

Fig. 4.49 Screw press (source: Voith).

4.2.10
Dispersion

Depending on the furnish quality as well as on the requirements of the finished product, the tasks of a dispersing system vary widely. They are e. g.

- to reduce the size of dirt specks to below the limit of visibility
- to reduce the size of stickies
- to break down coating and sizing particles
- to distribute wax finely
- to detach ink or toner particles from fibers
- to disintegrate fiber bundles
- to treat fibers mechanically and thermally
- to mix in bleaching agents
- to decontaminate the stock as regards microorganisms.

Dispersing is used in secondary fiber processing. It is located at the point of water loop separation where the suspension is dewatered up to a consistency of about 25 to 35 %. Often bleaching is done in combination with dispersing. For high quality demands two dispersing steps may be applied in the process.

During dispersing high shear forces are applied to the debris particles to be dispersed and also to the fibers. The shear forces have to exceed the strength of these debris particles in order to reduce their size. Hence stock consistency must be about 24 to 30 % to ensure the transfer of the required amount of dispersing energy, and the temperature has to be elevated to reduce their strength.

A dispersing system consists of three major process steps (Fig. 4.50):

- dewatering the suspension from 4 to 10 % up to the required consistency of about 22 to 35 %
- heating the dewatered stock to a temperature of about 85–90 °C (at ambient pressure) or higher (up to 130 °C under pressure)
- applying shear forces to disperse the stock.

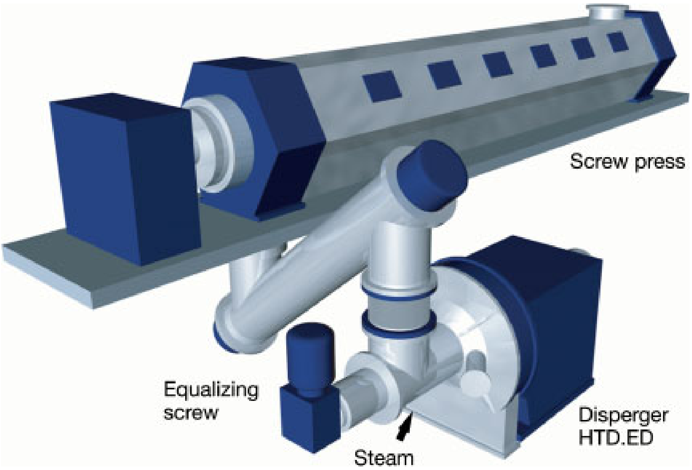

Fig. 4.50 Schematic of a Disperger system (source: Voith).

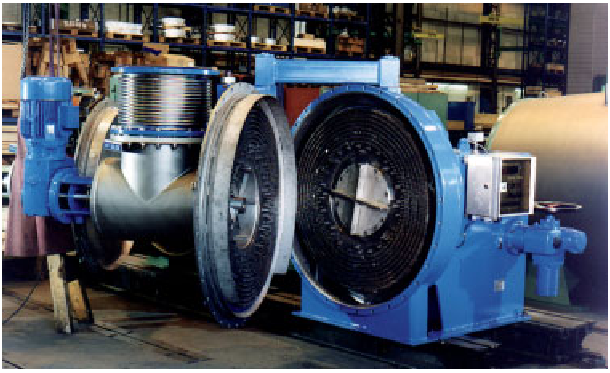

Fig. 4.51 Disk disperger (opened) showing the fillings (source: Voith).

Dewatering of the suspension is done in a screw press – in some systems in a twin wire press (see Section 4.2.9). The required stock temperature during dispersing is obtained by direct steam heating which may be done either in a separate heating screw or by steam fed directly into the disperser. Dispersing itself is done either in a high-speed disk disperger (Fig. 4.51) or in a slow-running kneading disperger (Fig. 4.52).

The fillings of a disk disperger (Fig. 4.53) usually have intermeshing teeth or sometimes refiner-type bars. The rotor/stator element spacing is 1 mm or less, peripheral speed is about 50 to 100 m s^{-1}. The specific energy demand is 50 to 80 kWh t^{-1}, in certain cases up to 150 kWh t^{-1}. Disk dispergers are always operated at elevated temperatures otherwise the loss in freeness would be considerable. This effect may have use for HC refining of recycled fibers (see Section 4.2.5).

Fig. 4.52 Kneading disperger with fillings (source: Voith).

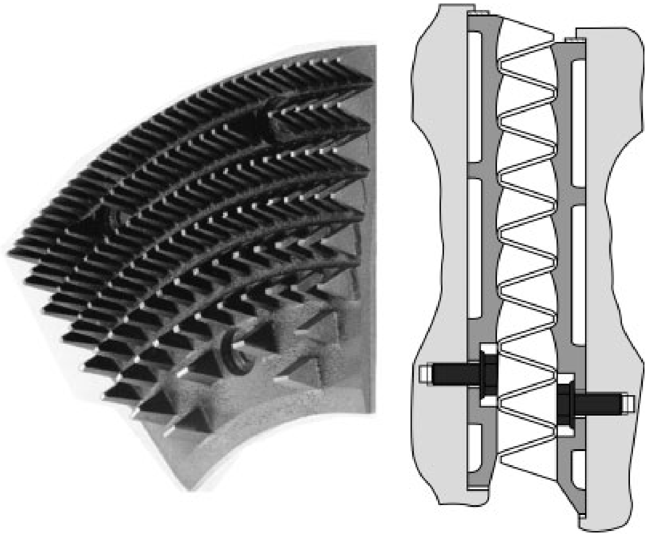

Fig. 4.53 Disk disperger fillings (source: Voith).

The fillings in a kneading disperger are much coarser than in a disk disperger. The rotor/stator spacing is about 10 mm, the peripheral speed is 5–15 m/s. The design may be 1-shaft or 2-shaft. Energy input for kneading dispergers is usually between 30 and 80 kW/t, in special cases up to 120 kW/t. They can be operated unheated at normal process temperatures without noticeably decreasing freeness of the stock.

Control of the transferred dispersing energy for the kneading disperger is by adjusting the entering stock consistency. For the disk disperger energy control is by adjusting the spacing of the rotor/stator elements.

The effects of the two disperger types in general are very similar with some differing tendencies:

- the disk disperger may be advantageous when good sticky and dirt speck reduction is required
- the kneading disperger is recommended when high porosity and bulk of the finished product are a priority.

4.2.11
Mixing and Storing

Mixing has to ensure that all individual component flows entering a mixing apparatus have been uniformly distributed in the exiting suspension flow. When mixing is done in a chest its whole volume has to be agitated continuously. This requires relatively high energy input.

Mixing of suspensions in chests is usually done at stock consistencies of 3 to 5%. The geometry of mixing chests should have an approximate 1:1 up to 1:1.6 diameter to height ratio for minimum energy demand and good mixing effect. The suspension is agitated by a chest mixing propeller similar to a ship's propeller as shown in Fig. 4.54. Specific energy demand is 0.2 to 0.5 kW m^{-3}, depending on the size and geometry of the chest as well as on the stock type and consistency.

During storage of a suspension, demixing of water and fibers and other components may occur at low and medium consistencies. This has to be avoided. Stirring only a small part of the suspension at regular intervals at different positions in the storing chest is sufficient to hinder or correct separation and reflocculation. Thus the energy demand is limited.

Vertically suspended stirrer shafts with pairs of propeller blades at several levels of the shaft are used to prevent demixing. In larger diameter storing chests the shaft rotates epicyclically. The kind of equipment in Fig. 4.55 is applied at smaller and medium storage volumes. The energy demand is about 0.02 to 0.1 kW m^{-3}.

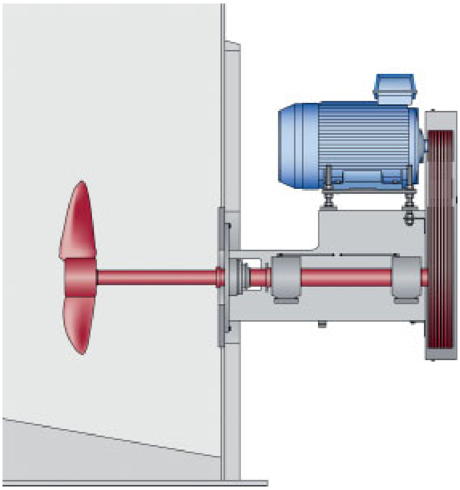

Fig. 4.54 Chest mixing propeller with horizontal axis (source: Voith).

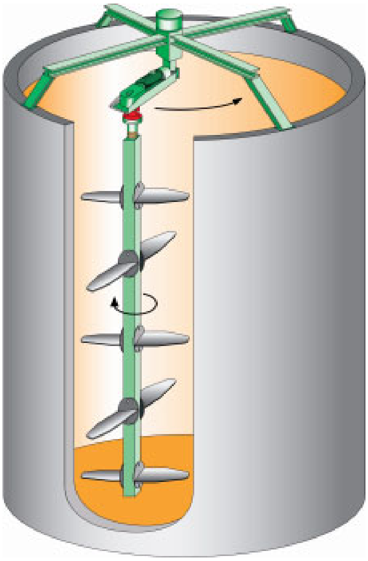

Fig. 4.55 Storage chest with a vertical stirrer shaft to prevent demixing (source: Voith).

For large storage volumes towers are used with reduced diameters at the bottom. Only this lower part is agitated by a mixing propeller. In this case stock can also be stored at higher consistencies, even above 10 %.

In storing high consistency stock of about 10 to 15 %, the crucial requirement is the continuous removal of the stock. For that the stock is diluted close to the outlet. Here demixing is usually not a problem.

4.3
Systems for Fiber Stock Preparation
Andrea Stetter

The target of fiber preparation systems is to modify the raw materials for paper production so that the stock suits the requirements of the paper machine as well as those of the finished paper or board. Raw materials are virgin fibers from different sources such as chemical pulps from hard- or softwood or mechanical fibers like SGW, PGW, TMP or CTMP. The largest portion of raw materials today is recovered paper which is processed into secondary or recycled fibers. The recovered paper grades differ a lot as regards fiber compostion and cleanliness levels (see Vol.1). Therefore the processing systems have to take into account these differences as well as the various quality requirements of the finished stock.

4.3.1
Systems for Primary Fiber Preparation

The systems for primary fiber preparation are less complex than a recovered paper processing system due to the much lower level of impurities and contamination in virgin fiber pulps. Depending on the paper type produced and the availability of the various fiber types, a paper machine, or especially a multi-layer board machine, may be fed by several different fiber qualities, each of them treated in separate lines with different process steps.

Integrated paper mills have their own chemical and/or mechanical pulping plants. Here the fibers usually are not dried before they are supplied to fiber preparation. In nonintegrated mills the primary fibers are supplied dried in bales or flash dried in flakes. Therefore the fiber preparation in an integrated mill usually simply consists of refining (of mainly chemical pulp), whereas nonintegrated mills have to use more complex systems including slushing, removal of contraries and impurities ahead of deflaking and/or the refining. Fig. 5.56 shows a conventional system for virgin fiber preparation of chemical pulp.

The virgin pulp is delivered in bales, which must be placed individually on a conveyor belt. The wires holding the bales together are cut and removed by hand or automatically. The bales reach the LC-pulper via a weighing device, and slushing takes place at a consistency of 4–6 %. The high consistency (HD) cleaning stage – a hydrocyclone device – operates at the same consistency and removes heavy particles in order to protect the following deflaking and refining stages from mechanical damage. The following optional intensive deflaking breaks down the remaining flakes. It also has to prevent the so-called “fish-eyes” in the final paper, which are caused by nondisintegrated fiber bundles when flash-dried pulps are used. Subsequent refining achieves the desired final fiber properties in order to meet the

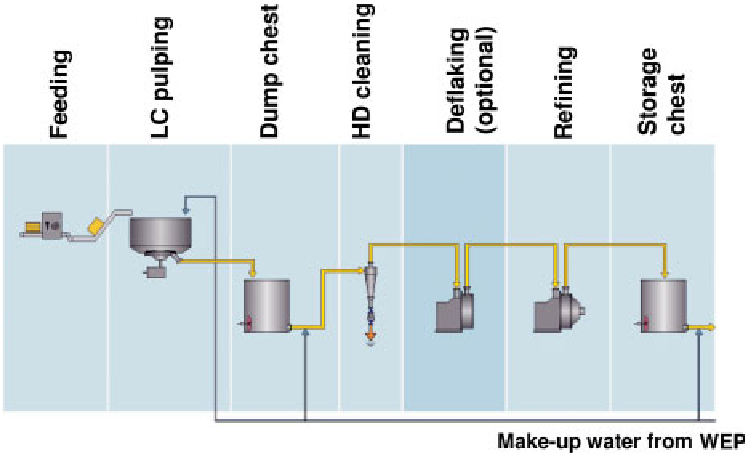

Fig. 4.56 Fiber preparation system for chemical pulp (source: Voith).

quality parameters of the final product. Due to the wide variety of virgin fibers, refining has to be adapted to each raw material and each paper quality target. By refining, strength properties, formation, optical properties of paper and special demands like electrical insulation or greaseproofness are influenced. The same is true for machine runnability.

4.3.2
Systems for Secondary Fiber Preparation

Secondary fiber preparation systems are extremely diverse. This is due to the wide variety of recovered paper grades with their different paper components and quality levels, the quantity and type of nonpaper components like fillers, debris and other detrimental substances, the varying production ranges, and especially the requirements of the paper machine and the final product. Furthermore, governmental regulations regarding waste water, waste disposal and noise levels also have to be considered. On the other hand it is possible to get to an optimum paper quality at lower production costs by using recycled fibers rather than virgin fibers.

4.3.2.1 Systems for Graphic Paper Grades

The raw materials for graphic paper grades mainly comprise graphical post-consumer recovered papers and smaller portions of unprinted or printed pre-consumer grades. Wood-containing recovered paper is generally called deinking material and consists of old newsprints (ONP) and old magazines (OMG). Woodfree recovered paper consists of mixed office waste (MOW) and other coated and uncoated woodfree (CWF and UWF) printing papers. In these grades unbleached chemical fibers and mechanical fibers have to be avoided because in systems for white paper grades high demand is put on optical properties.

The product from a secondary fiber preparation plant for white grades is usually called DIP (**De**inked **P**ulp) as there is at least one process step for ink removal integrated in the system. In most of the cases this deinking step is done by selective flotation. Washers may be used for deinking in special cases when very finely dispersed printing inks (like water-based flexo inks) are present in the recovered paper or when not only the ink, but also the major share of the ash content needs to be removed, as is true e.g. for tissue grades.

The main parameters characterizing the quality of a DIP are brightness, stickies content, dirt specks and ash content. Depending on the application, namely the recovered paper grades used and the paper grades produced, different requirements are imposed on the DIP quality and thus on the system layout and efficiency.

4.3.2.1.1 System for Wood-containing Graphic Papers

The graphic paper grade with the highest secondary fiber content today is newsprint. There are a great number of paper mills producing newsprint, improved newsprint or even SC-B as well as some LWC grades based on 100% recycled fibers, especially in middle Europe. High grade SC-A and LWC papers may also contain up to 30% recycled fibers. The main recovered paper source for these grades is the so-called deinking grade (European grade classification: 1.11) which represents a mix of 40–60% ONP and 60–40% OMG. The significant quality parameters of this raw material and of the DIP for graphic paper grades are shown in Table 4.2.

A fiber preparation system for white paper grades generally consists of the process steps shown in Fig. 4.57.

Recovered paper is delivered in bales or loose and is fed to a conveyor belt where the wires holding the bales together are cut and automatically removed. The raw material gets to the pulping stage via a weighing device. From the measured weight the necessary amount of water for slushing and dilution, as well as the necessary amounts of deinking chemicals, are calculated and fed to the high consistency (HC) pulping stage. Pulping is done at a minimum consistency of 15% (and up to 28% in drum pulpers) for gentle fiber-fiber friction and a low degree of contaminant break down. Operation is either batchwise in a high consistency pulper or continuous in a drum pulper. For good ink detachment, in wood-containing systems pulping is done in an alkaline environment. Sodium hydroxide assists the ink detachment, sodium silicate avoids redeposition of the ink on the fibers and stabilizes hydrogen peroxide, which is added to compensate for the alkaline induced yellowing of mechanical fibers. Deinking additives like soap and/or surfactants can also be added in the slushing stage (see Section 3.6.7.2).

Table 4.2 Quality parameters of European ONP/OMG mix and DIP for different wood-containing graphical paper grades.

Grade	DIP Brightness % ISO	DIP Dirt count > 50 μm $mm^2\ m^{-2}$	DIP Stickies[a] mm^2/kg	DIP Ash content (575 °C) %
recovered paper (Mix ONP/OMG)	45–48	1500–3000	4000–8000	20–25
newsprint	60–62	100–200	< 200	12–16
improved newsprint	65–68	100–200	< 200	12–16
supercalendered (SC)	65–68	50–100	< 100	12–16
light weight coated (LWC)	68–72	50–100	< 100	9–13

[a] According to TAPPI T277 (measurement with Somerville laboratory screen with 0.15 mm slotted screen plate).

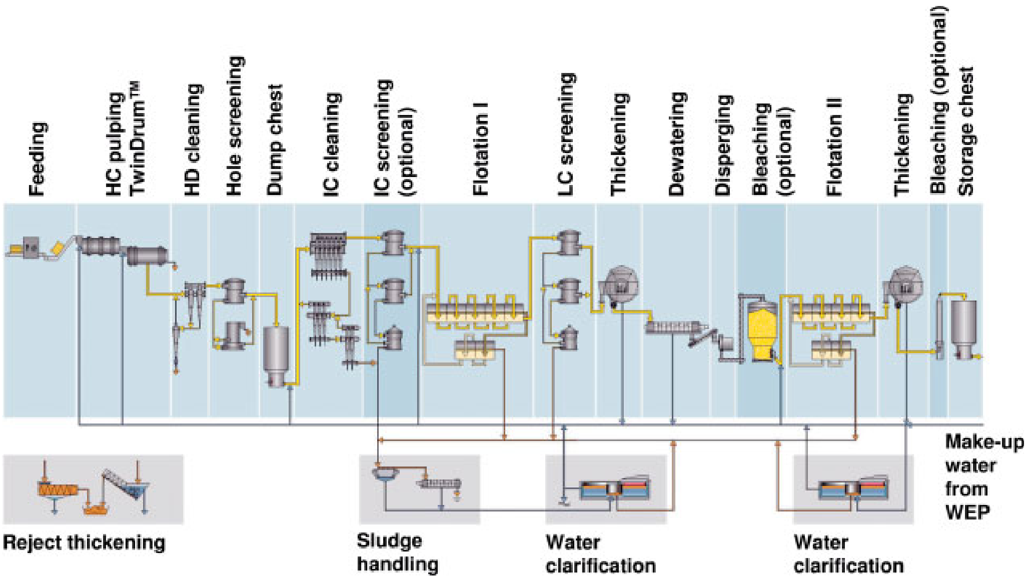

Fig. 4.57 Fiber preparation system for wood-containing deinked pulp production (source: Voith).

After slushing the larger contaminants are removed from the suspension by coarse screening at a consistency of approximately 4.5% in detrashing machines and/or sorting drums. Hole sizes here can vary from 4 to 16 mm. High consistency cleaning removes major heavy contaminants like glass, stones or staples. The following medium consistency screening is carried out with hole baskets with a minimum hole diameter of 1.0 mm. These are especially effective for reduction of flat particles. Medium consistency means a level of 3.5% in the first cleaning stage and dilution in the subsequent stages.

For high quality demands an intermediate consistency (IC) slot screening stage (with slot width a minimum of 0.20 mm) follows at 2% consistency as the next step for removal of stickies and other cubic or round particles. This stage is protected against mechanical damage by a cleaning stage for sand removal which also operates at intermediate consistency.

Deinking flotation represents the “heart” of the whole deinking plant. It follows after dilution down to a low consistency (LC) of approximately 1.2%. The main target of the flotation stage is the removal of printing inks but small lightweight particles, stickies and ash, are also removed in the deinking cells when these particles are hydrophobic. As mentioned above, the deinking chemicals like soap and/or tenside are added either in the pulper or directly before the deinking stage, but sometimes the soap dosage is split between both stages (see Section 3.6.7.2).

The multistage fine screening system operates with slot widths of 0.15 mm. If the fine screening stage is the only slot screening stage in the system, a cleaner plant ahead of it for sand removal is recommended for protection against wear.

Table 4.3 Effect of the process stages on quality parameters of wood-containing DIP.

Quality parameters Process stage	**Brightness**	**Dirt specks content**	**Stickies content**[a]	**Ash content**	**Debris content**	**Fiber design**
pulping coarse screening	detachment and dispersion of smaller printing ink particles	detachment and dispersion of larger printing ink particles	saving screen-ability		removal of coarse contaminants	
HC cleaning					removal of heavy particles	
MC hole screening			reduction		removal of flat particles	
IC cleaning					removal of sand and debris	
IC screening			reduction		removal of cubical/round particles	
flotation 1	increase by removal of printing inks	reduction	reduction	reduction		
HW cleaning		reduction			removal of sand, debris and dirt specks	
fine screening		reduction	reduction		removal of cubical/round particles	
washing/ thickening/ dewatering	increase by removal of printing inks[b]			reduction[b]		
dispersion 1	reduction by detachment and dispersion of smaller printing ink particles	particle size reduction	particle size reduction			
flotation 2	increase by removal of printing inks	reduction	reduction	reduction		
dispersion 2	reduction by detachment and dispersion of smaller printing ink particles	particle size reduction	particle size reduction			

Table 4.3 (continued).

Quality parameters Process stage	Brightness	Dirt specks content	Stickies content[a]	Ash content	Debris content	Fiber design
oxidative bleaching	increase (fibers)					
reductive bleaching	increase (fibers and color stripping)					
refining						increase in strenghth properties and fiber flexibility

[a] According to TAPPI T277. b Only, when filtrates are clarified.

Fine screening is followed by thickening of the suspension with disk filters and subsequent dewatering by wire or screw presses to a minimum consistency of 30%. This is the precondition for dispersing. Dispersion takes place at elevated temperatures. The temperature increase is realized by steam injection, either in a heating screw or directly in the disperser. In the dispersion stage further ink detachment as well as reduction of the size of dirt specks and stickies takes place.

In addition, if bleaching of the fibers is necessary to meet the brightness targets, the dispersion stage is the optimum dosing point for oxidative bleaching chemicals (e.g. peroxide), because of favorable consistency and high mixing efficiency (see Section 3.3). If bleaching chemicals are added, a high consistency bleaching tower for adequate retention time at 30% consistency is installed after dispersion.

All the above described process stages can be installed in the first water loop of a wood-containing DIP system. State of the art nowadays are DIP systems with two loops, where, in the second loop, the residual ink, as well as ash, stickies and other hydrophobics are removed by a second flotation stage. The stock is then thickened again in disk filters to a consistency of approximately 12%. For the high quality demands of SC or LWC papers, it is dewatered once more to 30% consistency, heated and sent to a second dispersion stage for further break down of stickies, printing inks and dirt specks to sizes under the visibility limit. Optional reductive bleaching is involved either after the disk filter or, if installed, after the second dispersion stage. Chemicals used for reductive bleaching are hydrosulfite/sodium-dithionite or FAS (see Section 3.3)

Finally the stock is pumped into the storage tower. As a summary Table 4.3 shows the effect of the process stages on the quality parameters [1–5].

For high grade DIP, an additional fiber design stage, consisting of a minimum one low consistency refining stage is often implemented between the storage tower and the approach flow system of the paper machine. This is to modify the fiber characteristics in order to improve the final paper quality, namely strength and surface properties.

4.3.2.1.2 System for Woodfree Graphic Paper Grades and Market DIP

Woodfree recovered paper, such as MOW, CWF and/or UWF, is used as raw material to produce woodfree DIP grades for tissue, woodfree graphic paper grades or market DIP as a chemical pulp substitute. Table 4.4 shows the raw material quality parameters and the quality demands on woodfree DIPs for named applications.

A typical fiber preparation plant for woodfree DIP production basically uses nearly the same process stages as a plant for wood-containing DIP (Fig. 4.58).

The main differences from the wood-containing process in Fig. 4.57 are found in the thickening stages. In order to be able to achieve the required low ash contents of 2% in tissue production, a washing stage is used instead of the otherwise standard disk filter in both loops for thickening. The washer filtrates contain a large amount of ash and fines. These solids are removed from the filtrate in a subsequent dissolved air flotation unit (DAF) and the ash is thereby removed from the process. Of course in these applications, the yield will be significantly lower than the wood-containing DIP. For woodfree graphic papers or as a chemical pulp substitute, the DIP should not have more than 5% ash content and a maximum of 20–40 $mm^2\ kg^{-1}$ stickies (according to TAPPI T277, measured in a Somerville laboratory screen with 0.15 mm slotted screen plate) and 100 $mm^2\ m^{-2}$ dirt count

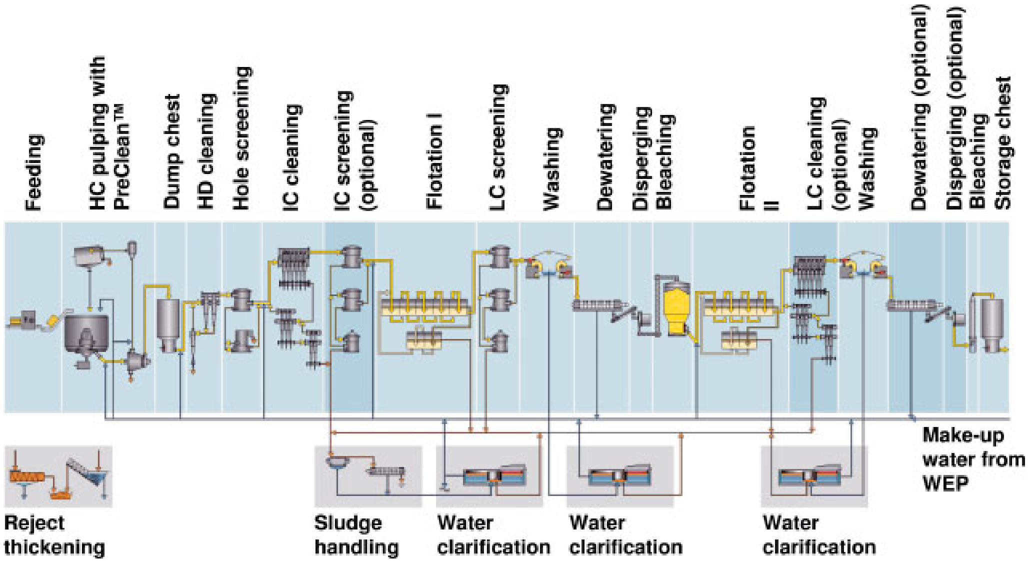

Fig. 4.58 Fiber preparation system for woodfree deinked pulp production (source: Voith).

Table 4.4 Quality parameters of European MOW/UWF/MWF mix and DIP for different woodfree graphical paper grades.

Grade	DIP Brightness % ISO	DIP Dirt Count > 50 μm $mm^2\ m^{-2}$	DIP Stickies[a] $mm^2\ kg^{-1}$	DIP Ash content (575 °C) %
recovered paper (Mix MOW/UWF/CWF)	60–70	1000–5000	5000–20 000	15–25
tissue	80–90	< 150	< 200	< 2
market DIP as substitute of chemical pulp	80–90	< 100	< 20–40	< 5

[a] According to TAPPI T277 (measurement with Somerville laboratory screen with 0.15 mm slotted screen plate).

(> 50 μm). This is achieved by installing at least one washing and a second dispersion stage [1–5].

4.3.2.2 Systems for Packaging Paper and Board Grades

For packaging paper and board grades, recovered paper is the main fiber source with a share of about 60 % worldwide. In Europe most of the mills produce packaging papers based on 100 % recycled fibers. The main recovered paper qualities for the packaging grades are mixed recovered paper from households and supermarkets, the latter mainly being old corrugated containers (OCC). The recovered paper qualities for packaging grades contain much more debris than “white” recovered paper grades.

The recovered paper quality in general, and especially for the “brown” grades, tends to steadily decrease. At the same time the production costs, the stock quality demands concerning the paper machine runnability as well as the final product properties put high demands on the fiber preparation systems. This results in these more sophisticated than they used to be in earlier times. The major objectives in systems for packaging grades are cleanliness, strength characteristics and high yield. The importance of optical characteristics is steadily increasing as packaging material is often printed.

Many of the packaging paper and board grades are multilayer products, meaning that they consist of different layers using different fiber types, virgin and/or recycled. Therefore different individual fiber preparation systems are often needed. In the case of 100 % recycled fiber based production with multilayer or multi-ply paper machine forming sections one completely separate fiber preparation plant is installed for each layer. Or, as is also state of the art, different recycled fiber qualities are produced, starting with one fiber preparation line and then separating the stock flow into lines of different qualities by fractionation. These fractions can then be used either separately for each layer on the paper machine or they can be remixed in desired proportions [1, 2].

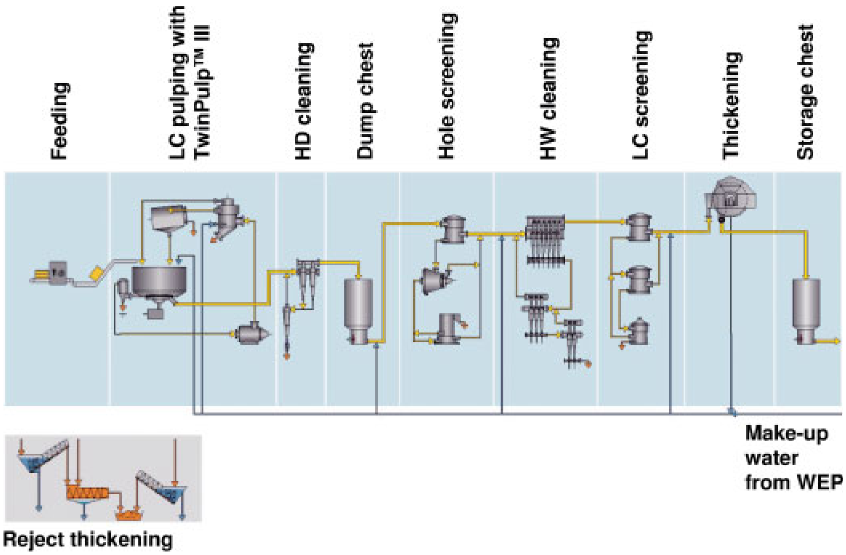

Fig. 4.59 Fiber preparation system for packaging grades without fractionation (source: Voith).

Fig. 4.59 shows a state-of-the-art fiber preparation system for packaging grades without fractionation. The recovered paper, delivered in bales, is put on a conveyor belt where the wires are cut, but not removed, and sent to a LC pulper working at a consistency of 4.5–5.5%. In the pulper wires, strings and other spinning contaminants are removed by the ragger. As various other types of contaminants accumulate in the pulper, an efficient detrashing system is one of the key components of a fiber preparation plant for packaging paper. The slushed stock, after high consistency cleaning, can still contain up to 20% flakes. It is fed into a dump chest with a certain retention time, to assist the defibration of the flakes further down in the process.

After the dump chest the stock is treated in a hole screening stage at a consistency of approximately 3.5%. The design of this stage depends to a high degree on the flake content of the stock. For high flake contents, disk screens (hole sizes 2.4 mm) are recommended, at least in the second stage, as they are more robust and they have a distinctly higher deflaking potential than cylindrical screens (hole sizes 1.6 mm). The first and second stages are fed forward.

After hole screening, the flake content should not exceed 4% to ensure a good runnability of the following cleaning and fine screening stages. Heavyweight cleaning is done after dilution of the stock and is followed by the fine screening with slot widths of 0.20–0.15 mm. Here the major part of the stickies and other contaminants is removed from the process. After that, the stock is thickened in a disk filter for separation of the water circuits of the fiber preparation and the paper machine and to reduce the volume of the following storage tower.

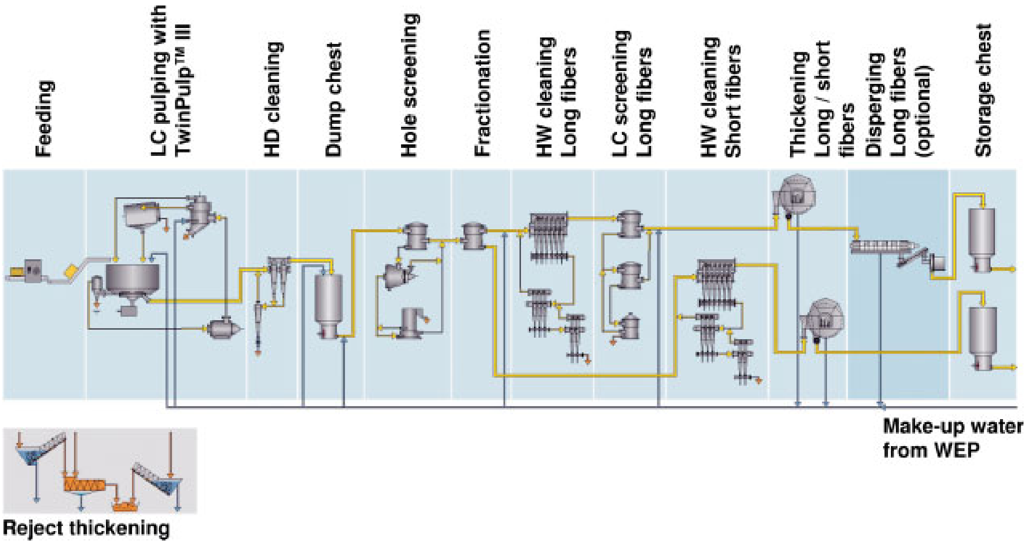

Fig. 4.60 Fiber preparation system for packaging grades with fractionation (source: Voith).

In the case of a fiber preparation line with fractionation (Fig. 4.60), the stock after hole screening is fractionated by screening at slot widths of 0.20 to 0.15 mm. The accept fraction represents the so-called short fiber fraction and is treated further by removing sand through heavyweight cleaning and thickening before storage. The "rejected" fraction is called the long fiber fraction and is treated much more intensively than the short fibers. This fraction contains, besides the longer fibers, an increased amount of contaminants. Therefore it needs to be treated, as a minimum, by a heavyweight cleaning stage and a fine screening stage. If the demand on optical cleanliness is very high, a dispersion stage is used for homogenization. If the recovered papers potentially contain waxes, as in American OCC grades, lightweight cleaners in both fractions as well as a dispersion unit in the long fiber fraction should be installed. For applications, where the recovered fibers still show a potential for strength development, refining of the long fiber fraction is also recommended [1, 2].

4.3.3
Systems for Broke Treatment

Broke is an important stock source and occurs on a continuous basis as trims from the wire as wet broke and from the winders as dry broke. It can also occasionally occur as reel slab-offs, in the finishing room or during breaks in the paper machine or coating equipment. Usually all broke is fed back to the process in the approach flow system. Broke treatment starts with slushing in different pulpers. These pulpers are installed under the machine and dimensioned according to the paper machine width like couch pit pulpers for wet broke and size-press and reel pulpers for dry broke. Alternatively, they are installed separately like winder, finishing room and broke roll pulpers for dry broke (see Section 4.2.2). The design of a broke treatment system depends on the requirements of the paper machine and can contain several stages like thickening, screening, cleaning and deflaking (see Section 4.2). Sufficient buffer capacity for the broke is also important because it should be fed back in controlled portions as it has different properties from fresh stock due to drying, chemical content or, in coated paper production, to high filler content. In specialty paper production, e.g. wet-strength papers or impregnated papers, broke has either to be further treated (for example by mechanical dispersion, increased temperature through steam injection or the use of special chemicals for repulping) or be taken out of the papermaking process. In colored paper production, dry broke has to be used immediately or, if this is not possible, stored until the same color is produced again [6].

4.3.4
Peripheral Systems in Secondary Fiber Preparation

In secondary fiber preparation, peripheral systems are very important for the runnability of the whole plant as well as for cost minimization and environmental issues. Peripheral plant components are the reject system, sludge treatment and water handling (see Fig. 4.56–4.60). Coarse rejects from the pulping section, heavy particle separation and hole screening are dewatered to a dry content of approximately 60 %. If thermal treatment is involved for these rejects, metal components have to be removed and the particle size adapted to the burning process by means of shredding.

Fine rejects and sludges from the flotation stages and the DAFs are also drained to approximately 60 % dry content and either sent to energy recovery or used in the concrete or brick industry [3]. Water handling is another key element as it affects – besides costs and environmental issues – various quality parameters of the finished product such as brightness, cleanliness or odor (see Chapters 5 and 10).

4.3.5
Process Engineering and Automation

Today, advanced process engineering and automation are – due to the complexity of the plants – basic requirements for fiber preparation systems. Engineering provides the right connection of all the described process stages by planning the process layout and selecting adequate pump, pipe and chest designs and sizes for low energy consumption and economic investment. State of the art is a nearly chest-free stock preparation system between pulper dump tower and storage tower, where fan pumps (like in the paper machine) have widely replaced chests.

The main field of automation in a fiber stock preparation system lies in the control of those operational parameters which are important for every stage in the process e.g. consistency, flow, pressure, level, power consumption and temperature. It also includes programs in the DCS for automated start-ups and shut-downs of the different subsystems or even the whole fiber preparation system. Advanced automation concepts ensure, in the case of production (i.e. oven-dry tonnage) changes, that each subsystem is simultaneously adjusted to the new production requirements. Here a production set point is entered by the operator or automatically controlled as a function of paper machine production or the level of the storage tower. The production control value for each subsystem is then calculated, whereby the losses of the individual subsystems are taken into account [7].

Another advanced approach in automation for fiber preparation systems is the introduction of quality control systems. As an example, the operator chooses the desired brightness value of the final stock in the storage tower. So-called model predictive controls calculate the necessary bleaching chemicals according to the actual conditions measured ahead of a bleaching stage(s) to control the brightness on a feed-forward basis instead of the conventional feed-back control strategy. This reduces dead times significantly and leads to more constant quality as well as to reduced costs for bleaching. An additional cost-control module for multistage bleaching processes calculates the most quality- and cost-efficient dosage of bleaching chemicals for each individual bleaching stage [8].

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Section 4.2.3

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5
Water Circuits

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5.1
Introduction

Water is, besides fibers of course, the key component in pulp and paper manufacturing and fulfills numerous functions in the process. It is used as a transport medium, for cleaning and cooling, as a lubricant and finally as the “binding agent” for forming hydrogen bonds between the fibers within the paper sheet. In earlier times paper was produced with a high specific fresh water consumption in the range of 500 l (kg paper)$^{-1}$. For economic and, in the last decades, also for ecological reasons, the average water consumption has been reduced to less than 15 l (kg paper)$^{-1}$ as state of the art. This dramatic reduction was only feasible thanks to the increasing closure of the in-house water circuits and because most of the former fresh water consumers are now fed by clarified circuit water [1].

5.2
Fresh Water

The source of fresh water (FW) in a paper mill is usually surface water and to some extent groundwater, depending on the availability and local conditions. Surface water in particular does not meet the required quality parameters and therefore has to be conditioned by filtering and/or chemical coagulation and flocculation and subsequent sedimentation before use. For boiler house use and in specialty paper, e. g. photographic base paper or cigarette paper, production, the fresh water is softened and/or desalinated. With the limited amount of fresh water available nowadays, this resource must be used efficiently. In general the fresh water taken into a mill is first used for cooling then it is distributed to its process consumers either directly or after further heating. There are only a few fresh water consumers in modern mills, like for instance chemical preparation and dilution systems, sealing water consumers (mainly vacuum pumps) and some high pressure sprays for felt conditioning.

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5.3
Process Water

The majority of water used in a paper mill is process water, meaning water that is recycled in the different water loops of the water circuit of the system before disposal. The process water is "produced" in the thickening and dewatering stages of the papermaking process. Due to its content of solid, colloidal and dissolved substances, the quality of the process water is lower than that of fresh water.

5.3.1
Detrimental Substances

Major process changes in paper production in the last two decades have been
- a strongly increased use of recovered paper
- the change from acid to neutral systems in the paper machines
- the reduction of fresh water consumption.

These changes led to steadily growing problems due to an increased content of so-called detrimental substances in the water loops. Detrimental substances stem from wood components such as resin or lignin derivates, from freshwater as humic acids, from broke and recovered paper as coating binders, glues and adhesives, from additives as fatty acids or silicates, starch and others. Table 5.1 shows the composition and origin of detrimental substances in the process water [2].

Detrimental substances can cause a lot of problems throughout the whole papermaking process such as reduced efficiency of additives, reduced optical and strength properties, poor sizing, bad odor, negative effects on drainage and drying and therefore reduced paper machine speed. These substances are the main reasons for deposits and foam generation causing defects in paper as well as resulting in paper web breaks. Detrimental substances include anionic oligomers and poly-

Table 5.1 Composition and origin of detrimental substances.

Chemical compound(s)	Origin
sodium silicate	peroxide bleaching, deinking, recovered paper
polyphosphate	filler dispersing agent
polyacrylate	filler dispersing agent
starch	coated broke, recovered paper
humic acids	fresh water
lignin derivates, lignosulfonates hemicelluloses	chemical and mechanical pulp
fatty acids	mechanical pulp, deinking

electrolytes as well as nonionic hydrocolloids [3]. Their content in the water circuits is usually measured with the help of sum parameters as so-called anionic trash, measured as cationic demand by polyelectrolyte titration in a streaming current device or as chemical oxygen demand (COD).

Inorganic dissolved substances, i.e. salts, are measured as increased conductivity. Salts are also detrimental to the process performance and potentially for the paper properties. Electrolytes reduce the swelling potential of fibers and chloride especially leads to corrosion of machine parts [4]. The content of detrimental substances in paper mill water circuit systems depends on the input of raw materials, on the output by bleeding through waste water disposal as well as by the degree of transfer to the final paper, on the loop design, and on the presence of "kidney" technologies in the mill.

For different applications, such as sprays in the paper machine, solids (mainly fibers, fines and fillers) in the process water are also disturbing and have to be removed before the water is used.

5.4
Water Circuits

All processing cycles in paper production are connected directly or indirectly by water loops. The objectives of the water circuit system are to offer the required volume rate and quality of water for each consumer and to treat and/or bleed out water containing detrimental substances. A water circuit system of a paper mill usually includes different water loops (Fig. 5.1):

- Paper machine (PM) loop including the approach flow system and the white water systems I (WW I) and II (WW II)
- One or two (in special cases, such as market DIP (deinked pulp) production, sometimes even three) water loops in the stock preparation.

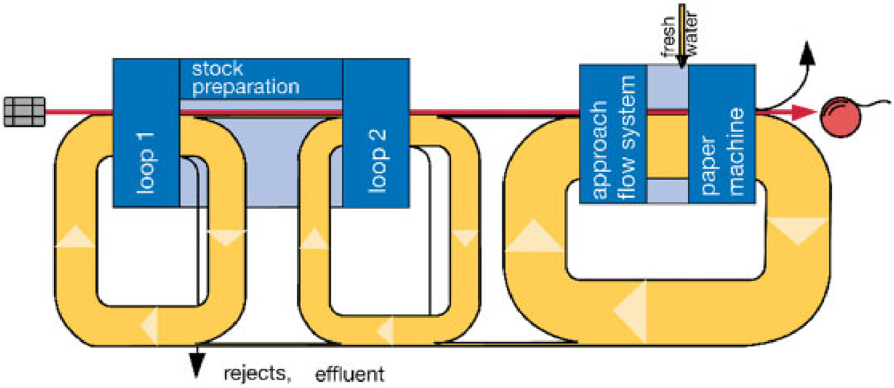

Fig. 5.1 Water loops in a paper mill (source: Voith).

End-of-pipe treatment for bled-out water is carried out in waste water treatment plants which are either owned by the mill or the public (see Section 10.1). In a few cases mills have completely closed their water circuits, meaning there is no waste water produced at all and fresh water therefore is only fed at the same volume rate (approximately 1.5 l (kg paper)$^{-1}$) as it is removed by evaporation in the dryer section of the paper machine and with the rejects leaving the mill.

Due to the challenges mentioned above, water management is an absolute must for every modern paper mill. Some main principles have to be followed in order to manage the water circuit system successfully:

- Efficient loop separation, i.e. transferring stock from one process loop to the following one only at high consistency (preferably 30%), which means at low water content, in order to avoid, to the greatest possible degree, transferring detrimental substances from one water loop to the following one.
- Application of counter current flow, meaning fresh water is added only at the paper machine, excess water from each loop must only be sent backwards and waste water is disposed of only from the first loop in fiber preparation (lowest quality water).
- No mixing of water from different production lines in mills where more than one paper machine is operated
- No mixing of water from different fiber preparation lines and/or pulp preparation plants
- Use of kidney technologies for removal of solids and/or detrimental substances
- Adequate sizing of the water buffers for each water loop in accordance with the stock storage volumes for avoiding uncontrolled overflows in start-up, shutdown or paper machine sheet break situations.

5.4.1
White Water Circuit System

The white water circuit of a paper machine, also called the paper machine loop, consists of the white waters I (WW I) and II (WW II) and the save-all unit. White water I, coming from the wire section, is used to directly dilute the main stock flow after the machine chest in the approach flow system and for profile control in the headbox. Whitewater II originates also from the forming section but additionally from the press section (after removal of felt hairs, usually with a bow screen), from broke thickening and from the overflow of white water I. White water II is sent to a buffer tank and from there it is used at the end of stock preparation to dilute stock from high consistency (12–30%) to storage consistency (4–12%) and for slushing and diluting broke. A defined amount of white water II, preferably the majority of it, plus the trimmings from the forming section are fed to the save-all unit. Save-alls have a dual function: stock recovery and water clarification. Most of the modern paper machines are equipped with a disc filter save-all treating a certain volume of white water II by filtering it through a fiber mat. This mat is formed by adding a so-called sweetener stock to the white water II filter. For sweetener stock usually the best dewatering stock component used at the paper machine is selected in order to limit the size of the disc filter. In addition to cloudy and clear filtrate, disc filter save-all applications also produce a superclear filtrate with very low solids content. This superclear filtrate is used as a fresh water substitute for spray applications in the paper machine. The clear filtrate is stored in a buffer tank. The cloudy filtrate is usually fed directly back to the inlet of the disc filter, the "used" sweetener, including the recovered stock, is fed back to the thick stock in the approach flow system. DAF (dissolved air flotation) type save-alls are used in older machines and nowadays when a certain degree of ash and fines removal from the process is demanded. In this case, the sludge of the DAF is rejected. The advantages of a disc filter save-all compared to a DAF save-all are higher filtrate quality, no chemical consumption and less space requirements (see Sections 4.2.6.2 and 4.2.9).

There are two reasons why there is always an excess of water present in the paper machine loop. First, the paper machine loop is continuously fed with fresh water, used for spraying and chemical dilution. Secondly, the incoming water content of the stock is higher (consistency 12–30%) than the water content in the sheet after the press section (consistency up to 50% and more). This excess water is sent, in the form of clear filtrate, from the save-all unit backwards, as make-up water, to the stock preparation, thus following the counter current principle. This make-up water is often additionally treated in a DAF with coagulation and flocculation chemicals in order to remove detrimental substances before feeding it backwards.

5.4.2
Water Circuit Systems in Stock Preparation

In some cases the water circuit system of a paper mill consists of only one water loop, for example when chemical pulp is the only fiber source or in lower quality packaging paper production. For systems using mechanical fibers and/or recovered paper, the strict separation of the water loops in stock preparation from the paper machine loop is essential in order to meet high runability and quality demands because this strategy keeps detrimental substances from the paper machine. Depending on the required quality of the prepared fiber stock and thus on the design of the stock preparation system, the water circuit system in the stock preparation can consist of from one to three water loops. The loops are separated by the thickening/dewatering process stages (disc filter plus wire press or screw press). The filtrates of these stages are sent backwards for dilution purposes in the same loop, the excess water (usually clear filtrate from the disc filter) replenishes the preceding loop. A water buffer tank, usually fed by clear filtrate from the disc filter in loop I, avoids uncontrolled overflow to the waste water treatment plant. Waste water is disposed of from the first water loop as filtrate from reject and sludge thickening, as these filtrates are of low quality. Usually they are treated chemically/mechanically in a DAF unit. Depending on the fresh water consumption, a certain amount of this treated filtrate can be recycled into the process.

To reduce the content of detrimental substances within a water loop, DAF units are used as so-called kidneys for circuit water cleaning, usually in the second loop of the stock preparation. In this case a combination of coagulants and flocculation aids are added to part of the disc filter clear filtrate in loop II in order to precipitate and flocculate detrimental substances into a flotatable form and subsequently remove them from the process in the DAF. A high ash content in recovered paper is also problematic for some paper grades. Here washing stages in the stock preparation only make sense when large amounts of ash need to be removed. Therefore nowadays the filtrates of screw presses are often deashed in order to achieve a reduction in ash content in the final stock. Usually the screw press filtrate is precalibrated in a spray filter for fiber saving and the fiber-free but ash-containing filtrate is then also sent to a DAF unit after the addition of flocculation aids.

5.4.3
Examples of Mill-wide Water Circuit Systems

Three examples show in detail how the different water circuits for the various paper grades are designed.

5.4.3.1 Water Circuit System for Graphic Papers

5.4.3.1.1 Water Circuit System in a DIP-based Newsprint Mill

Figure 5.2 shows the water circuit system for a modern newsprint mill using deinked pulp (DIP) as the fiber source.

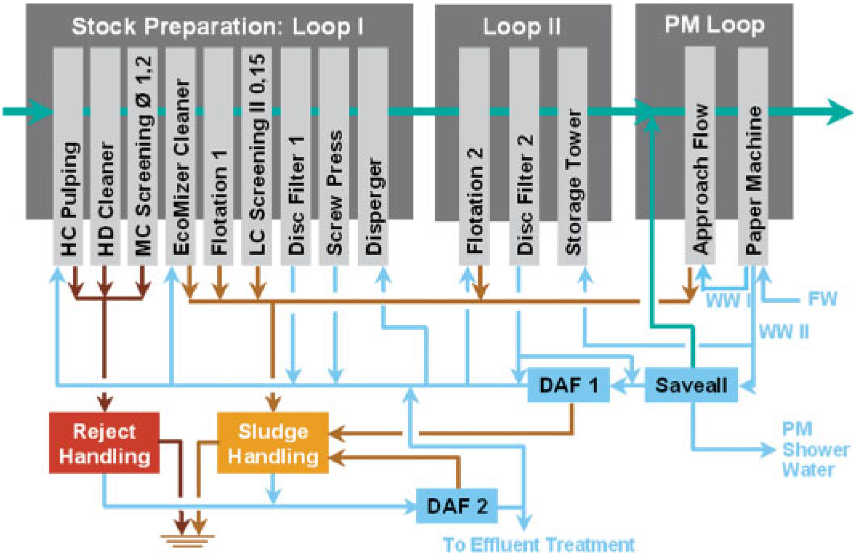

Fig. 5.2 Water circuit system in a DIP-based newsprint mill (source: Voith).

The system consists of three water loops, two in stock preparation (because of the combination of flotation – dispersion – flotation) and one in the paper machine. The water circuit design follows the previously mentioned principles of counter current flow and thereby allows the fresh water to be used to the maximum effect. In addition the save-all is followed by an additional DAF unit. DAF 1 is used as a kidney for removal of detrimental substances, treating the make-up water from the paper machine (clear filtrate) together with part of the clear filtrate from the disc filter in loop II. DAF 2 treats the filtrates from reject and sludge dewatering. The clarified water is partly recycled back into loop I, the rest being sent to the effluent treatment.

5.4.3.1.2 Water Circuit System in a DIP-based LWC Mill

Figure 5.3 shows the water circuit system for light weight coated (LWC) paper also using DIP as the fiber source.

There are again three process water loops and the counter current principle is consequently used. Compared to the newsprint, LWC based on DIP requires a higher DIP quality (see 4.3.2.1.1.). The lower ash content required in the final stock and the higher demands on brightness justifying two bleaching stages necessitate bigger efforts also in the water circuit system, i.e. in kidney technologies. Therefore three DAF units are installed. DAF 1 is used for removal of detrimental substances from the paper machine make-up water. DAF 2 provides the necessary ash removal from the filtrates of the screw presses in loops I and II after precalibration and treatment of the disc filter filtrate in loop II. DAF 3 clarifies filtrates

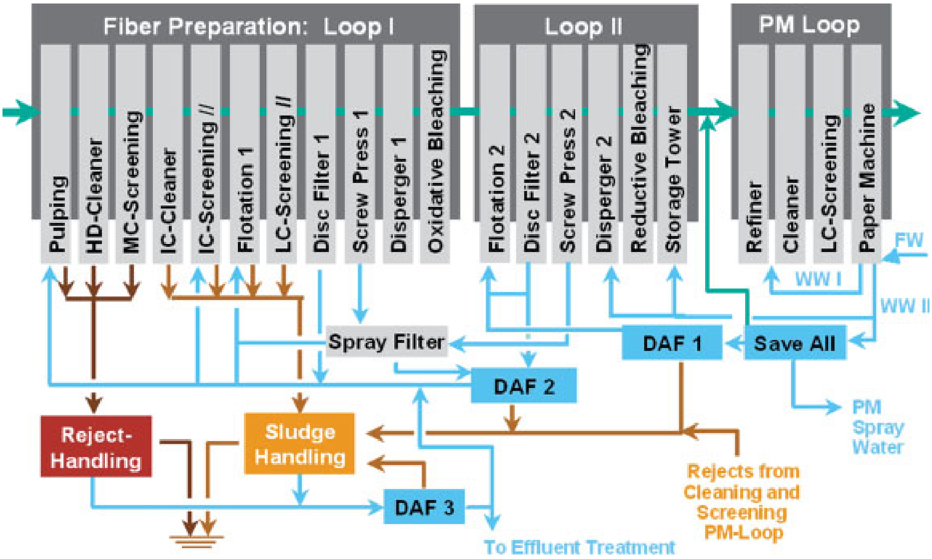

Fig. 5.3 Water circuit system in a DIP-based LWC mill (source: Voith).

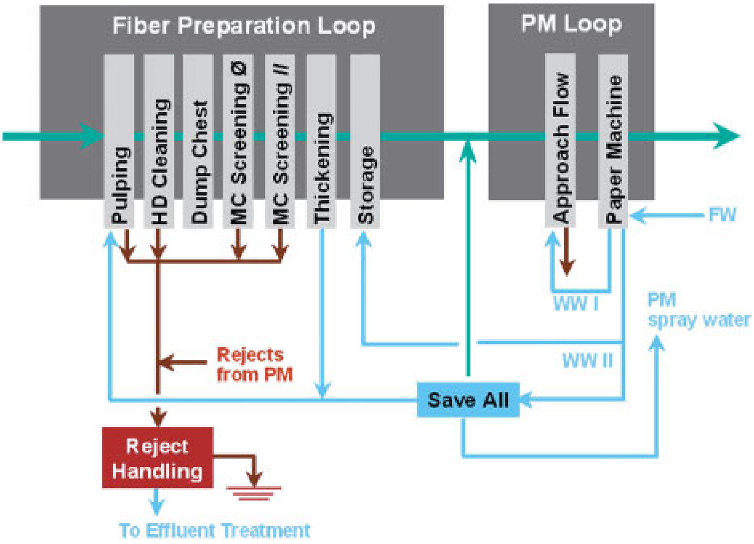

Fig. 5.4 Water circuit system in a mill for packaging paper (source: Voith).

from reject and sludge treatment, which are then partly recycled, the rest being sent to the effluent treatment.

5.4.3.1.3 Water Circuit System in a Mill for Packaging Paper

The configuration of water loops in systems for packaging grades is less complex than for graphic paper grades. Older or lower quality packaging paper systems are often single loop systems. Modern systems with an integrated LC-screening in the stock preparation plant use a thickening stage before storage and therefore consist of two water loops, one for the paper machine and one for the stock preparation system. Figure 5.4 shows such a water circuit system in a modern mill producing testliner and fluting.

Again, the fresh water is added only at the paper machine. White water II is used for redilution after thickening in the stock preparation plant. The save-all clear filtrate is used for make-up in the fiber preparation system. Filtrate from the thickening stage in the fiber preparation system is the main source of water for slushing and dilution. Waste water is sent as filtrate from reject handling to the end-of-pipe effluent treatment.

5.4.4
Current Limits on Circuit Closure

The maximum re-utilization of the water employed is limited by the various detrimental substances in the process water. Their concentration, measured as COD concentration in the water (in ppm), increases at a disproportionate rate when

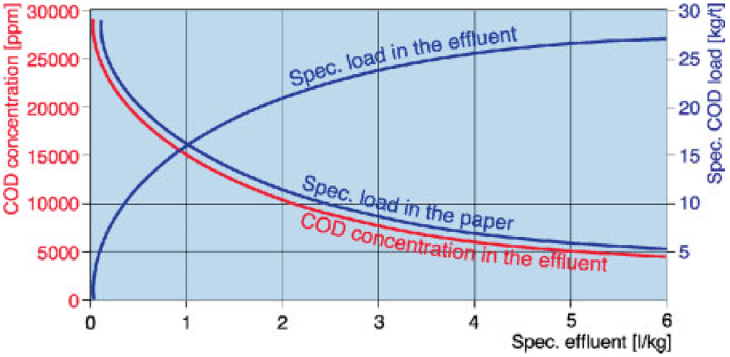

Fig. 5.5 Effect of loop closure on COD values [5] (source: Voith).

reducing the specific effluent (in l (kg paper)$^{-1}$). The higher the water circuit system is closed, the more COD (in (kg COD) (t paper)$^{-1}$) is loaded into the paper instead of being bled into the waste water (Fig. 5.5) [5]. This leads to a disproportionate increase in various problems due to detrimental substances, as mentioned above. Therefore the state-of-the-art systems are limited to certain specific (l (kg paper)$^{-1}$) effluent volume rates with respect to certain minimum fresh water consumption as shown in Table 5.2.

Consequently, the multi-loop systems for graphic paper grades nowadays follow the counter current principle and partly use circuit water cleaning according to the kidney principle. So it is possible to reduce the specific water emissions down to 8–10 l (kg paper)$^{-1}$. Further closing would lead to increased amounts of detrimental substances. This would negatively affect product quality, e. g. decreased optical properties and increased stickies and dirt content as well as runnability problems on the paper machine, such as felt and shower pluggings, reduced retention, scaling and slime formation. The typically simpler board and packaging grade systems with their somehow lower demands on water management can work with specific

Table 5.2 Present limits of system closure.

System application	Specific effluent volume/ l (kg paper)$^{-1}$	Disturbing effects limiting further closure
Graphic paper grades several water loops counter current flow circuit water cleaning (kidney)	8–10	decreasing product quality felt/shower plugging lower particle retention scaling slime
Board and packaging grades single or two loops water treatment only for showers	3–5	odor problems (water and product) corrosion deposits

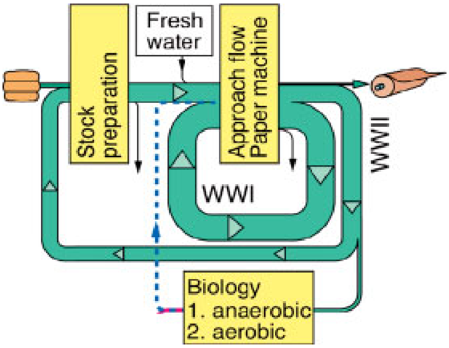

Fig. 5.6 Zero effluent concept for a packaging paper mill [6] (source: Voith).

effluent volume rates of a minimum of 3–5 l (kg paper)$^{-1}$. Further closing these loops without using additional internal circuit water cleaning could lead to odor problems both in the mill and in the paper itself, as well as corrosion and deposits and the paper machine runnability would be significantly reduced.

5.4.5
Zero Effluent Systems

Reducing the effluent volumes to zero means that fresh water consumption is reduced to approximately 1.5 l (kg paper)$^{-1}$. Here problems would arise from the extremely high amounts of detrimental substances, which will be bled out of the process only by transferring them into the paper. The only solution to these problems is to remove the detrimental substances from the process with suitable highly efficient kidney technologies. These include, in addition to circuit water cleaning by coagulation and flocculation with subsequent removal in a DAF unit, anaerobic/aerobic combinations of biological treatment (see Section 10.1), different membrane filtration technologies like micro-, ultra- or nano-filtration down to reverse osmosis or evaporation [6, 7].

Some packaging paper mills in central Europe today run with zero effluent systems (Fig. 5.6) using a combination of anaerobic/aerobic biological treatment (see Section 10.1) as kidney technology for COD reduction [6].

The driving forces for reducing the effluent to 0 l (kg paper)$^{-1}$ for these mills were unique to each mill. In one case there was high cost-saving potential by completely avoiding effluent fees for disposal into a public effluent treatment plant. In another the reason for complete water circuit system closure was the lack of available fresh water due to the local conditions when installing additional production capacity [7].

The other mentioned kidney technologies, i. e. membrane filtration and evaporation, are mainly known as pilot scale applications as they are quite cost-intensive and still not proven state-of-the-art [7].

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6
Paper and Board Manufacturing

6.1
Overview of Paper and Board Machines

Herbert Holik

The objective of the process on the paper machine is to produce a continuous paper web of the required quality, uniform in machine (MD) and cross machine (CD) directions. The process equipment consists of the approach flow system, the headbox and the wire section, the press section, the dryer section, often a size press, sometimes a coating station, a calender and a pope reeler. After the web has been reeled up this full width mother reel is cut into smaller rolls with widths and diameters according to the customers' requirements. The rolls are then wrapped and made ready for shipment.

The various paper and board grades require special furnish make-ups as well as paper machine layouts. For economic and quality reasons these machines are now tailor-made for graphic paper, packaging paper, board, specialty or tissue paper production. They differ for instance in wire, press and dryer section design, in machine width and in operating speed. Machine widths are dependent on the grade produced, since the width depends on the customer's equipment such as printing or corrugating board machinery. For instance, for corrugating board machines widths of 2.5 m, or 3.3 m for the new generation, are standard. So a trimmed width of 10 m at the paper machine would fit both corrugating machine widths (4 × 2.5 m and 3 × 3.3 m).

The technical history of paper machines shows many major changes in their design and operation over the last three to five decades:

- Use of recycled fibers putting higher demands for instance on fabric cleaning for high machine efficiency
- Changing the pH value of the suspension in the approach flow system from acid to neutral, allowing the application of calcium carbonate fillers and ensuring more durable papers
- Hydraulic headboxes enabling higher machine speeds, higher throughputs and easy application of twin wire gap formers
- CD basis weight profiling in the headbox by dilution, resulting in improved paper uniformity and quality, thus enabling fiber savings by lower mean basis weights

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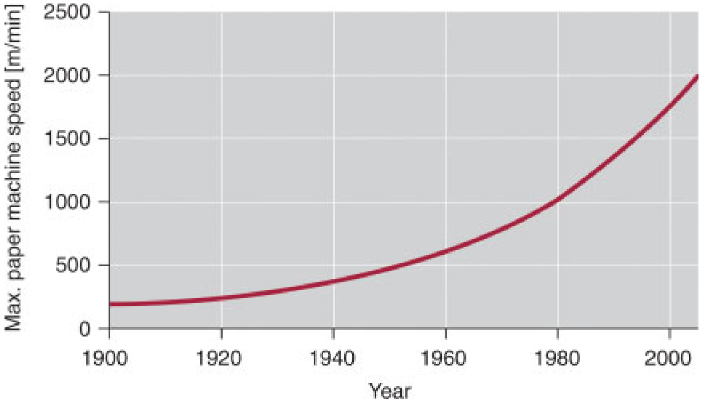


Fig. 6.1 Increase in maximum speed of paper machines over the last 100 years (source: Voith).

- Twin-wire formers providing more symmetrical z-structure of the paper and high machine speeds
- Shoe presses with high dewatering capacity for high web dry content on entering the dryer section, thus saving drying energy and improving machine runnability due to increased web strength
- The one-nip shoe press reducing investment costs, space requirements and operating costs to a minimum
- No-draw press enabling higher machine speed and better machine efficiency
- No-draw dryer section enabling higher machine speed and machine efficiency and changing the CD web shrinkage curve
- Synthetic forming, press and dryer fabrics to best customize the fabrics to the requirements of application for uniform dewatering, smooth web surface structure and long lifetime
- Process control with advanced measuring techniques and control strategies allowing the operators to continuously monitor the operation, see trends in paper quality and machine condition and take appropriate action
- Machine speed: five decades ago the typical paper machine ran at a speed of about 300–350 m min^{-1}. Today maximum machine speeds are above 2100 m min^{-1} for tissue machines, more than 1900 m min^{-1} in newsprint production and above 1550 m min^{-1} for woodfree grades (Fig. 6.1)
- Machine width: The typical paper machine of five decades ago had a machine width of about 3–3.5 m. Today machines with 10 m trimmed width (packaging paper) or 10.35 m paper width (untrimmed) at the pope reeler (newsprint) are found as a maximum (Fig. 6.2)
- Soft covers of calender rolls allowing integration of calenders into the paper machine at high machine speeds for high quality paper grades
- Integration of coating (and calendering) into the paper machine even at high speeds of up to 1550 m min^{-1}.

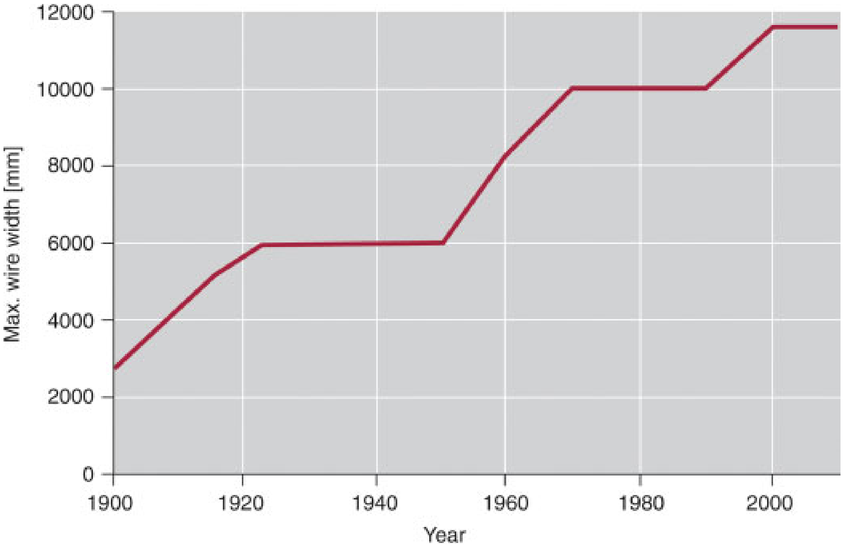


Fig. 6.2 Increase in maximum machine width of paper machines over the last 100 years (source: Voith).

When coating and calendering are integrated into the paper machine the efficiency of the whole process decreases as there are two more sensitive process steps with their interfaces to the pre- and succeeding process steps. Here the weakest link in the chain limits the overall production efficiency. On the other hand in off-line coating and calendering the loss in high quality production due to the batch process is high. Therefore there is clear trend towards on-line coating and calendering for most applications.

Today paper making is a continuous highly sophisticated process with high demands on precision and reliability of all components. For instance the slice opening of headboxes should have an accuracy of about 1/100 mm (or 10 µm) over a width of 10 m in order to obtain the required CD basis weight uniformity and uniform main fiber orientation in CD. Precision in calender roll grinding should be about 3 µm, which is equivalent to 5 % deviation when comparing it for instance with a paper thickness of 60 µm.

Paper machines are in operation 24 hours per day throughout the year only interrupted by short planned or unplanned shutdowns. Both mean loss in production which has to be minimized.

Predicted machine maintenance or wire and felt changes are examples of planned shutdowns and should be synchronized. Unplanned shutdowns are caused for instance by web breaks, or failure of machine components or energy supply.

The forces which the paper web undergoes during its run through the paper machine are as follows:

- A force to release the web from a surface, which is dependent on the surface properties and on the moisture content and other properties of the web.
- A vacuum force is built up in the vicinity of the detachment line which is dependent on the detachment angle as well as on the machine speed.
- A dynamic pressure force acting in a free draw results from any air flows and is dependent on their velocity and the size of the impinged unsupported area.
- A force due to the dead weight of the web is dependent on the total web weight, the length of and the sag in the free draws.
- The centrifugal force in the free draws is a function of the total web weight and the machine speed.
- A dynamic pressure due to the entrained air builds up in the gap where the web is going to contact the next surface (the actual friction forces of the air may be neglected here) and is mainly a function of the machine speed.
- The mechanical draw force which has to be applied must at least overcome the above acting forces to ensure safe web run.

The applied draw force must be well below the strength of the web to avoid web breaks. Force application results in web stretch, so the web should run faster. During drying the web shrinks, which means that the web runs more slowly if there is no force to counteract the shrinking forces. This force, again, has to be well below the web strength. At low sheet dryness the strength is lower whereas at higher dryness the shrinkage is greater. The stretch potential of the paper web at different dryness varies correspondingly and is lowest at high dryness. In these most sensitive areas of low strength or low stretch potential the felt speed differential between the individual press nips as well as the size and speed of dryer groups have to be adjusted accordingly. Furthermore free draws of the web have to be avoided at higher machine speeds. Local nonuniformities such as poor profiles of basis weight or moisture in CD and MD further raise the web break risk.

After a web break (or at the machine start up) the web has to be threaded through the machine as fast as possible to reduce production downtime. This is done by feeding either the web at full width or just a “tail”, a web strip of about 20 cm, at the machine tender side which is then widened to the full machine width after completion of tail threading. The equipment for web or tail feeding includes air blowing nozzles, suction rolls, wires and felts, rope guides or vacuum-supported transfer belts.

The web width changes during the run through the paper machine by:

- edge trim at the end of the forming section reducing the wet web width by about 150 to 200 mm,
- running the web under tension (draw) and
- shrinkage in the dryer section reducing the web width by about 2–8 %.

A paper machine comprises a framework at the tending side and one at the drive side of the paper machine supporting different kinds of rolls and stationary elements like dewatering elements or beams for sensors. Almost throughout the whole paper machine the paper web is in contact with forming wires, press felts and dryer fabrics. When worn fabrics are to be replaced, the front framework is opened ("cantilevered") and an endless forming wire or press felt is installed. Alternatively, in the press and dryer section a non-endless fabric is first thread throughout the machine part and then closed inside the machine with a seam.

6.2
Rolls in Paper and Board Machines

6.2.1
General Aspects

Different types of rolls are used throughout the paper or board machine as well as in off-line machines and fulfill a variety of functions:

- Guide rolls give a stable run either to the paper web or to wires, felts or belts. They are about 400 to 1000 mm in diameter and are covered with coatings (Section 6.2.4). They are also used in tension control devices to ensure that the fabrics operate at adequate tension in the machine direction and in wire and felt guide systems for continuous control of the fabric position in the cross machine direction.
- Suction rolls apply controlled vacuum at a certain angle to the roll circumference to dewater the web or for pick up and transfer (Section 6.2.2).
- Press rolls form a loaded press nip for mechanical dewatering of the paper web.
- Calender rolls equipped with special covers and coatings generate web smoothness and gloss (Sections 6.2.4 and 6.9).
- Spreader rolls spread the paper web or fabrics in the width direction in order to avoid wrinkling or flutes. They consist of several short cylindrical roll sections which are covered by one common flexible hose. The overall axis can be bent for spreading.
- Deflection control rolls (Section 6.2.3) overcome the disadvantages of deflection of the conventional rolls resulting from internal and external forces.

Depending on their application these rolls are made from steel, cast iron, bronze or fiber reinforced plastics. Each roll may be driven by its individual drive, and thus may drive in turn the paper web, the wire, felt or belt. Alternatively, the rolls are driven through friction by a wire, felt or belt. Depending on their application the rolls are equipped with varying covers and coatings (Section 6.2.4). Increased machine speeds make good roll balancing ever more important in order to avoid machine vibrations with their negative effect on paper quality and machinery.

6.2.2
Perforated Rolls

Perforated rolls are used in the wire section as well as in the press and dryer sections. Their open area (2 to 85 %, total area of the openings/holes related to the overall roll surface) and their design vary considerably. Their tasks are

- to dewater the paper web
- to store the water and to release it in a controlled way
- to remove the air between web and felt ahead of the press nip
- to hold the web to the roll surface for a certain circumference.

So perforated rolls are used under various operating conditions:

- Without vacuum application, just storing water when it is pressed into the voids of the roll and releasing it afterwards. These rolls are used at lower machine speeds. A special application of such a roll type is the Dandy roll for formation improvement.
- With vacuum application in the wire section and dryer sections.
- With vacuum application and line load as suction press rolls in press nips.

Most rolls with vacuum application emit a loud noise due to the siren effect when the holes under vacuum are suddenly refilled with ambient air. The noise level may be so high as to make ear protection measures necessary. The actual noise level depends on the roll drilling pattern, the vacuum level, machine speed and the design of the sealing of the vacuum chamber inside the roll. Some typical perforated rolls are described in more detail below.

6.2.2.1 Forming Roll

The forming roll (Fig. 6.3) is a suction roll positioned at the beginning of the wire section e. g. in high speed twin wire formers. Here a high amount of white water has to be stored and low vacuum is applied (up to about 0.15 bar). The forming roll has a two-layered shell with an outer ring of high void volume (about 85 %) and a perforated inner ring. A sealed vacuum chamber inside the shell defines the suc-

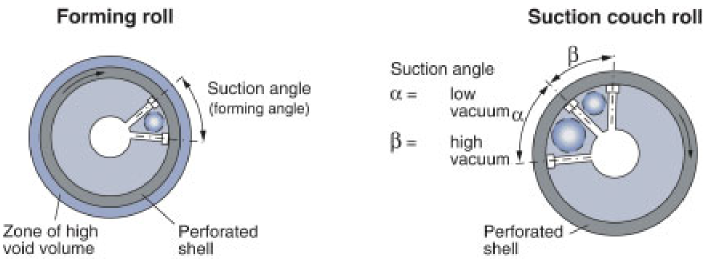


Fig. 6.3 Schematic of a forming roll and a suction couch roll (source: Voith).

tion angle where the vacuum is applied. This is used for web formation control as regards for instance web symmetry in the z-direction.

6.2.2.2 **Suction Couch Roll**

This roll (Fig. 6.3) is placed at the end of the wire section where the web is already formed. It further increases the density of the web and increases its dry content. A small amount of white water is removed and the operating vacuum is about 0.3 to 0.7 bar. The vacuum chamber is divided into two zones with stepwise increase in vacuum. Shadow marking may occur on sensitive papers with too high vacuum application or inadequate drilling pattern. The open area is about 60%.

6.2.2.3 **Suction Press Roll**

This type of roll is an open press roll with vacuum application at part of the circumference. The vacuum removes the air between the web and the felt ahead of the press nip and holds the web on the felt. It enables the water squeezed out in the press nip to flow from the web and felt to the roll void volume where it is stored and released after leaving the vacuum zone.

These rolls are very sensitive with regard to their stressing and material strength. Their main load is the linear force (up to about 120 $\mathrm{N\ mm^{-1}}$) in the press nip for dewatering. Additional loading occurs from the forces due to vacuum, felt tension and dead weight. These forces result in a dynamic stressing of the shell. Stress concentration due to the drilling pattern and open area as well as the shell thickness has an impact on the actual maximum stress which may be either more "beam bending" (rolls with small diameter, high wall thickness) or more "shell deflection" (rolls with large roll diameter, low wall thickness).

Suction press rolls run in a corrosive ambience, so corrosion fatigue strength is the important material property. Corrosion fatigue strength decreases with the number of cycles and time. As a rule of thumb it can be stated that 10% more stress (or less corrosion fatigue strength) leads to a factor of about ten in lifetime reduction, which can be translated into a lifetime of either 10 years or 1 year. Suction press rolls are designed for a lifetime of at least 10^9 cycles. The material applied is bronze or special alloys exhibiting good corrosion fatigue characteristics.

Shell thickness and open area define the amount of air to be removed constantly during vacuum build up which affects the amount of energy consumption. Hole diameters (about 4 mm, open area about 15 to 30%) in the metal shell are larger than those in the cover (about 2.5 to 4 mm, open area about 10 to 20%). The holes in the cover are drilled after the coating has been applied. The coating holes have to match the pattern in the shell which is easier with smaller hole diameters in the coating.

6.2.2.4 Dandy Roll

These rolls are driven and are used in fourdrinier wire sections, the aim being to improve formation and surface smoothness or to generate watermarks. Dandy rolls are wire covered rolls with a very open structure behind the wire, either built up of rings and bars or of a honeycomb design. They are placed between two flat suction boxes a short distance ahead of the "water line" (where there is no more free water on top of the web surface). Here the structure of the freshly formed web is still weak enough to be partly rearranged without being completely destroyed. The dandy roll dips into the wet web, dewaters it for a short moment during the contact and "rewets" the web on leaving the nip. At higher speeds more and more water is thrown out at the exit in the form of droplets. The application of these rolls is limited to machines speeds of below about 1000 m min^{-1} (see section 6.4.3).

6.2.3
Deflection Control Rolls

Rolls undergo a deflection under forces which may be due to roll dead weight, wire or felt tension, linear load in press or calender nips or low inside pressure at a certain circumference angle of the shell. However, most often a straight press nip or a uniform nip load in the cross machine direction is required with only small deviations allowed. One simple means of achieving this is to crown the roll. This is done by grinding a curve onto the originally cylindrical shell with larger diameter at the roll center than at the edges, thus compensating for the deflection and resulting in a uniform nip load across the width. One disadvantage of roll crowning is that the local circumferential speed of the roll is different across the width due to the varying diameters. This may create problems in paper quality or in fabric operation.

The above nip conditions also have to be reached for different operating conditions, such as varying linear loads in press nips. A given crown only really precisely fits for instance one line load. So changing operating conditions result in deviations from a constant line load in the nip over the width or from a straight press nip. With increasing width of the paper machines the problem gets worse as deflection increases by the cube of the roll face.

With the introduction of deflection control rolls this general flaw can be overcome. The principle of all such rolls is that the bending deflection is taken by an axial beam which supports the shell by means of a kind of hydraulic "cushion", be it just one or several "cushions" across the width of the roll. This "cushion" presses the shell to the counteracting roll.

6.2.3.1 One-zone Rolls

6.2.3.1.1 Swimming Roll

The swimming roll (Fig. 6.4) was introduced into the paper industry in 1960 by Küsters (Germany). In principle the shell rotates around a fixed axial beam with

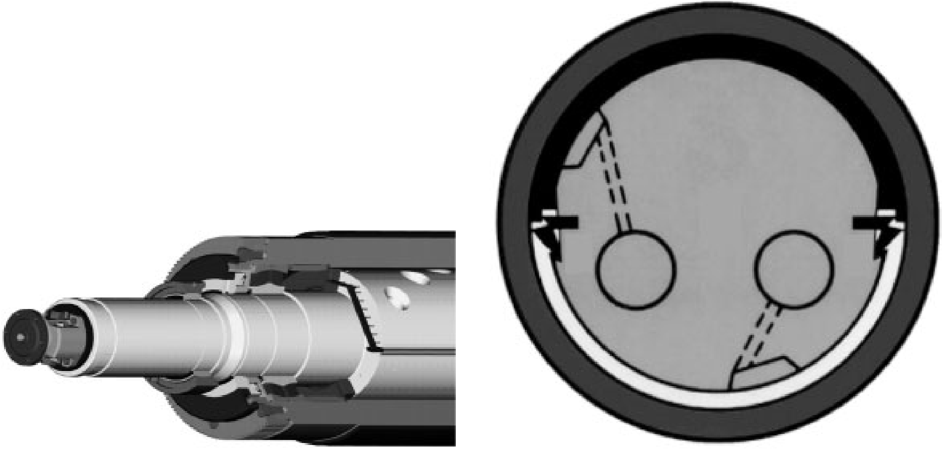


Fig. 6.4 Swimming roll, an example of a one-zone roll (source: Voith).

bearings at each end. A pressurized oil chamber is placed between the shell and the beam which is sealed along the axis against the rest of the inside shell volume and against the roll ends. The oil pressure can deform the shell towards the counteracting roll. The forces acting on the shell are carried by the axis supporting the oil chamber. High oil pressure tends to “blow up” the shell, resulting in more local load at the center of the press nip whereas reduced oil pressure will reduce the local load at the center compared to that at the edges. Loading of the roll to generate the nip pressure is done by external loading devices. A further example of this type of roll is the Voith Econip Roll.

6.2.3.1.2 **CC Roll**

Introduced by Beloit in 1960, the shell of this crown control (CC) roll is supported by one shoe with hydrodynamic lubrication. The shoe can move in the nip direction in the fixed axial beam which takes the line load forces and deflects. Loading is external as with the swimming roll.

6.2.3.1.3 **Profile Roll**

Introduced by Voith in 1980, the shell support of this roll is similar to that of the CC roll. One main feature is that the distance between its end bearings equals the distance of the bearings of the counteracting roll, therefore it is also called the equidistance roll. Loading is external.

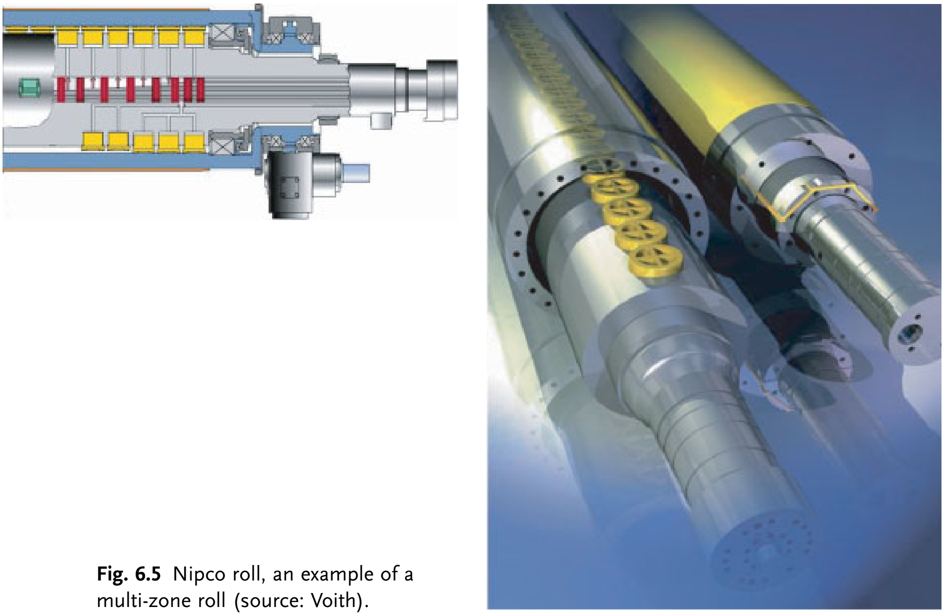


Fig. 6.5 Nipco roll, an example of a multi-zone roll (source: Voith).

6.2.3.2 **Multi-zone Rolls**

6.2.3.2.1 **Nipco Roll**

The Nipco roll (Fig. 6.5) was introduced in 1971 by Escher Wyss. It not only compensates for deflection but also allows one to control the line load in the press nip locally. Here the shell is supported by a number of hydrostatic pistons, which are grouped in at least six or eight zones with two counteracting zones at the edges. All zones are pressurized separately in order to "design" the CD line load curve. The pistons are supported by a fixed beam which takes the press force and deflects. One special feature of the Nipco roll is the self-loading characteristic of the F-type. Self-loading means that no external loading devices are required to load the press nip. The movement for loading or opening the nip is performed by the before mentioned hydrostatic pistons. This movement is made possible by special bearings which allow the shell to move in the nip direction only.

6.2.3.2.2 **Hydrein Roll**

Introduced by Kleinewefers in 1979, the roll principle is similar to the Nipco Roll with the special feature of having "double pistons" in a circumferential direction.

6.2.3.2.3 **Hydro Vario Roll**

This roll was introduced by Küsters in 1980. It consists of a shell, a fixed axial beam and in between these a pressurized oil chamber. For local line load control hollow pistons placed inside the oil chamber are tightly pressed to the shell to eliminate the oil pressure and thus reduce the press force at that position. In addition these pistons can be applied with a higher oil pressure than in the pressure chamber itself which increases the line load locally.

6.2.3.2.4 **Nipcorect Roll**

Voith introduced the Nipcorect roll in 1994. These fine control rolls have been developed to control the line load profile in a much finer pattern, e.g. with a roll having more than 30 and up to 60 zones. In order to make this fine control effective the rigidity of the shell has to be reduced dramatically, for instance by using very thin metal or nonmetal shells. Further examples of this kind of roll are the multi-HV-roll of Küsters and the Sym CD roll of Metso.

6.2.3.2.5 **Controls**

Complicated calculations are needed to define the optimum oil pressure in the different zones in order to give the best approximation to the desired CD line load profiles. These have to take into account all elastic bending characteristics not only of the deflection control roll itself but also the whole roll system involved. A control system based on these models assists the operator or closes the control loop in automatic operation.

6.2.4

Roll Covers/Coatings

Norbert Gamsjäger

6.2.4.1 **Objectives and Basic Design Criteria**

Depending on their application, roll covers or coatings in the paper machine have to fulfill various functions. The main objective of roll coverings or coatings may be:

- to protect the roll body against corrosion in a corrosive environment
- to protect the roll against wear from doctors or wires or felts
- to generate a soft – and thus wide – nip compared to a hard – and thus narrow – nip
- to reduce the hydraulic pressure in a press nip
- to ensure good release of the paper web
- to transfer coating or sizing to the paper
- to provide elastic support for the paper in calendering
- to avoid the agglomeration of deposits
- to support the paper in winding operations.

The various applications in the paper industry require a considerable variety in the design and materials of roll covers and coatings. The materials used range from very hard metallic coatings to very soft elastomeric covers, the surface geometry

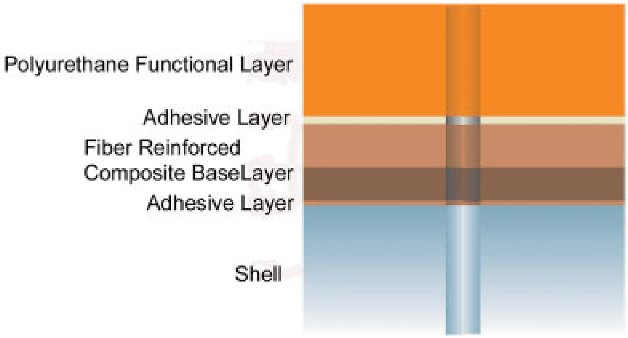


Fig. 6.6 Multilayer design for suction press roll cover (source: Voith).

from plain polished to profiled with a highly open surface. In the following the term cover is used for cover thicknesses of approximately 10 to 30 mm, the term coating is used for coating thicknesses of less than 1 mm. This is not a standardized nomenclature, but is established in the industry.

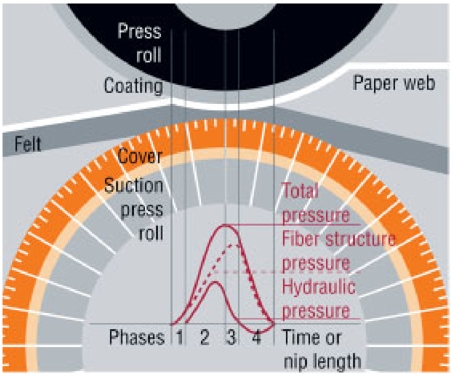
The design of a cover or coating is either defined by the application or by the design needs of the cover material used. Covers and coatings for the paper industry normally have a multilayer design (see Fig. 6.6) where the outermost layer provides the function of the cover for the papermaking process and the innermost layer ensures the bonding to the metal roll body. The use of additional intermediate layers is often required in order to withstand the shear stresses within the cover in loaded positions. A gradual adjustment of material properties like hardness, Young's modulus, thermal expansion etc. in the radial direction is also desirable in order to avoid residual stresses in the cover. These residual stresses are caused by the differences in material properties of the metallic roll shell and the cover/coating.

Covers/coatings have to reach extremely high load cycles during their operational lifetime. In double nip installations, where the cover is loaded twice per revolution of the roll, the number of load cycles goes up to 10^9. This dynamic load, in combination with temperature and the, eventually wet, chemical environment, requires high fatigue resistance of the cover/coating. Covers are usually ground several times before recovering is required. Depending on the application, operation lives of a cover of between 18 months and several years are standard.

6.2.4.2 Application and Function

6.2.4.2.1 Corrosion and Wear Protection

Covers for paper, wire or felt guide rolls have to protect the metallic roll body against corrosion or wear. In general, these covers are plain and relatively hard materials are used. In drive roll applications the cover has to transfer the torque to



Phase 1:
Compression of felt and paper

Phase 2:
Saturation of paper, transfer of water from paper to felt and from felt to the open roll surface

Phase 3:
Mechanical pressure on sheet increases up to the point of maximum sheet dryness

Phase 4:
Expansion of paper and felt, partial rewetting of paper

Fig. 6.7 Press nip.

the driven wire or felt, depending on machine design, softer elastomeric covers are also applied.

6.2.4.2.2 **Nip Design in the Press Section**

In the press section the individual rolls are hard or soft covered. The press nip (Fig. 6.7) is created either by two profiled rolls or by a combination of one profiled and one plain roll. Covers with high open surface area, similar to tyre technology, offer the necessary storage capacity for the water squeezed out in the press nip. The various surface designs include grooves, blind drilled holes or suction holes as well as combinations of these.

The press nip geometry is mainly defined by the diameters of the press rolls, the deformation characteristics of their covers and the compressibility of the felts. The deformation characteristics depend on the dynamic Young's Modulus of the cover material, the thickness of the cover and its surface design. The press nip geometry defines the nip pressure profile, which in turn affects dewatering in the press nip and thus the final paper sheet properties. Optimization of press dewatering means optimum press nip geometry as well as optimum water storage capacity and includes the rolls with their covers and surface geometries as well as the felts.

6.2.4.2.3 **Release Properties**

In some press designs with hard plain press rolls, the paper web comes into direct contact with a cover or coating. It needs to be pulled off the roll surface uniformly with preferably low force as it exhibits low strength due to its high water content. Web elongation in the machine direction also needs to be reduced to a minimum. Therefore, easy release of the paper web from the cover or coating is required for good paper quality and high machine runnability. This can be achieved by a special cover or coating material design, which has been optimized with regard to hydrophilic/hydrophobic areas and defined surface porosity.

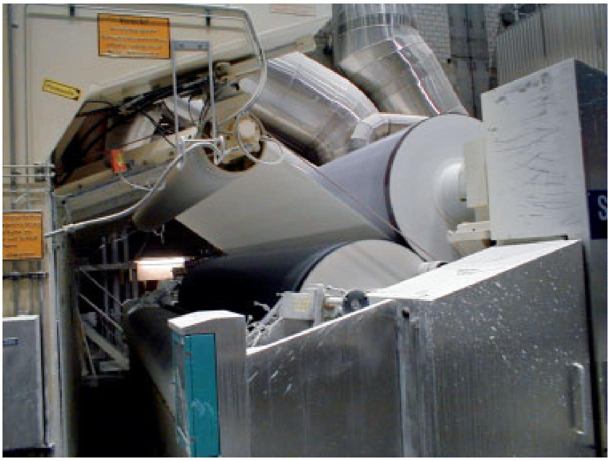


Fig. 6.8 Film press cover (source: Voith).

Coating of drying cylinders in some positions aims to reduce the deposition of stickies or color on the roll surface. The release characteristics of the coating allow easier removal of the deposits by doctoring.

6.2.4.2.4 Nip Design in Coating and Sizing

For coating, sizing or pigmenting in film transfer presses the primary purpose of the cover is both to provide a soft nip and to transfer the applied liquid film uniformly to the paper web. Abrasion resistance is important for keeping the nip geometry constant, as the film thickness of the applied coat/size is extremely thin and any nonconformity in the nip results in nonuniform film application. Good wettability and film splitting properties are also required.

Figure 6.8 shows a film press cover.

In conventional puddle size presses the hard and elastic covers must mainly ensure a uniform nip, in which the size is pressed into the paper web. Both temperature and chemical resistance of the covers are essential.

Coater backing rolls give elastic support and ensure transport of the paper web without slipping of the web, which is coated on the opposite side. Elasticity and optimized deformation behavior are the crucial parameters for roll cover design.

6.2.4.2.5 Nip Design in Calenders

The functions of covers or coatings in soft nip calenders are twofold. The hard heated roll in the calender is either a chilled iron roll with a hard wear-resistant surface, or it is coated for even more improved wear resistance. The surface of the hard roll needs to be extremely smooth, as the roll surface is imprinted onto the paper surface. Since thermal energy must be transferred to the paper through the coating, its thermal conductivity and thickness are important.

The soft elastic roll presses the paper web against the heated roll. This cover must exhibit a certain local deformation ability in order to at least partly follow the "microscale" topography of the paper web in the calender nip. The compression modulus of the cover is of similar magnitude to that of the paper. The local deformation of the cover ensures that the paper is not just calibrated in the nip, but that the thinner areas of the web are calendered as well. Thus soft nip calendering results in better printability compared to hard nips for most printing processes.

6.2.4.2.6 **Other Applications**

In winding, reeling and cutting operations the covers mainly have to support the paper without affecting the paper surface negatively. Soft, sometimes compressible covers are used, providing lower shear stresses in the nip compared to incompressible elastomeric covers.

6.2.4.2.7 **Application Overview**

The functions of roll covers and coatings are various and significantly influence paper quality as well as the runnability of a paper machine. This explains the need for a variety of materials which enables one to have custom-designed covers and coatings for all applications. Each of the major materials has its unique advantages, nevertheless an overlap of the different cover materials exists for many applications. Table 6.1 gives an overview of the materials presently used as roll covers and coatings, their main properties, as well as their major applications in paper machines. In the following sections these materials are described in more detail.

Future development of covers and coatings must take into account ever increasing production speeds as well as the demand for improved runnability of paper machines. Here reliability, predictable operation (grinding) intervals, predictable lifetime and safety aspects in the case of damage are the main goals. The main issues in paper technology are innovations in coating and calendering to give improved printability of the paper.

6.2.4.3 **Materials**

6.2.4.3.1 **Rubber Roll Covers**

Rubber roll covers are the covers with the longest tradition. The hardness ranges from very soft elastomeric covers to hard rubber. Both natural rubber and synthetic rubber polymers are used. Typical rubber formulations consist of approximately 8 to 15 ingredients, such as polymers, fillers, processing materials, tackifiers, antidegradant components, colorants, activators and vulcanizing agents. The possibility of compounding standard formulations as well as high performance formulations makes rubber an excellent material for roll covers.

Hard rubber covers are used for guide rolls and hard press rolls. For guide rolls the compounds are cost optimized due to the large number of guide rolls in a

Table 6.1 Roll cover applications.

	Wet section				Press section								
											Special press		
	Wire guide roll covers (p)	Wire drive roll covers (p)	Wire suction roll covers (sd)	Lumpbreaker roll covers (p)	Paper guide roll covers (p)	Wire and felt guide rolls (p)	Hard press roll covers (p)	Hard press roll covers (g)	Soft press roll covers (g, bd, bdg)	Suction press roll covers (s, sg, sbd, sbdg)	Smoothing press, soft covers (p)	Shoe press counter roll covers (p, bd)	Long nip presses (Jumbo press) (bd)
Rubber covers	x	x	x	x	x	x	x		x	x	x	x	x
Polyurethane covers		(x)	x						x	x	(x)	x	
Composite covers (Resin covers)		(x)					x					x	
Composite covers Fiber reinforced	(x)												
Thermal coatings	(x)		(x)		(x)	(x)	x	x		(x)		x	

x = standard
(x) = special application
p = plain
s = suction drilled
bd = blind drilled
g = grooved

paper machine and the relatively low mechanical demands. Therefore a large amount of conventional inexpensive fillers is used. Depending on the application, single layer designs are usually used. Bonding of the covers to the metal shell is a combination of shrink fit of the hard rubber and chemical bonding, resulting in good corrosion resistance, which is the main reason for applying the cover.

For hard press roll applications the demand on surface quality and abrasion resistance is higher, therefore more expensive fillers and combinations of fillers are used. Release properties of the cover can be adjusted by addition of polymer fillers like PTFE. Two layer designs are frequently used, a cost optimized hard rubber bonding layer and a performance optimized functional layer.

Soft press roll covers are formulated for good dynamic properties in combination with high wear resistance. Chemical resistance and swelling characteristics are adjusted by selection of the polymer. The higher loads of the nipped positions require two or three layer designs in order to withstand the shear forces in operation. Bonding is achieved by chemical bonding supported by the shrink fit when using a hard underlayer.

Sizing/coating/pigmenting is the domain of the high end formulations. Synthetic polymers like Hypalon give outstanding abrasion resistance, nitrile rubbers

configurations			Dryer Section			Sizing, coating and pigmenting					Calender			Reeling	
Roll covers for tissue machines (bd, sbd)	Press roll covers for marking press (p)	Press roll covers for glazing cylinders (p)	Paper guide roll covers (p)	Wire and felt guide rolls (p)	Coatings for drying cylinders	Paper guide roll covers (p)	Hard roll covers for puddle size press (p)	Soft roll covers for puddle size press (p)	Film press roll covers (p)	Coater backing and applicator roll covers for coating machines (p)	Paper guide roll covers (p)	Elastic roll covers (p)	Hard roll covers (p)	Reel spool (p)	Reel drum (p)
x		x	x	x		x	x	x	x	x	x			x	x
	(x)							(x)	x					x	
			(x)	(x)		(x)						(x)	x		
												x			
			(x)	(x)	x	(x)	(x)				(x)		x		x

for example result in good chemical resistance. Properties like heat build up, dampening, wettability, roughness, and low compression set for marking resistance must be considered for development of the compound in these applications.

Most roll cover manufacturers carry out their own rubber compounding because of the variety of the formulations, the demand for high quality and the small batch sizes. Mixing of the compounds is frequently done on open mills (Fig. 6.9) due to the small batch sizes, the high number of different compounds as well as hardness variations and the good quality of this compounding procedure. The use of internal mixers is not always justified due to high equipment costs.

After mixing the rubber compound, it is strained to remove impurities and converted into either a feeding strip for an extruder or a calendered sheet for direct application.

The surface of the roll is carefully prepared by cleaning and sandblasting before the application of chemical adhesives or rubber cements.

There are three basic methods for applying the rubber cover to the roll core:

- Extrusion: an extruded strip of rubber is spirally wound around the rotating roll body (Fig. 6.10)

Fig. 6.9 Rubber compounding on an open mill (source: Voith).

Fig. 6.10 Extrusion of rubber cover (source: Voith).

- Knott method: a narrow strip of calendered rubber is spirally wound around the rotating roll body
- Hand build: large calendered sheets of rubber are manually applied on the roll.

With each of these build up methods, the desired layers of different materials are applied. The choice of application method depends mainly on the compound and the requirements for cover homogeneity. The hand build method, as an example, is the most sophisticated and most expensive build method. For these reasons it is only used for applications with extremely high demands on surface quality such as sizing or coating.

Vulcanisation of the covers is done in steam autoclaves, where the rubber polymer is crosslinked to the elastomeric network. The cover is finished by mechanical tooling, drilling and grinding to the required geometrical dimensions.

6.2.4.3.2 **Polyurethane Roll Covers**

Polyurethane roll covers were introduced to the paper industry at the end of the 1980s. The outstanding mechanical and dynamical properties make polyurethane the most suitable material for soft elastomeric covers in press positions. Depending on paper quality and press design, high open surfaces up to 45% with grooves, blind drilled holes or suction holes, as well as combinations thereof are used. An example of surface design is shown in Fig. 6.11.

For these types of covers in modern machines only polyurethane elastomers are able to provide enough wear resistance to reach acceptable grinding intervals. High performance polyurethane formulations are used, giving the required mechanical strength and elasticity as well as outstanding hydrolytic stability.

Usually the cover has a multilayer design in order to ensure excellent bonding of the polyurethane functional layer to the core as well as safe running properties. State of the art are composite base-layers with endless fiber reinforcements, which allow a gradual adjustment of the mechanical and thermal properties of the cover in a radial direction. This results in a gradual adjustment of the shear forces created by the nip load within the cover layers. Two layer designs with a harder polyurethane underlayer are also used to provide bonding to the shell.

In fast running machines the dynamic heat build up in the cover limits the application of elastomeric materials. Polyurethane polymers, based on special formulations with excellent dynamic properties, ensure good performance in these applications with minimal heat build up. An example of such an application is the substitution of grooved steel rolls by elastomeric covers in shoe presses.

The functional layer of polyurethane covers is manufactured by casting processes, thus ensuring very homogeneous material properties.

Roll preparation is similar to that for rubber, chemical adhesives are used to bond the base layer. The base layer can be a fiber reinforced composite, which is applied in a wet impregnation process of the reinforcement material. The glass fiber reinforcement (tapes or rovings) is impregnated in a resin bath and then spirally wound onto the roll shell. Curing of the base layer with infrared heating and/or ovens and tooling to a defined geometry are the next steps.

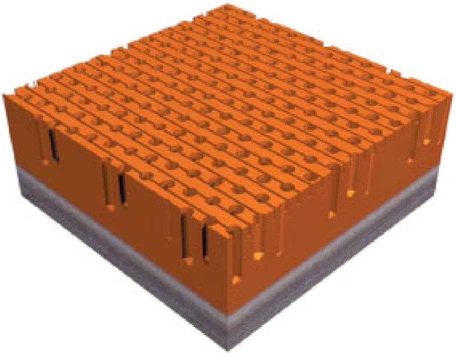


Fig. 6.11 Example of surface design for polyurethane press cover (blind drilled and grooved) (source: Voith).

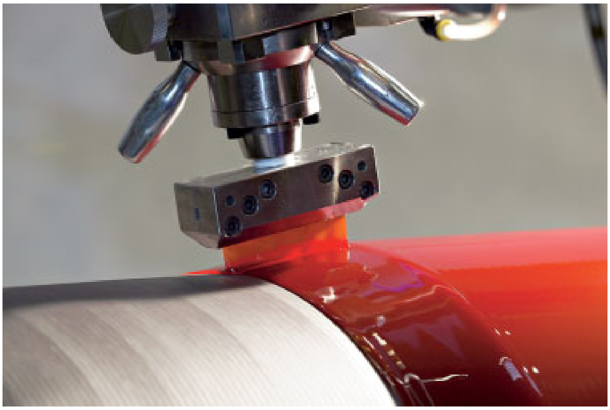


Fig. 6.12 Moldless rotational casting of polyurethane cover (source: Voith).

The polyurethane elastomer itself is a reaction polymer, created by the mixing of prepolymers and chain extenders or hardeners. This reactive mixture, which is created in the desired mixing ratio by special casting machines, is cast into a mold built around the roll shell with the base layer. The casting procedure can be carried out horizontally or vertically. Bonding to the base layer is done chemically with adhesives or reactive layers. The polyurethane material itself is not normally filled, thus providing outstanding elastomeric material properties.

Another method for manufacturing polyurethane covers is the moldless rotational casting process (Fig. 6.12). Here the reacting polyurethane mixture is cast as a spiral on the rotating roll, the fast reaction of the polyurethane mixture prevents the material dripping off the roll. Layers of different hardness can be applied easily with this method.

Most polyurethane formulations need to be post-cured at elevated temperatures for optimum material properties. The final mechanical manufacturing steps are similar to those of rubber covers.

6.2.4.3.3 **Composite Roll Covers**

Two basic composite designs for the functional layer of roll covers are used in the paper industry: Composite covers with a fiber reinforced functional layer and composite covers with a cast functional layer (resin covers).

6.2.4.3.3.1 **Fiber Reinforced Functional Layer**

Composite covers with fiber reinforcement in the functional layers are mainly used in calender applications. The use of fibers significantly improves the mechanical and thermal robustness of the cover. High performance materials like Aramide fibers are used, where a high damage tolerance is required. Compared with

Fig. 6.13 Elastic composite cover in multi-nip calender (source: Voith).

structural composites, where the fiber characteristics dominate the mechanical properties, the fiber volume content of the functional layer of roll covers is relatively low. The major physical properties like hardness, compressive modulus or strength of the covers are mainly dominated by the particle filled resin matrix.

The base-layers of the multilayer designs are mostly glass fiber reinforced, in these layers the fiber content is higher, and therefore the fiber properties dominate the properties of the composite.

For soft calendering different hardnesses – or more accurately different Young's moduli – of the covers are required in order to ensure the required paper properties. This can be achieved primarily by varying the amount and combination of different fillers in the fiber reinforced composite.

The surface of the covers must be as smooth as possible, the wear resistance excellent. These properties can be influenced for instance by the modulus of the fibers, particle size distribution and hardness combinations of the fillers and, to a minor extent, by the properties of the resin. Temperature resistance and low heat build up of the cover under dynamic load is mainly a function of the resin matrix system. Operating conditions of calenders such as 25 Hz load frequency, 90 °C surface temperature and 50 MPa nip pressure as well as expected load cycles of $>10^9$ make the elastic calender covers the most demanding applications of roll covers. Figure 6.13 shows an elastic composite cover in a multi-nip calender.

For lower demand applications composite covers with conventional fiber reinforcements (glass or polyester) are used. These covers are for applications such as guide rolls or special press positions.

6.2.4.3.3.2 **Cast Functional Layer (Resin Covers)**

Composite covers with cast functional layers are applied in the press section or in calenders. Typically, mineral filled resin systems are applied onto a fiber reinforced base layer. The advantages of the cast resin systems are extreme homogeneity of the functional layer and good abrasion resistance. These properties are important for applications such as soft calender covers or center press roll positions. Special formulations of the resin/filler composite allow the adjustment of sheet release properties as well as wear resistance. Limitations for this type of cover are the sensitivity to mechanical damage and thermal shocks due to the relatively brittle functional layer.

For the manufacture of composite covers wet impregnation processes are primarily used. The reinforcement fibers (tapes, rovings or nonwovens) are impregnated in formulated resin mixtures and wound onto the roll body. Multilayering with different fiber reinforcements and different fiber orientations is applied. The winding angle of the reinforcement material mainly governs the reinforcement direction of the fibers, creating anisotropic (direction dependent) material properties. These special material properties are used for design purposes, e. g. to influence the strength, thermal expansion behavior or modulus of the composite structure.

Particle filled functional layers are applied by casting processes similar to polyurethane covers.

The curing of the resin systems which are primarily epoxy-based, is done by infrared heating and/or by heated curing ovens. Mechanical processes are similar to those used for the other cover types. Final surface grinding requires special techniques to reach the desired smooth surface properties.

6.2.4.3.4 **Thermal Coatings**

Thermally sprayed coatings are gaining wider use in modern paper machines due to their outstanding wear resistance. Even thin coatings of 0.2–0.7 mm provide both excellent resistance and long lifetime. Different thermal spraying processes (e. g. plasma, HVOF, flame/arc spraying) allow the use of a large variety of materials.

6.2.4.3.4.1 **Ceramic Coatings**

Oxide ceramic coatings based on Al, Ti, Cr Oxides or combinations, are used in hard press roll positions. The outstanding wear resistance of the ceramic surface as well as excellent sheet release make these coatings suitable for high speed paper machines. Due to the well defined porosity structure of the ceramic, a hydrophilic coating surface is created. This results in excellent sheet release and a low tendency for deposition of hydrophobic stickies on the roll surface. The surface topography of the coating, an important factor for sheet release, is kept constant over its lifetime, even under doctored conditions.

The coating itself is usually a two or three layer design. The functional layer made of ceramics is, by its nature, porous. To ensure a corrosion resistant coating either chemical sealing of the pores is carried out or corrosion resistant nonporous underlayers are applied.

The main applications are for hard press rolls/center press rolls in fast running paper machines.

6.2.4.3.4.2 **Hard Metal Coatings**

Hard metal coatings are carbides, nitrides and borides of transition metals. Carbides of the Cr-group are mainly used for thermal coatings. These wear resistant layers are used for grooved or drilled press rolls providing increased grinding intervals. Optimized formulations of these multiphase coatings are used to coat heated calender rolls. These coatings can be polished to extremely fine surface smoothness. The durability of these systems allows continuous doctoring of the coatings.

6.2.4.3.4.3 **Metals and Alloys**

Metals and/or alloys are sprayed mainly as base or underlayers in combination with oxide ceramics and hard metal coatings. The difference in thermal expansion of the oxide layer and the metallic roll is partly compensated by these layers. The major features of these materials are ductility and toughness, improving the overall coating performance.

Thermal spraying is the build up of a coating on a substrate from particles sprayed at defined temperature and kinetic energy onto the roll surface. The thermal energy is required to melt the powder particles or the wire while the gas flow is necessary for the particle acceleration. Energy sources can be either electrical (arc, plasma) or chemical: H2, propane or kerosene (flame spraying). The melted and accelerated particles hit the surface, re-solidify and build up the coating layer by layer (approx. 10–20 μm/pass).

Arc and plasma spraying can be performed either in vacuum (VPS) or under atmospheric (APS) conditions, but only the latter is applicable for roll coatings. Differences in flame spraying mainly concern the particle velocity. High velocity spraying can be continuous (HVOF) or discontinuous (D-Gun). The plasma coating of a press roll is shown in Fig. 6.14.

Fig. 6.14 Plasma coating of press roll (source: Voith).

6.2.4.3.5 Chromium Coatings

Galvanic chromium coatings are used in special applications for coating the hard calender rolls. The supreme surface finish of an extremely dense homogeneous coating stays is balanced by its sensitivity to damage and limited doctorability. This is why thermal coatings compete in these applications.

6.2.4.3.6 Thermoplastic Covers, Sleeves and Coatings

Pure thermoplastic materials are applied only in niche applications.

Cast or extruded polyamide tubes are used as counter rolls in marking presses, e. g. for cigarette papers, thin PTFE sleeves are applied as hoses on bow rolls. High performance thermoplastic covers are applied in niche calendering applications.

Limitations of thermoplastic materials are their moderate wear resistance and the dimensional instability of thermoplastics under load.

Combinations of thermoplastic coatings with an extremely open layer of a hard metal coating combine the properties of both material classes. Release coatings of PTFE sintered on thermally sprayed hard metal coatings for good release properties are examples of these hybrid coatings. The hard metal underlayer ensures wear resistance, the thermoplastic PTFE layer fills the pores and creates the good release. This type of coating is applied e. g. in the dryer section for the first drying cylinders after the press or size press, as well as for critical guide roll applications.

6.2.4.3.7 Granite Rolls and Calender Paper Shafts

Granite rolls and paper or cotton filled paper shafts are not roll covers or coatings in the usual sense. Here the material which is providing the function is also part of the load bearing structure of the roll itself.

Certain properties of granite rolls or of cotton filled paper bowls were of great advantage to the paper maker and these were also targets for the steadily improved coatings and covers which in turn could provide additional advantages. Granite rolls, for instance, have become history, regardless of their excellent release characteristics, due to the operational risks at high machine speeds or the technical and economic problems encountered when building this equipment for modern paper machines of 10 m width or more. The release properties in the meantime were matched by ceramic coatings or synthetic composite or rubber covers.

In existing supercalenders the competition from composite covers is increasing due to the limited marking resistance of paper bowls.

These roll types have been replaced in most cases by rolls with modern coatings and covers.

6.3
Fabrics for Paper and Board Production
Herbert Holik

Almost throughout the whole paper machine the paper web is in contact with fabrics on one or both sides. Hereby quality issues such as surface characteristics of the paper or board are influenced as well as economic parameters, e. g. by ensuring continuous production by secure web guiding throughout the paper machine:

- In the forming section the forming wire is the auxiliary means of filtration when the suspension is dewatered, resulting in a wet web largely showing the surface characteristics of the wire.
- In the press section this formed web is mechanically dewatered under pressure which can be more than 100 bar. Here low flow resistance of the felt and minimized rewetting are economic factors. Again the surface of the press felt and its local elastic behavior will show up on the web surface.
- In the dryer section the dryer fabric has to ensure the undisturbed web transfer through the section, to enhance contact heat transfer from the cylinder surface to the web and to reduce web shrinkage in CD.

6.3.1
Forming Fabrics
Arved Westerkamp

6.3.1.1 Requirements

Forming fabrics are used in the forming section of the paper machine to dewater the fiber suspension and hence build up a continuous paper web. As web forming is the most critical phase in paper manufacturing, specialised fabrics have to be used to achieve the required paper sheet properties such as smoothness, filler distribution, or printability. The fabrics used for forming are woven on looms, where the machine direction yarns (warps) and cross direction yarns (weft) are interlaced with each other. Dependent on the paper machine, forming fabrics have a length between approximately 25 and 105 m, typically in a gap former the length of the wires would be between 25 and 30 m. As paper machine width has been increasing significantly in the past 10 years, the widest fabrics nowadays would be up to 11 m. The lifetime is between 30 and 120 days, most typically between 30 and 50 days.

The main requirements forming fabrics have to meet are:

- uniform dewatering of suspension exiting the headbox and uniform build up of the paper web
- gentle and uniform web support during intensified web dewatering at foils and vacuum suction boxes
- safe web transport to the couch position
- easy web release
- sufficient hold up, controlled transport and release of the filtrate, the so-called white water.

This means that the forming fabrics have in part to meet contradictory requirements, as for instance:

- the wire surface should be very smooth for uniform paper web support whilst having a large open area for uniform dewatering with low flow resistance
- the free volume in the wire should be large, resulting from thick weft diameters, but this leads to severe water carrying.

All these properties should be constant over the width and length of the individual fabric and over the whole lifetime, which should be as long as possible.

6.3.1.2 **Forming Fabric Design and History**

Historically phosphor-bronze and stainless steel were used to weave forming fabrics. Increasing paper machine speeds as well as demand for improved paper properties led to a change in the raw materials employed which started in the early 1960s with the use of synthetic materials, primarily polyester and polyamide.

By using plastics, product lifetimes increased significantly, while at the same time problems arose such as stretching of the fabric in the machine direction (MD) and narrowing in the cross machine direction (CD). So it became necessary to introduce new manufacturing processes such as heatsetting of the woven structure. Due to the change to plastic materials, welding technology could no longer be used so an entirely new seaming technology also had to be developed .

Since this time, the fundamental manufacturing process chain has remained the same.

It consists of:

- warping (winding up MD yarns on sectional warp beams)
- weaving (interlacing MD and CD yarns)
- heatsetting (locking the knuckles in the weave)
- seaming (forming an endless loop)
- finishing/packing (sanding the surface, width determination, marking).

Increasing paper quality demands (such as improved printability) as well as economical reasons (such as lifetime) and operational reasons (such as water carrying) led to a variety of new forming fabric designs, mainly during the 1970s and 1980s. Starting from the original single layer forming fabrics (forming fabrics with only one warp and one weft system in only one layer), the growing demand for, in particular, increased lifetime led to more sophisticated constructions having a highly abrasion-resistant wear side and a fine paper side (see Fig. 6.15).

As the quality requirements of papermakers were increasing, an improved weave was developed having an additional weft on the paper side, giving more support to the paper fiber (see Fig. 6.16).

Extended width and increased speed of paper machines called additionally for higher cross-direction fabric stability. This was provided by adding another weft system in the center of the fabric (see Fig. 6.17).

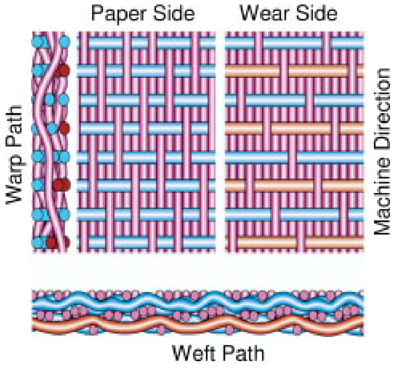


Fig. 6.15 8-Shaft forming fabric with 1:1 paper side/wear side weft ratio and 1 warp system (source: Voith).

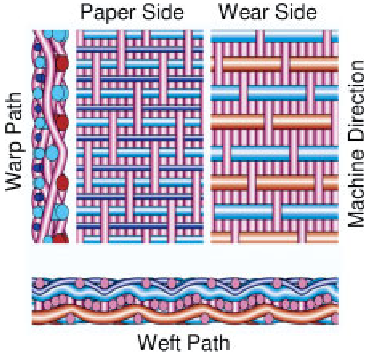


Fig. 6.16 8-Shaft forming fabric with 2:1 paper side/wear side weft ratio and 1 warp system (source: Voith).

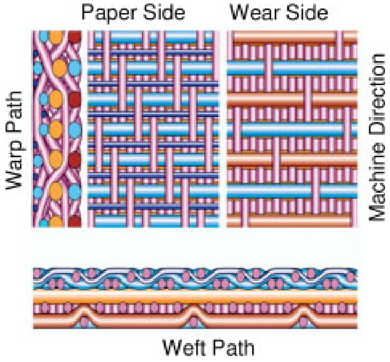


Fig. 6.17 14-Shaft forming fabric with 2:1:1 paper side/center/wear side weft ratio and 1 warp system (source: Voith).

As printing technology and quality demands were advancing rapidly this construction was no longer sufficient to fulfill the printability requirements of the paper industry's customers. Consequently even finer surfaces were developed (see Table 6.2), by using two or more warp systems with a fine top warp and a thicker bottom warp yarn to facilitate sufficient crimping of the wear side weft yarns during heatsetting. This development gave improved printability with similar or even longer fabric life.

Table 6.2 Sales development of forming fabric types by product type – global (source PCA report March 2004).

	1990 (%)	1995 (%)	2000 (%)	2002 (%)	2003 (%)
Triple weft, SSB (sheet support binders)	–	2	7	21	30
Triple layer	5	12	16	12	10
Double layer	69	77	70	61	55
Single layer	26	10	8	6	5

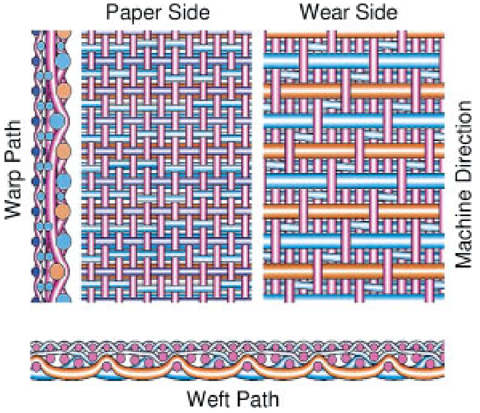


Fig. 6.18 20-Shaft forming fabric with 1:1 paper side/wear side weft ratio and 2 warp systems (source: Voith).

Nowadays modern forming fabrics for use on twinwire formers need to have a low void volume to reduce water carrying, extremely fine and planar surfaces for reduction of surface marking and a homogenous structure to give uniform dewatering across the whole width of the fabric. These designs use weft diameters on the paper side which are between 0.12 and 0.15 mm, on wear side diameters between 0.20 and 0.30 mm. The weft count per cm exceeds 70 as does the warp count (see Fig. 6.18).

6.3.1.3 **Manufacturing Technology**

Forming fabrics are manufactured on weaving looms with a width of up to 15 m, where CD yarns (wefts) and MD yarns (warps) are interlaced with each other. The weft insertion is typically made by using shuttles, projectiles or band rapier systems.

The weft insertion speed on the looms is up to 1200 m min^{-1}. The working principle of a loom is shown in Fig. 6.19.

After the fabrics are woven they are heatset. Here their final properties are determined by applying heat to the fabric while simultaneously stretching it in the MD

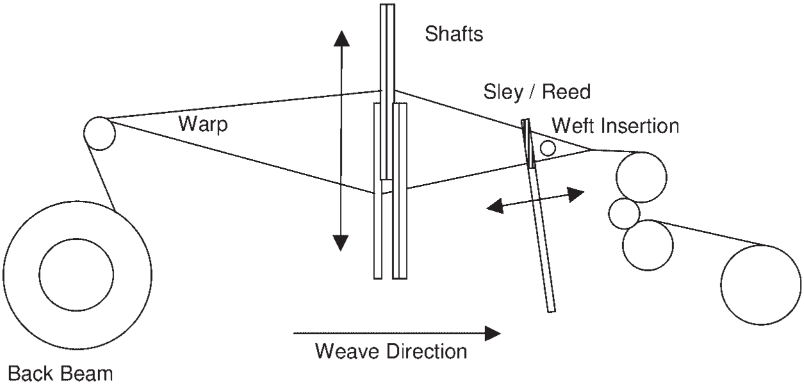


Fig. 6.19 Weaving principle.

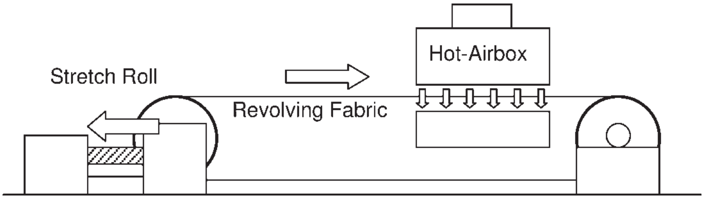


Fig. 6.20 Forming fabric heatsetting machine (source: Voith).

and allowing a controlled CD shrinkage (see Fig. 6.20). The temperatures depend on the materials used but are usually between 180 and 210 °C. During heatsetting the temperature is increased following a time sequence. The stretch achieved in the machine direction is normally between 8 and 12 %, narrowing is up to 9 %. As the fabric is only partially heated in the heating zone, total dwell time depends on the speed (2–4 m min^{-1}) and the number of revolutions.

After being cut for seaming, the fabric is made endless by using a single thread selection weaving technology called the Jacquard system, where the weave is rebuilt in the seam area by turning it through 90°.

In the final finishing, moderate temperature is applied to the fabric in order to stretch out creases. After any protruding yarn ends in the seam area are cut off, the fabric will usually be sealed at the edges (and sometimes ground to enhance smoothness) before it is packed for dispatch as defined by the customers (usually wound on poles in wooden boxes).

Usually forming fabrics are quality checked during manufacture, following the manufacturing process. As scrapping a completed fabric would be far too expensive, qualifying criteria are defined for each manufacturing step. Typical tests would be hysteresis/stress strain tests, profile testing (i. e. mass distribution, cfm, calliper).

During development, other criteria such as bending stiffness, sheer, warp burial, abrasion resistance, etc. are tested.

Comparability of data from all competitors is achieved by using similar test/calculation methods as defined in the standard test procedures by PCA (Paper Machine Clothing Association).

6.3.2
Press Felts

Matthias W. Schmitt

6.3.2.1 Requirements

Press felts are used in the press section of the paper machine and are tailor-made for every particular position in the different press nips. They are in direct contact with the paper surface and strongly influence both the quality of the paper and the economy of the papermaking process. Press felts are porous laminates, composed of a base weave layer with nonwoven layers on either side, which are assembled by a needling process. The caliper of a press felt is in the range of 3 to 4 mm, the length between 15 and 75 m, the weight per area between 800 and 1500 g m^{-2}, and the air permeability between 15 and 450 l dm^{-2} min^{-1} (5 and 150 cfm). The total production of press felts in Western Europe is about 4000 to 5000 tons per year (2003). The average value of press felts is in the range of 55 to 85 € kg^{-1} (2003), depending on the design. The lifetime of a press felt e.g. in a graphical paper machine is between 3 and 4 weeks.

The functions of press felts are

- to pick up the formed paper web from the wire in the forming section and guide it through the press section of the machine
- to support the wet paper web in the press nip and to store the water squeezed out of the web.

The resulting requirements press felts have to meet are as follows:

- smooth paper side surface for good printability of the produced paper and low rewetting (rewetting: water flows back from the press felt into the paper web after the press nip)
- low abrasion at roll side surface
- high storage volume to store the water removed from the paper web
- “constant” dewatering behavior over lifetime including quick start-up behavior (full operating capability within a short time after installation)
- very uniform distribution of nonwoven layers (base weave) in MD and CD for uniform dewatering conditions and in MD to prevent vibrations
- good dimension stability (no width change, no permanent elongation) over lifetime (12 m wide press felts running with a speed of close to 2000 m min^{-1} and with a press load of 120 bar).

The actual requirements put on each individual felt depend on the particular position of its application in the press section and thus focus and felt design may vary.

All press nips in modern paper machines are single or double felted. Shoe presses are mainly double felted. The pick-up felt is in the first press felt position; it has to transfer the wet paper web from the forming wire to the press section. Whilst the loads of the press nips increase from press position to press position of the press section, the diameter of the felt fibers on the paper side surface decreases. Changing from a coarser press felt surface to a finer one enables the transfer of the paper web, due to the increased adhesion by capillary forces and larger contact area.

During its lifetime the press felt runs several million times through the press nip. Reduction in felt thickness, abrasion and contamination are the main reasons why a press felt has to be replaced. Fillers such as calcium carbonate, clay/kaolin, other papermaking additives, and adhesives e. g. from recovered paper deposit in the press felt structure, impeding or even locally preventing water flow. In some cases not even alkaline and acids can re-open the press felt structure.

6.3.2.2 **Press Felt Design and History**

At the beginning of industrial paper making, simple cloths made out of wool were used. In the early sixties these felts were replaced by improved designs based on high-tech textiles. This replacement was necessitated due to the increasing demands (life time more than six days, use of abrasive fillers, higher machine speed).

Figure 6.21 illustrates the principle of a typical press felt structure. The base weave is found in the middle layer of the structure. The base weave is circularly woven; this means that the weft yarn during weaving is the yarn in the length direction of the finished press felt. The warp yarn is the yarn in the cross direction. The weaving loom produces a seamless hose, which can be up to 12 m in width and 70 m in length. Weaving looms can be up to 33 m in width. These endless felts are also called seamless felts and can be used in all applications.

Seamed felts, in contrast, are used mainly in the production of board and packaging and are not endless. They are closed in the paper machine with a seam, produced in a special variation of the weaving process. They are very common in North America (about 60 % of all press felts in NA are seamed felts) and are easier

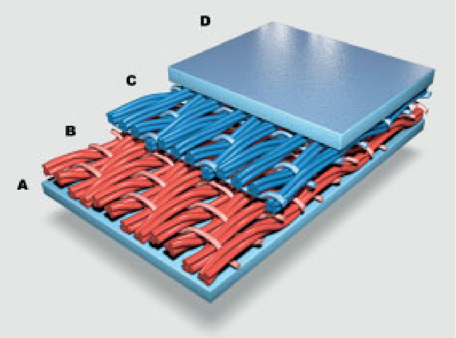


Fig. 6.21 Principle structure of a double-layer press felt A: roll side fiber layer; B: first base weave, C: second base weave, D: paper side fiber layer (source: Voith).

and safer to install in the paper machine. A disadvantage is the marking of the seam, a small stripe in the cross machine direction which may negatively affect the printability of the produced packaging paper or board.

The nonwoven layers on the top and bottom of the base weave consist of staple fibers with different yarn count (3.3 to 100 dtex which means a diameter of 20 to 100 μm). The nonwoven layer on the bottom is in contact with the roll covers and protects the press felt against abrasion. The nonwoven layer on top is in contact with the paper surface and ensures a low and uniform water flow resistance during dewatering of the paper web. A coarser nonwoven layer is used in the first press nips with a higher amount of water removed from the paper web, finer nonwoven layers have use in the further press nips with a lower amount of water extraction.

Polyamide 6 and polyamide 66 are the raw materials used for both the base weave and nonwoven layers. In some cases polyamide 6.10 is used to increase the cross machine stability during the felt lifetime, due to its reduced water absorption.

6.3.2.3 **Manufacturing**

The fiber batt for the nonwoven layers on both sides of the base weave is produced from compressed staple fibers by carding lines. The fiber batt is stabilized in a preneedling machine which makes it manageable for the further production steps. On the finishing needling machine (Fig. 6.22), the top and the bottom fiber batt are connected to the stretched base weave. After 5 to 15 revolutions in the needling stage, the press felt is washed to remove the spin finishing, and decontaminated. The following hot air drying causes both base weave and fibers to shrink, which results in a dense and stable press felt.

Fig. 6.22 Finishing needle machine (source: Voith).

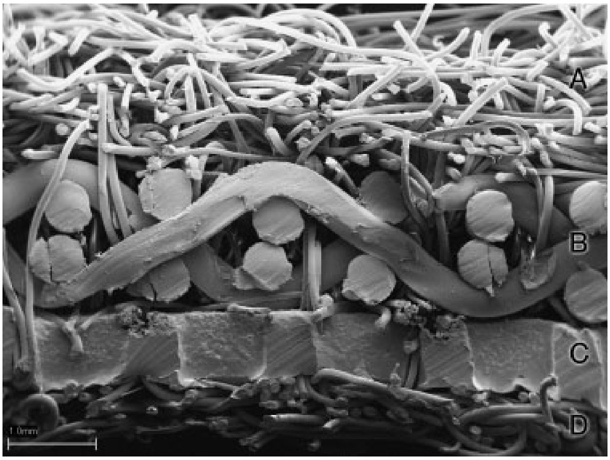


Fig. 6.23 SEM-Image of a press felt cross section A: Top fiber layer, B: Base weave, C: Punched plastic film, D: Bottom fiber layer (source: Voith).

Some press felts have additional special layers, like membranes or punched plastic films as one of the middle layers. These have been introduced to control the water flow and to prevent rewetting or to act as an elastic damper against vibrations (Fig. 6.23).

Quality control during production includes caliper, weight per area and air permeability. As the allowed tolerances are small high production accuracy and uniformity are required.

6.3.2.4 **Transfer Belts**

Transfer belts are a specialty used in the second bottom position of a double shoe press replacing a press felt. These transfer belts guide the paper web from the press section to the dryer section. The requirements transfer belts have to meet are as follows:

- smooth paper side surface for good printability of the produced paper
- impermeable to water to prevent rewetting
- easy pick-up and release behavior of the paper web
- long lifetime (90 to 180 days)

The manufacture of a transfer belt is based on an endless press felt which is covered with a polyurethane or rubber layer on the paper or both sides. Figure 6.24 shows the SEM image of the cross section of a transfer belt with a smooth paper side.

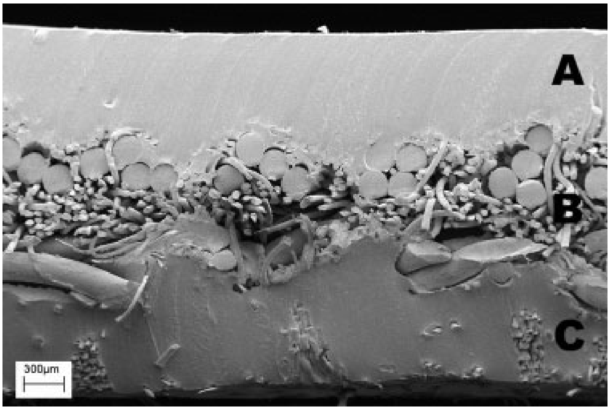


Fig. 6.24 SEM-Image of a transfer belt cross section A: Paper side, B: Base weave, C: Roll side (source: Voith).

6.3.3
Dryer Fabrics
Antony Morton

6.3.3.1 Requirements

Dryer fabrics are utilised as the medium to transport the paper web through the dryer section of a papermaking machine and to press the web to the hot cylinder surface to increase the drying rate. The resulting requirements are :

- Paper contacting surface to have a high contact density for optimisation of heat transfer from cylinder to paper web.
- Smooth paper contacting surface and in-line seam for non-marking of the paper.
- Sufficient vapor permeability to allow evaporative drying to occur freely. The permeability profile must be uniform across the full fabric width to ensure that it does not influence the moisture profile of the paper web. Permeability must not be too high or this will adversely affect web runnability. For example, for high speed single tier type dryer sections web transport and control is critical. For heavier weight packaging grades running at slower speeds heat transfer may be of primary importance.
- Aerodynamic surfaces and low void volume for reduced air carrying to maintain good web runnability and tail feeding.
- Assist in safe transfer of the web between one dryer section and another and within a conventional dryer section.
- Uncomplicated structure to allow effective cleaning.
- High performance and quality running lifetime in hot, humid conditions.
- Dimensional stability and high performance and quality during running lifetime (typically 12–18 months) in hot, humid conditions.
- Safe, fast installation. All dryer fabrics are joined on the paper machine.

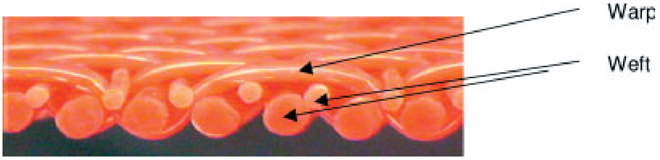


Fig. 6.25 Cross section of a dryer fabric for high speed machines (source: Voith).

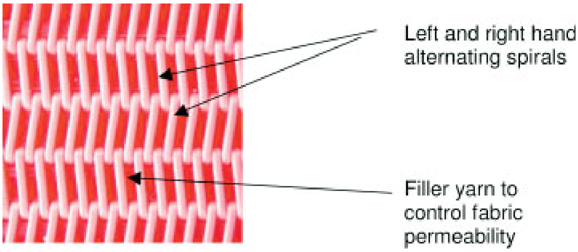


Fig. 6.26 Top view of a spiral fabric design (source: Voith).

6.3.3.2 **Fabric Design and History**

Before the invention of "man-made" fibers, dryer fabrics were made from natural materials such as cotton.

Advances in chemistry saw the invention of polyesters and polyamides. These materials could be spun and formed into monofilaments. Polyester quickly became the preferred choice for dryer fabrics.

State of the art dryer fabrics are made from either polyester based polymer derivatives or polyphenylene sulfide (PPS). PPS material is inert to the environmental conditions encountered in a paper machine. This material would be used for the construction of fabrics running on the hotter, more humid machines, e. g. packaging machines.

Dryer fabrics comprise machine direction (warp) yarns and cross machine direction (weft). These yarns may comprise monofilament, multifilament, spun, plied (twisted) etc. Figure 6.25 shows a dryer fabric suitable for high speed, state of the art paper machines.

Dryer fabrics may also be produced by linking a series of alternating left- and right-handed spiral monofilaments. The spirals are linked together by a connecting monofilament. Figure 6.26 shows a spiral fabric design.

6.3.3.3 **Dryer Fabric Manufacture**

Dryer fabrics are woven as a continuous, flat fabric. The machine direction warp yarns are held on canister spools at the back of the loom and passed through a series of "reeds" and "sheds" (spacers and pattern makers). During the weaving process sheds are raised and lowered according to the desired final weave pattern.

At each shed motion a weft system is fired through the so formed "warp tunnel". The reed then pushes the newly formed section tightly into line with the rest of the fabric body.

The fabric is removed from the loom and relaxed and stabilised through the use of heat and tension. A typical heat setting temperature is 180–200 °C for dryer fabrics. The tension is set according to the running tension on the paper machine section to which the fabric will be applied.

A seam is then created either from the machine direction yarns looped around themselves, or by insertion of a spiral yarn around looped warp yarns.

In the case of a spiral link fabric there is no weaving to be done. The left- and right-handed spirals are formed around a hot "mandril". These are then meshed together and joining wires used to link adjacent spirals. Spiral fabrics may or may not be "stuffed" with filler material in order to control their permeability.

Dryer fabrics typically range between 1.2 and 2.5 mm in thickness, depending on the fabric design required for the application. Their weight is typically 800–1500 g m^{-2}.

Dryer fabrics are typically supplied through the application range 60 cfm to around 100 cfm.

6.4
Forming Section
Herbert Holik

The goal of the forming section is to produce a continuous wet paper web of a certain basis weight and of the required uniform quality parameters in both cross machine (CD) and machine directions (MD). This is accomplished by

- feeding a constant volume rate of suspension of constant consistency and furnish ratio to the headbox (approach flow system)
- equally distributing the suspension in the cross direction of the paper machine, accelerating it and transferring a suspension jet of high uniformity to the formation section (headbox)
- dewatering the suspension and hence forming an endless web (wire section).

6.4.1
Approach Flow System
Andrea Stetter

The approach flow system is the connection between stock preparation and the headbox of the paper machine. It is responsible for metering and mixing the different stock components, diluting and blending them with other components like fillers, chemicals and additives and after possibly cleaning, deaeration and screening, finally feeding them to the headbox [1]. A constant flow rate of the suspension at constant pressure, constant consistency and compound must be ensured in order to obtain a uniform basis weight distribution in the paper. This is done by

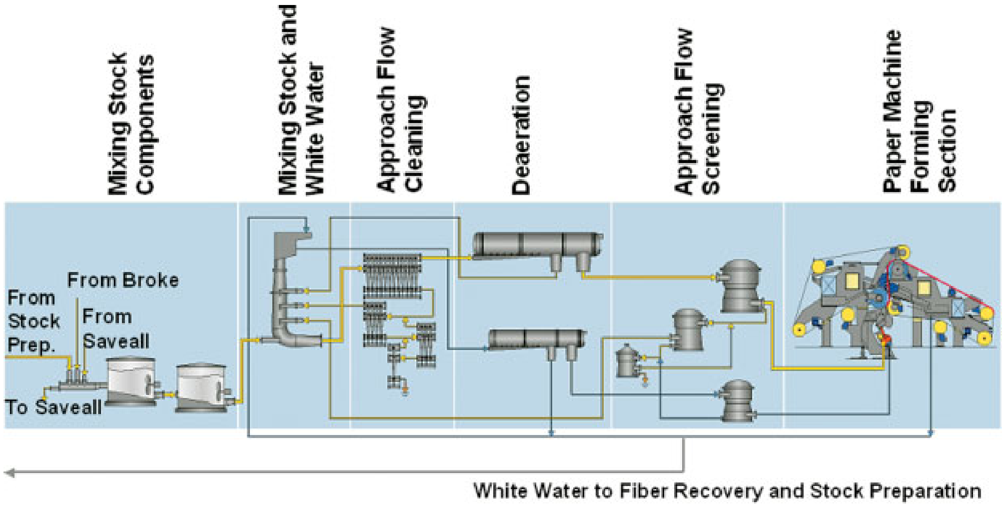


Fig. 6.27 Approach flow system for a modern high speed paper machine (source: Voith).

- constant metering/proportioning of the components, particularly of thick stock and white water
- uniform, effective mixing of all suspension components, particularly of thick stock and white water
- constant feeding of the suspension to the headbox.

Final cleaning and screening of the suspension are applied in many cases to prevent wear or damages in the paper machine, for instance clothings, foils, rolls etc., and to improve the final paper quality with respect to cleanliness. In some installations, for instance for board and packaging production, part of the stock preparation tasks are, for economic reasons, taken over by the approach flow system. Deaeration devices are also often installed for runnability and quality purposes. Special engineering and automation measures support the necessary high constancy of the suspension fed to the headbox. The main process stages of an approach flow system for modern high speed paper machines are shown in Fig. 6.27. In the following the individual stages of an approach flow system and its equipment are described in detail.

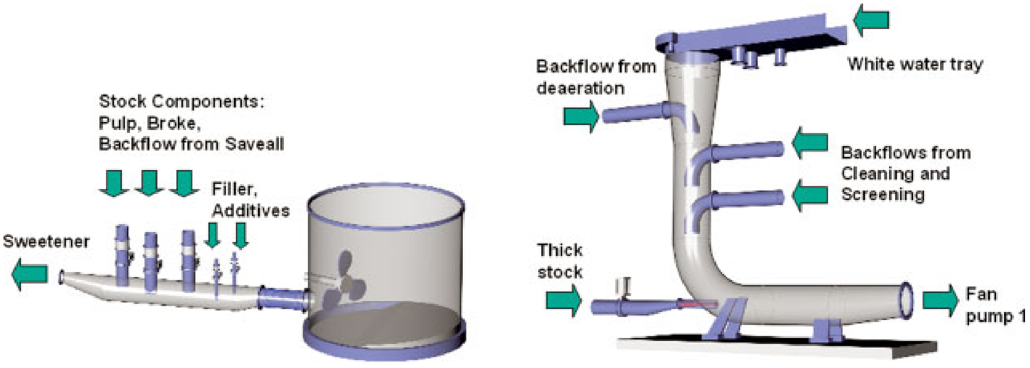
6.4.1.1 **Metering/Proportioning and Mixing**

First the various furnish components (e.g. fiber stock and fillers) including stock from fiber recovery and broke treatment systems are metered and mixed in the desired proportions. Apart from the required solids ratio of the individual components, constant total stock consistency which usually lies in the range of 3 to 4% must be ensured. Therefore a constant consistency of each stock component is an issue. Subsequently the mixed stock is diluted with white water I to a consistency of 0.1 to 1.5% (depending on the paper grade and machinery). Ideally the suspension will now have a constant consistency and composition. All variations in consistency will result in basis weight deviations in the paper web of the same order of magnitude.

In the past, big buffers, i.e. stock chests and water silos, with agitating devices were used in order to fulfill the demands on constancy. In modern machines the volumetric throughput to the headbox can be about 1.5 $m^3\,s^{-1}$ or more. This means that the necessary buffer sizes would require huge investments and excellent mixing. Deaeration in the tank is also more difficult as the air bubbles have to rise upwards against the suspension flow direction. As the demands on paper machine efficiency are steadily increasing, grade changes consequently should be as quick as possible. This cannot be achieved with big buffer volumes resulting in long deadtimes. Therefore the metering and mixing of different stocks as well as the metering and mixing of stock and water is crucial in order to avoid large tanks and to ensure constant suspension feeding at the same time [2–5].

6.4.1.1.1 Mixing of Stock Components

In modern approach flow systems the conventional sequence of mixing chest and machine chest are either minimized in volume or partly replaced by special mixing devices. These may consist of a hydraulic mixer followed by a chest to ensure the complete mixing of all stock components (Fig. 6.28). Here the different furnish components are fed tangentially into the mixing pipe in the order of dewatering behavior and filler content: the component with the best dewatering characteristics being fed first, so it can be also used as sweetener stock for the saveall unit in the



State-of-the-art unit for metering and mixing of stock components

State-of-the-art unit for mixing of stock and white water

Fig. 6.28 Metering and mixing in the approach flow system [2] (source: Voith).

case of a disc filter installation (see Section 5.4.1.). The remaining small consistency variations may be further reduced in the following mixing chest [2–5].

6.4.1.1.2 **Mixing of Stock and White Water**

The huge volumes of the white water silos can lead to microbiological pollution and also result in long process deadtimes. The silos therefore have been re-engineered and replaced by stock-water mixers, as shown in Fig. 6.28. One task of these mixers is to re-combine backflows e. g. from deaeration, cleaning and screening, by adding them to the white water I before the thick stock injection in the vertical collector. The kinetic energy of the back flows is used to pre-mix the streams. The thick stock is injected in the center at the lower part of the mixer. Good mixing of the thick stock is provided by optimum velocity difference between thick stock and white water at injection [2–6].

6.4.1.2 **Final Cleaning and Screening**

Depending on the process design of the preceding fiber preparation plant, the final cleaning and screening in the approach flow system may only have a "police function". In this case the stock preparation system includes sufficient cleaning and screening capacity. On the other hand, especially in packaging paper mills, for cost reasons screening and cleaning are often partly or completely done in the approach flow system.

6.4.1.2.1 **Final Cleaning**

Cleaning is done after thick stock dilution with hydrocyclones (see Section 4.2.4) in a multistage cascade system in order to remove small dense debris. The debris can be sand, grit, shives, pitch or other dense particles. In the case of coated paper production, the end-stage of the cleaner cascade is very rich in pigments or filler. Due to the separation principle of the cleaners, especially coarse filler particles and agglomerated pigments from coated broke are rejected. The amount of rejects can be reduced by recovering these minerals [1].

6.4.1.2.2 **Final Screening**

Even if all stock components including broke were previously fine-screened, bundles and lumps can be created thereafter by deposition. Secondary stickies and pitch particles may also form in the paper machine system. Final screening is therefore done directly before the headbox with pressure screens (see Section 4.2.3). In most cases the screen baskets are slotted. Due to their position in the process, the screens exhibit special characteristics, i. e. very low pulsation generation by using special rotary elements, polished surfaces to avoid deposits, high availability by simple design and special design to prevent air pockets [1].

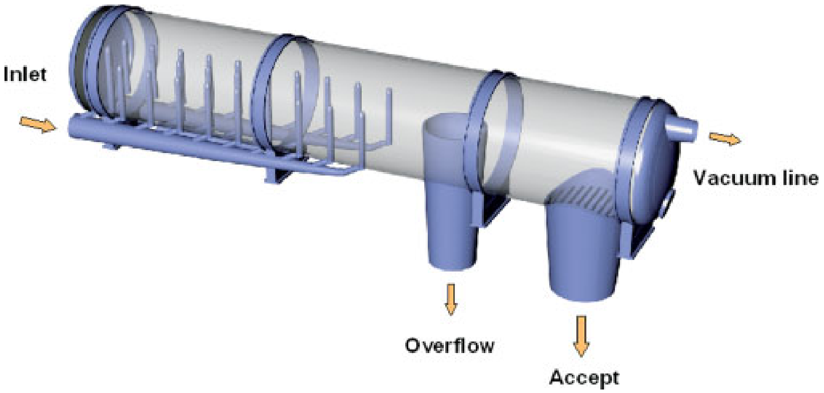


Fig. 6.29 Deaeration tank [2] (source: Voith).

6.4.1.3 **Deaeration**

Air in the system may cause problems during paper production. It can lead to reduced machine runnability by reducing the dewatering capacity and sheet breaks, to decreased pumping and screening efficiencies, to foam problems and subsequently accumulation of hydrophobic and sticky material as well as to increased microbiological activity. Paper quality can also be negatively affected by poor formation, by pinholes and by dirt inclusions. As air may lead to cavitation and pressure and flow velocity variations, poor basis weight profiles can result. Air intake in water and stock happens through splashing in the forming unit of the paper machine, in the white water tray and in the chests.

Deaeration usually refers to physical (vacuum) treatment of the stock suspension after dilution and/or of the dilution water (white water I). It is mainly applied in high speed paper machines as well as for fine paper production. The vacuum treatment takes place in deaeration tanks, like the one shown in Fig. 6.29. Here air is desorbed when operating at the boiling point, and is effectively driven out by creating a large surface while impinging the suspension onto the interior surface of the tank. A sufficiently high vacuum is used so that boiling can take place without the need to heat the suspension. The minimum required vacuum therefore depends on the feed temperature. For a feed temperature of 50 °C, the vacuum in the deaeration tank is about 0.87 bar. The overflow of the deaeration tank enables hydaulic decoupling of the system, so that any pump pulsations from the first (i.e. cleaner feeding) fan pump do not affect the down-stream system [1, 2, 4, 5]. Another possibility for physical deaeration is to use special centrifugal degassing pumps where, in a rotating chamber, the gas bubbles are removed from the stock suspension under the action of centrifugal forces and are eliminated from the system [3]. Chemical deaeration with defoaming agents is also possible (see Section 3.7.3).

6.4.1.4 Engineering

A good performance of the approach flow system is not only due to its components but also to a large extent due to the system design as a whole. For instance the layout of piping and chests has great influence on the stability of the system. This means for instance that all pipes should have a positive gradient in the flow direction, all flows should have a defined flow direction, and suspension velocities in pipes should be high enough in order to prevent de-mixing, build-up of bacterial slime or fiber stringing. In many cases polished surfaces are chosen in order to prevent deposits. Dosage positions (e. g. when shear sensitive and/or different chemicals are used) and dosing techniques (for instance multiple injectors) for chemicals have to ensure good and fast mixing and high efficiency of the chemicals. [1, 2]

6.4.1.5 Automation

Automation by fast, stable and accurate control loops for consistency, flow, pressure and level is elementary for providing the necessary constancy in the approach flow system. Variations in pressure for example will mainly directly influence the MD profile whilst stock consistency deviations will affect both CD and MD basis weight profiles. In addition the retention on the paper machine and the chemical conditions of the water systems must be kept constant. Here a retention control loop is standard in many applications keeping the white water consistency constant by adapting the quantity of retention agent added. Controls for filler, color, air content, cationic demand or zeta potential are also available today. Combining the different controls to a total control concept will lead from purely functional controls to control systems which also address quality and production issues.

6.4.2

Headbox

Herbert Holik

The goal of the headbox is to equally distribute the suspension in the cross direction of the paper machine and to supply a suspension jet of high uniformity and about machine speed to the wire section. Here dewatering of the suspension takes place. The high uniformity of the jet exiting the headbox has to be ensured by adequate distributor and nozzle layout, design and manufacture. The required high uniformity relates to equal velocity and thickness as well as to equal direction of the jet, both over the whole machine width (CD) and over time. Thus the headbox is a key element in the paper machine defining many important quality parameters of the finished paper.

The suspension is delivered from the approach flow system through piping that has a circular cross section. The flow must be turned and distributed uniformly and with great accuracy across the full width of the headbox. It must then flow out of a narrow slit (normally called a slice, 6–25 mm in height, and more in certain applications) that can be more than 10 m wide. In modern headboxes, this uni-

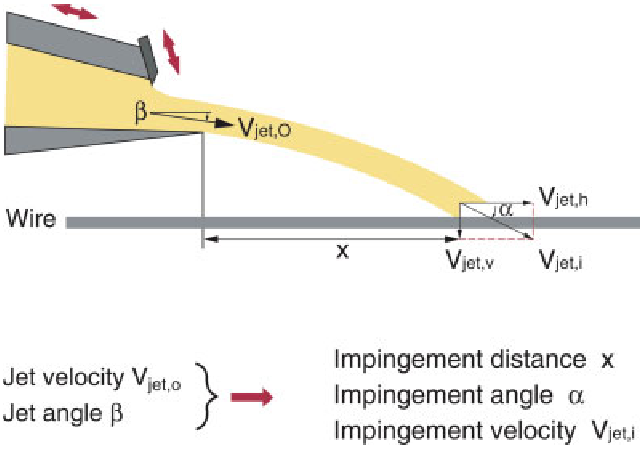


Fig. 6.30 Jet impingement parameters depending on jet exit conditions (source: Voith).

form distribution across the width is achieved by passing the suspension through a distributor on the backside of the headbox to at least one perforated plate. The many individual streams thus produced are reunited to form a single uniform stream in the nozzle, which then provides a constant jet of suspension. Essential requirements for good sheet formation are the breaking of fiber flocs that have already formed, and the prevention of flocculation, at least for a short time until the suspension is transferred to the wire. For this purpose, turbulent shear forces are generated in the suspension. The turbulence intensity should be adjusted to the stock type, and the wavelength (i. e., effective length) should be short. In modern headboxes (high-turbulence headboxes) turbulence is produced by friction in tubes and channels, or by changes in cross section as carried out in step diffusors.

In the headbox nozzle, the suspension is accelerated to approximately machine speed. The thickness of the jet and, therefore, the amount of suspension is usually adjusted by swinging the upper wall of the nozzle. The slice at the nozzle outlet is often limited by a bar, which can be adjusted to an accuracy of ca. 1/1000 mm by means of spindles. This bar can be adjusted locally across the width; this has been used or is still used in older headboxes to compensate for deviations in the cross machine weight profile of the web. The direction of the jet in the machine direction can be influenced by horizontally shifting the upper wall of the nozzle. In this way, the point and angle of impingement of the jet on the wire can be adjusted (Fig. 6.30).

A wide variety of headbox designs is found in the paper industry. This is due to the many different paper machine designs and forming sections resulting from individual production requirements of the various grades. Figure 6.31 shows some examples of earlier as well as more recent headbox designs for different applications. The pond slice headbox (A) is open and no longer meets the modern de-

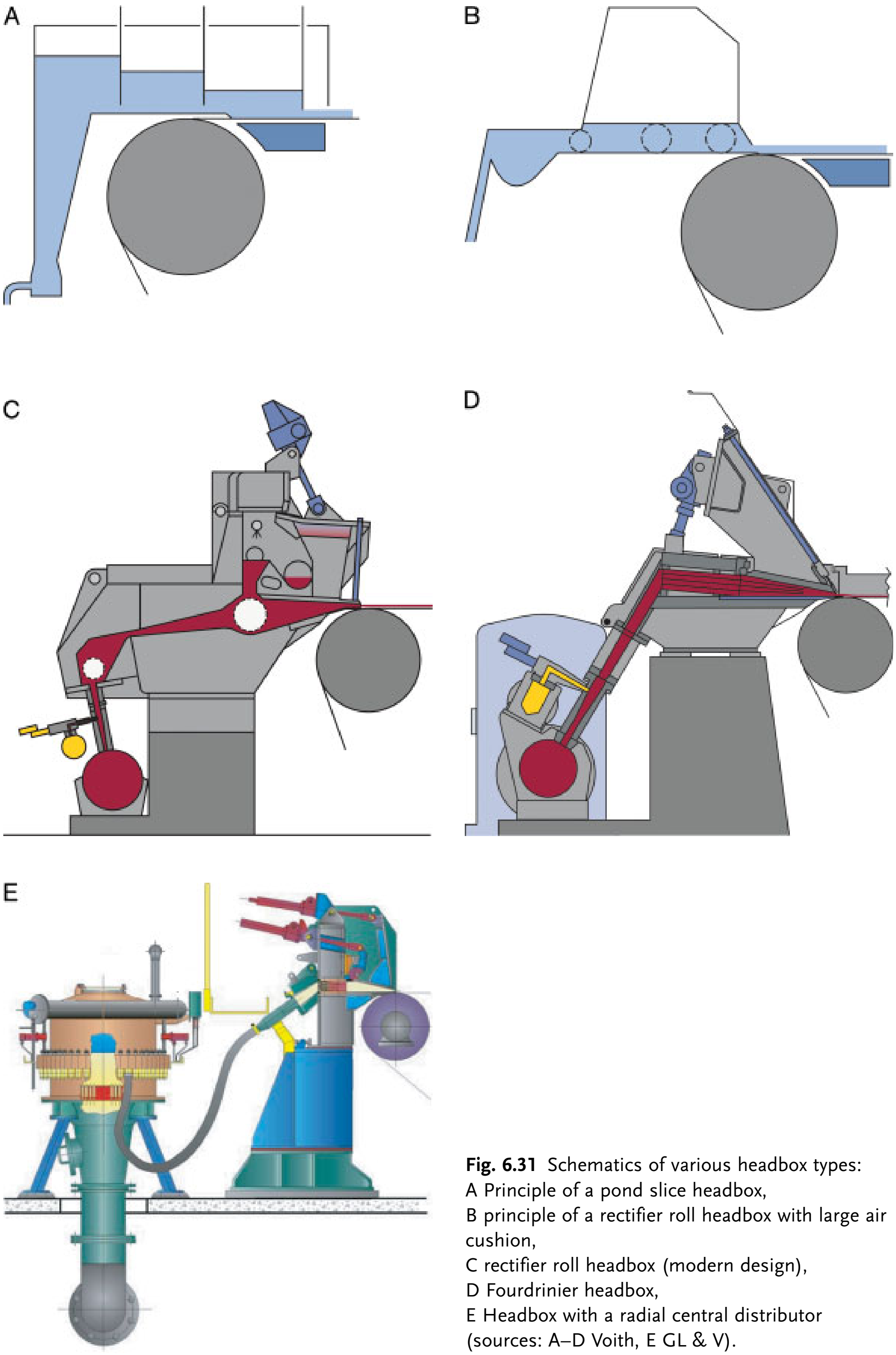


Fig. 6.31 Schematics of various headbox types:
A Principle of a pond slice headbox,
B principle of a rectifier roll headbox with large air cushion,
C rectifier roll headbox (modern design),
D Fourdrinier headbox,
E Headbox with a radial central distributor
(sources: A–D Voith, E GL & V).

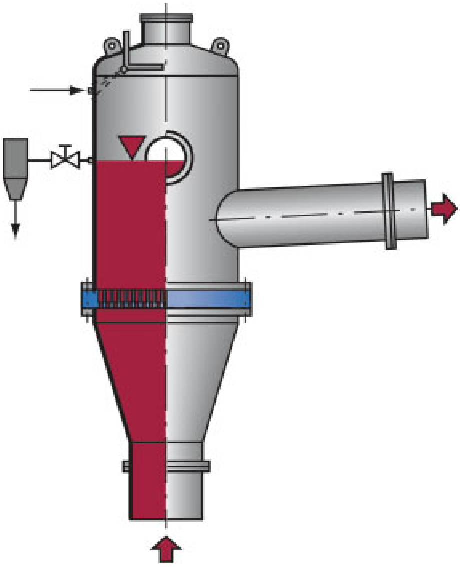


Fig. 6.32 Pulsation damper with perforated plate and hydro-pneumatic tank (source: Voith).

mands on throughput and speed. The essential functional elements for distribution and dispersion in evener roll headboxes (B) are the perforated rectifier rolls that rotate in the suspension. The suspension passes through these rolls, thereby generating shear forces. The air cushion above the suspension is usually under pressure (air cushion headboxes). This headbox principle has been improved and is still used in special cases for lower throughputs and machine speeds (C). The state-of-the-art high-turbulence headboxes (also called hydraulic headboxes) have a closed suspension guidance without a free surface. Here a headbox for Fourdrinier machines (D) can have a separate pulsation damper (Fig. 6.32) or the dampening system may be integrated in the headbox. A single-layer headbox and a two-layer headbox, both for gapformers, will be described later in detail. Another headbox design (E) makes use of a centrally positioned tank reducing pulsations and distributing the suspension to a plurality of flexible pipes of equal pressure loss ending at the backside of the headbox equally distributed across the width.

The mean basis weight (g m^{-2}) to be produced is related to the mean volumetric flow through the nozzle and the consistency of the suspension. If the consistency has to be lowered (or increased) for operational reasons at a given basis weight, a higher (lower) volumetric flow is required to obtain the same basis weight. This is reached by opening (closing) the nozzle. The headbox control device keeps the preset jet velocity constant by adjusting the headbox pump motor speed.

Process machines installed upstream of the headbox, for instance the fan pump or the screen, generate pulsations which may be higher than allowed (for instance less than 1% deviation). In such a case a pulsation damper reducing pulsations over a wide frequency range should be installed ahead of the distributor of the headbox or integrated into the headbox. Figure 6.32 shows an example of such a damper with a perforated plate to reflect incoming pulsations, the upper part of the tank being partly filled with air thus acting as a hydro-pneumatic damping system. This is to absorb and dissipate most of the remaining pulsation energy passing the perforated plate.

The delivery of a constant jet velocity timewise and over the machine width is a basic paper technological requirement. The velocity ratio of suspension on the wire and the wire itself affects web structure by the degree of fiber orientation. Assume that the fibers in the suspension jet are randomly orientated in the three dimensions, the suspension flow on the wire is parallel to the machine direction and no velocity difference is given to the wire itself. The fibers then remain randomly oriented on the wire. When there is a certain velocity difference between the suspension and the wire, the amount of fibers laid down in the machine direction during web formation is greater than in the cross machine direction. The fibers tend to align mainly in the direction of the velocity difference between the suspension and the wire, be it drag or rush. This results, for instance, in differences in the web characteristics, such as tensile strength or stiffness, in MD versus CD. It also influences shrinking behavior during web drying and expansion behavior when the finished paper sheet is exposed to heat or moisture. This might be of interest for instance in a copy machine or during printing in the press room. Figure 6.33 gives an example of how higher (rush) or lower (drag) suspension velocity on the wire in relation to the wire itself affects formation quality and the MD/CD tensile strength ratio.

As today's machine speeds exceed 2000 m min^{-1} the pressure in the nozzle chamber is about 5 bar and above. For operational reasons, especially for improved dewatering characteristics in the wire and press sections the suspension is fed to the headbox at elevated temperatures, for instance at 40 to 75 °C, and in special applications up to more than 90 °C. Furthermore a headbox of more than 10 m width has a high dead weight. All these parameters induce a strong deflection of the originally straight structure of the headbox, and on the most sensitive parts

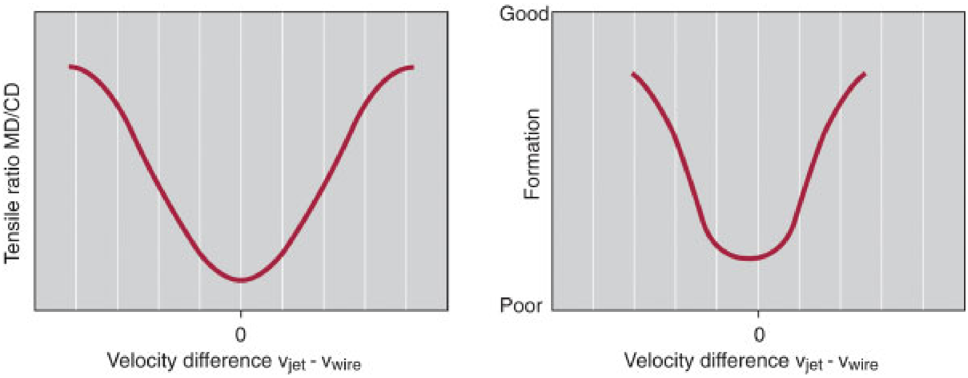


Fig. 6.33 Formation quality and MD/CD tensile ratio vs. velocity difference between suspension on the wire and the wire itself.

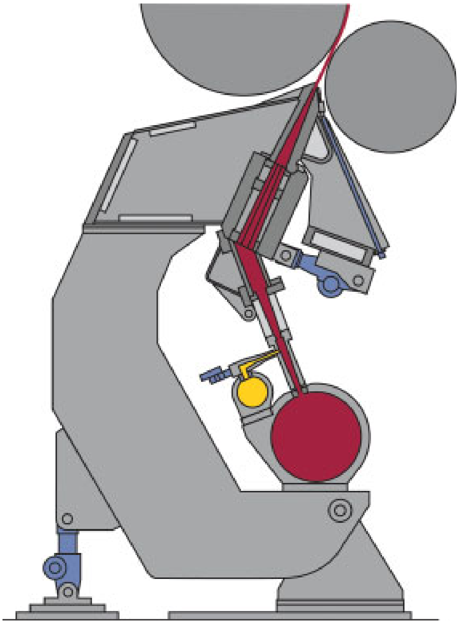


Fig. 6.34 State-of-the-art headbox with dilution control for a gap former (source: Voith).

which are the nozzle chamber and the slice blade. These deflections would negatively affect the uniformity of the suspension jet exiting the headbox. To avoid these problems the headbox design has to overcome these influences.

Figure 6.34 shows a typical design of a state-of-the-art headbox for twin wires meeting the high demands of fast running paper machines. It consists of

- the header redirecting the suspension flow into the machine direction and equally distributing the suspension across the machine width
- a stilling chamber for coarse turbulence reduction and further equalizing of the CD suspension distribution
- a turbulence generator built up in one or several rows which has to break up fiber flocs and feed the suspension equally to the nozzle,
- the nozzle to accelerate the suspension up to the required velocity
- lamellas for optimum jet surface quality and random fiber orientation in the suspension
- the slice blade at one of the nozzle lips to finally form the jet
- two heated chambers, one for the top lip and one for the turbulence generator, to eliminate negative thermal influences on the CD structure uniformity of the nozzle chamber
- two supports across the width carrying the dead weight and ensuring that the headbox structure stability is independent of machine width
- a controlled pressurized chamber at one lip (or both lips) of the nozzle chamber to counteract the bending impact of the nozzle chamber pressure on the CD structure uniformity.

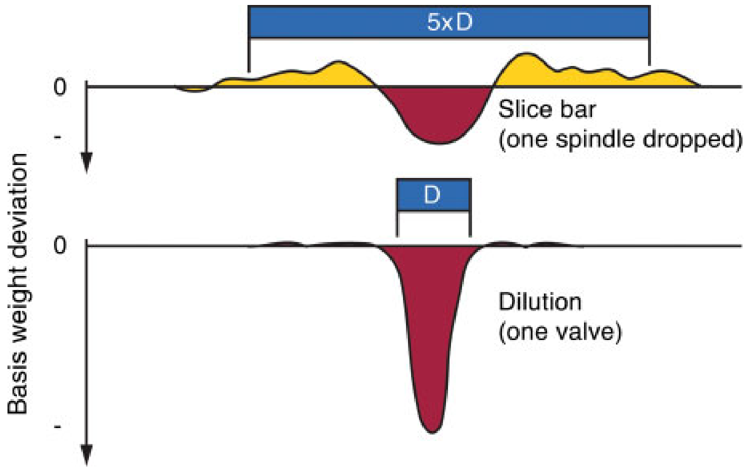


Fig. 6.35 Effect of local slice adjustment and local dilution on basis weight profile (source: Voith).

The deviation from the desired CD basis weight has to be a minimum, for instance 0.5%. In order to obtain such a high accuracy a control device is required. Furthermore, for operational reasons, the ideal CD basis weight profile should often have somewhat lower values at the edges. As a standard for a long time in the past – and still today – the CD basis weight profile has been and is controlled by a slice blade. This is equipped with a lot of spindles across the width with a standard spacing between these spindles of about 75 mm. Adjusting one or more spindles the nozzle opening is locally reduced or increased according to the requirements. The effect on the basis weight profile is shown in Fig. 6.35. It demonstrates that at the position of the lowered spindle the basis weight is reduced to a certain degree, whereas in the neighborhood at both sides of the adjusted spindle the local basis weight is increased. Furthermore a larger width in the basis weight profile is affected compared with the width of slice lip adjustment. This kind of response is induced by local cross flow of the suspension in the nozzle when adjusting the local slice opening. The cross flow in the exiting jet also has a disadvantageous impact on other quality parameters of the formed web such as surface markings and out-of-plane defects.

In the last two decades a different kind of CD basis weight control principle, the dilution principle, has been developed and has become the state-of-the-art control device. Here a constant “high consistency” volumetric flow is fed to the headbox where it is mixed with a “low consistency” stream. At positions across the width where a lower basis weight is required, the “low consistency” stream is increased at a constant local overall flow rate. If the local basis weight should be increased the local “low consistency” stream is reduced at a constant local overall flow rate. The minimum spacing of the control modules can be as small as the modules of the construction, for graphic paper grades modules of about 60 mm are standard. Thus a very narrow area can be influenced.

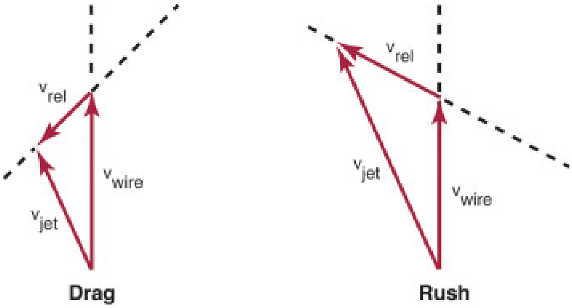


Fig. 6.36 Influence of jet velocity, jet angle and wire speed on main fiber orientation.

A major advantage of the dilution principle is that CD profiles of main fiber orientation can be rectified (Fig. 6.36). As mentioned before local slice bar adjustment causes cross flow in the nozzle chamber and in the exiting jet. Even a small angle of the jet velocity vector against the machine direction results in a large main fiber orientation angle. The main fiber orientation angle describes the direction of the plurality of the fibers in the paper and can be measured by laser or by ultrasonic devices. It has an impact on other important paper properties.

The example in Fig. 6.36 shows that a deviation of 1° in the jet at 1000 m min^{-1} means a CD velocity component of 10 m min^{-1}. Together with an MD velocity difference between the suspension on the wire and the wire itself of for instance 40 m min^{-1}, an angle of 14° in the resulting velocity vector on the wire occurs. This angle of the velocity factor defines the orientation of the plurality of the fibers which are laid down during dewatering of the suspension in the forming process. At a jet velocity of 2000 m min^{-1} and again 1° deviation in the jet the CD component is 20 m min^{-1}. With the same MD velocity difference between the suspension and the wire it adds up to an angle of about 27° of the main fiber orientation. This demonstrates the necessity for the application of high level fluid dynamics knowledge in the design and construction of a headbox. On line control of the quality parameter main fiber orientation is currently being developed, with a special challenge being the on line measurements.

In recent years some multi-layer headboxes (Fig. 6.37) have been installed in tissue, fluting and graphic paper production. Here two separate suspension lines with different furnishes are fed to the headbox, which in principle consists of two headboxes in one housing. The two suspension lines are kept separate up to the nozzle end. Only in the jet itself and during dewatering can mixing of the two suspensions occur. A multi-layer headbox is advantageous

- for multi-ply production by saving one of the forming sections
- in single-ply production by hiding inferior furnish under the more expensive cover furnish.

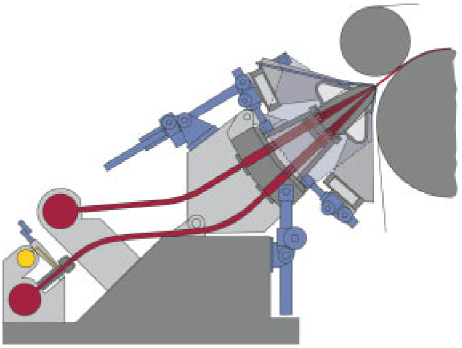


Fig. 6.37 Two-layer headbox (source: Voith).

6.4.3
Wire Section

In the wire section, a fiber web is formed out of the suspension supplied by the headbox. The kind and quality of suspension delivery from the headbox to the wire has a strong impact on the quality of the paper web formed. Therefore headbox and wire section – together with the approach flow system – have always to be regarded as one unit. The main objectives of the wire section are:

1. Extensive separation of fibers from water (drainage)
2. Well-ordered deposition of the fibers on the wire (oriented shear)
3. Prevention of too much fiber flocculation (turbulence).

The separation of the fibers from water is a combined filtration and thickening process. During pure filtration a filter cake is built up above the auxiliary filter layer whereas the consistency of the suspension above the filter cake remains the same as before. Pure thickening means that the consistency of the suspension as a whole is increased. In paper web forming filtration prevails. The water extracted from the suspension contains fines, fillers and fibers and is called white water.

The driving forces for dewatering the fiber suspension can be hydrostatic, vacuum or mechanical:

- The height of the suspension above the wire including additional pressure application.
- A vacuum behind the wire, produced by direct vacuum application or by the hydrodynamic effect of dewatering elements.
- The pressure generated by the tension of the outer wire covering the suspension when running in a sandwich over a curved surface which may be a roll or a curved shoe. The pressure p exerted on the suspension is $p = S/R$ with S representing the wire tension in N cm^{-1} and R the radius in cm. p has to be larger than the centrifugal forces acting on the suspension and on the wire. Due to the centrifugal acceleration $c = v^2/R$ a suspension thickness of t represents a suspension height of c^*t/g in the gravity field. The pressure acting against the inner wire is reduced by this amount, which is remarkable at high machine speeds.

Since the days of Robert, Donkin and Fourdrinier a wide range of web forming principles has been developed and used for different purposes (Fig. 6.38):

- Fourdrinier wire section, the most common forming principle in the past and which has been continuously improved since its early invention, is a horizontal forming wire supported by different kinds of dewatering elements.
- Mold former where the wire covers a water-permeable cylinder rotating in a vat filled with suspension.
- Suction former, forming the web within a short section of the circumference of an open cylinder covered with a wire.
- Inclined wire, forming the web on a straight inclined wire supported by dewatering boxes with a controlled height and pressure of the suspension in the forming zone.
- Twin wire hybrid former where a rotating second wire is mounted on top of the fourdrinier wire, dewatering part of the suspension through the top wire.
- Twin wire gap former, which is the state-of-the-art wire section in high speed web forming, mostly dewatering the suspension to both sides.

  The different elements used in the wire section for wire support, dewatering and formation improvement are:

- The forming board, positioned at the beginning of the fourdrinier wire where the stock jet impinges. It consists of several blades or bars arranged closely together. Thus, it performs gentle, initial drainage of water from the suspension. Too intensive drainage at this position would increase drainage resistance in the following drainage elements because of excessive compaction of the formed fiber mat.
- Table rolls (Fig. 6.39), used in the fourdrinier section for drainage and to generate turbulence. Pressure is developed in the upstream wedge between the wire and roll, and a vacuum is induced in the downstream nip. With increasing machine speeds the pressure and vacuum pulses increase over-proportionally and thus limit the application of table rolls to machine speeds of about 500 m min^{-1}.
- Dewatering foils (Fig. 6.40), used on both the fourdrinier wire and twin wire formers. They have an acute-angled leading edge to doctor off the water hanging under the wire and a slope on the downstream side (foil angle of 0–3°) which induces a vacuum for drainage. Apart from wedge-shaped foils, step foils are also in use.
- Foil boxes which combine several foils in one unit. In addition, the foil box can operate under controlled vacuum (vacuum foil box).
- Blades being “foils” with zero foil angle, whereas counter blades are blades which are not fix mounted but are pressed with adjustable forces perpendicularly to the wire. Their main target is to doctor off the water and to improve formation quality.
- Wet suction boxes, which are dewatering elements that are located in front of the water line. They operate under vacuum and, in contrast to suction boxes, they mainly remove white water from the suspension. The water line is a line beyond which no free water is present on the surface of the freshly formed web and that is discernible on the fourdrinier wire by a change in light reflection.

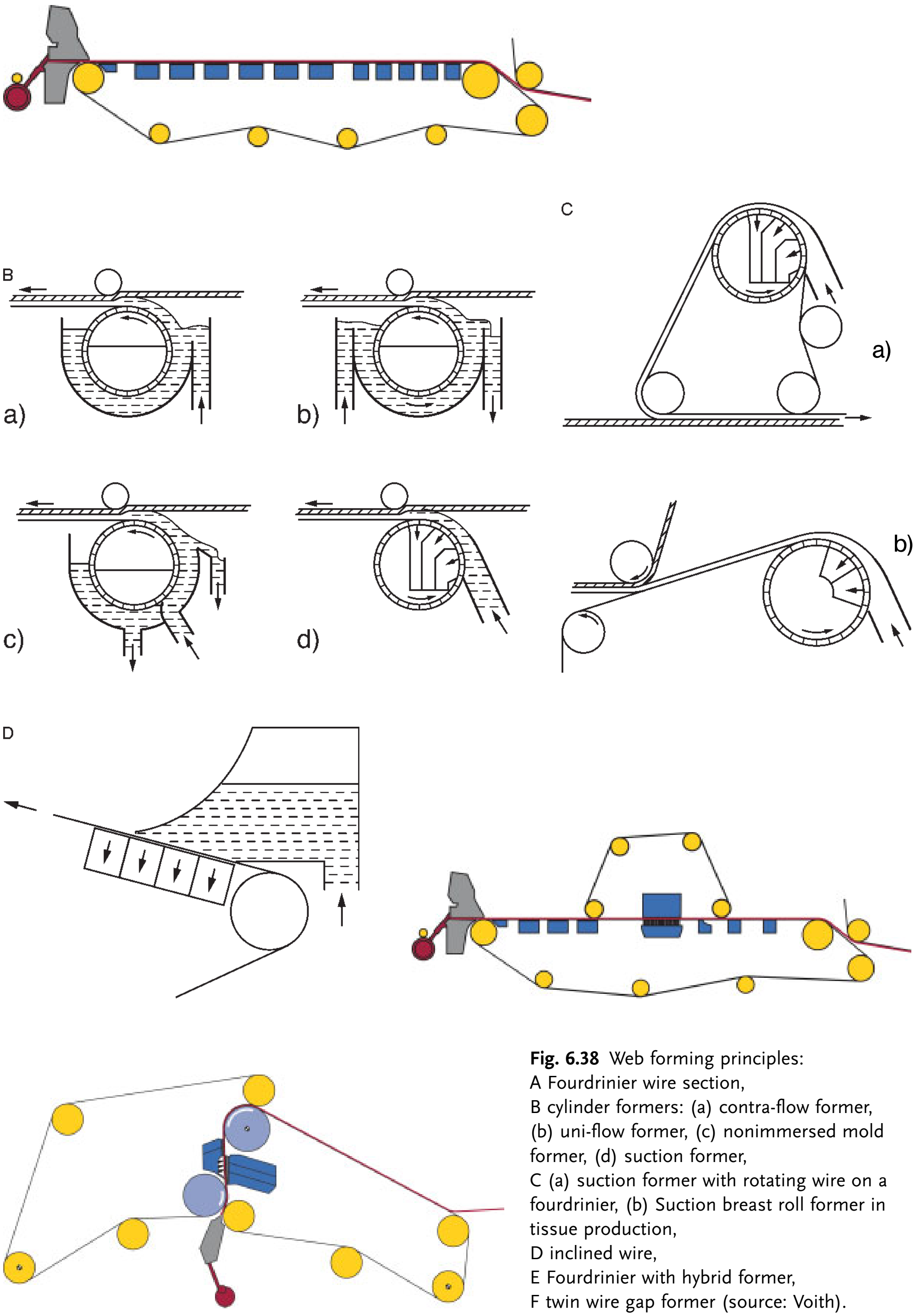


Fig. 6.38 Web forming principles:
A Fourdrinier wire section,
B cylinder formers: (a) contra-flow former, (b) uni-flow former, (c) nonimmersed mold former, (d) suction former,
C (a) suction former with rotating wire on a fourdrinier, (b) Suction breast roll former in tissue production,
D inclined wire,
E Fourdrinier with hybrid former,
F twin wire gap former (source: Voith).

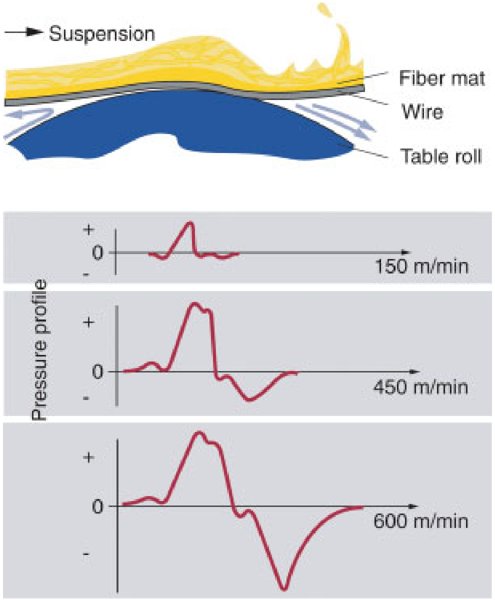


Fig. 6.39 Schematic and operation mode of table rolls.

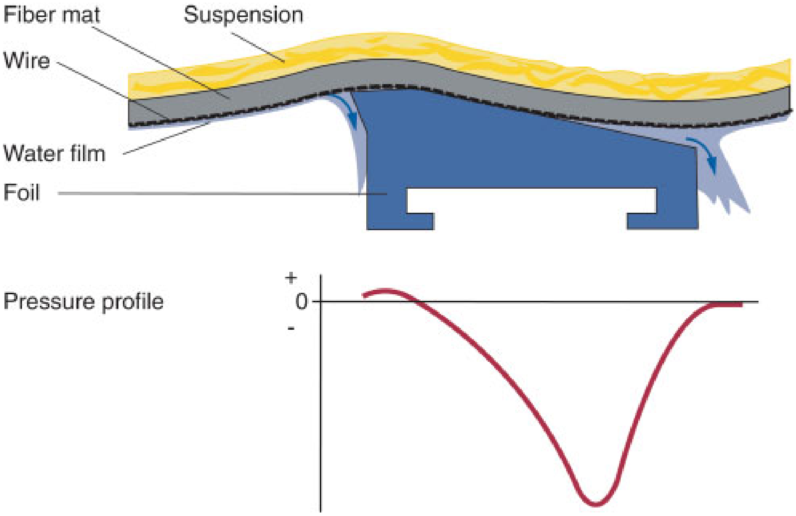


Fig. 6.40 Schematic and operation mode of foils.

- Suction boxes, which are dewatering elements that are generally located behind the water line. They operate under vacuum and, in contrast to wet suction boxes, also suck air through the paper web.

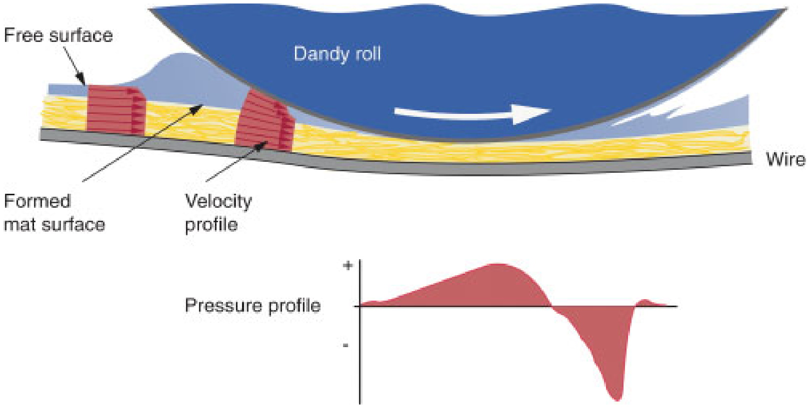


Fig. 6.41 Dandy roll.

- Suction rolls, which have an open shell of different design. Vacuum is applied through the interior. They are used in sheet formation as suction breast rolls, suction formers, suction forming rolls, or suction rolls at the end of the wire section. Suction rolls accelerate drainage and increase the dry content in the web.
- Dandy rolls, which are highly open, wire covered rolls used on fourdrinier machines ahead of the water line, for improvement of formation quality and for watermark application (Fig. 6.41).

Drainage is opposed by the resistance to filtration, which depends on the degree of beating, chemical treatment, and type of stock, as well as on the amount of fines and fillers present. The dry content after the wire section in most cases is about 18–20 %. The water removed in the filtration process (white water) carries away fibers, fines and fillers. The percentage of solids of the suspension retained on the wire, also called retention, can be increased by the addition of retention aids. The white water is reused to dilute the thick stock in the stock approach flow system. Figure 6.42 shows the filler distribution in the *z*-direction (across the web thickness) for dewatering the stock to only one side and symmetrically to both sides.

The short-wave turbulence (micro-turbulence), generated in the suspension in the headbox to maintain fiber deflocculation, dissipates rapidly. For this reason, good formation requires either the fiber web to be fixed very quickly or additional turbulence to be generated in the suspension to be dewatered. This can be achieved by means of pressure and vacuum impulses from table rolls, foils and blades. However, impulses that are too strong are harmful, for example by table rolls at machine speeds above approx. 500 m min^{-1} or by foils with too high a foil angle at elevated machine speeds. In special cases, on fourdrinier wires, formation is improved by agitating the wire. A shaker vibrates the breast roll and thus the fourdrinier wire horizontally in the cross machine direction with a frequency of up to 10 Hz and an amplitude of up to 25 mm. It is used at low machine speeds and

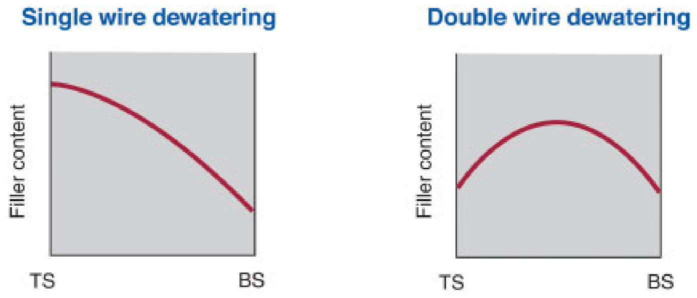


Fig. 6.42 Filler distribution in the *z*-direction for one- and two-sided dewatering (TS: top side, BS: bottom side).

where consistencies are still low, i. e. at the front end of the wire section of fourdriniers and hybrid formers.

The difference between the velocity of the jet and the wire is decisive for the controlled deposition of the fibers on the wire. If the jet and the wire have the same velocity, the fibers are deposited with random orientation or due to a possible pre-orientation in the headbox nozzle. If the jet is slower or faster than the wire, more fibers are aligned in the machine direction. The highest value for the tensile strength of paper is observed in the direction of the main fiber orientation. The relationship between the properties in the longitudinal and cross directions is often important in the processing and use of paper. So, depending on the various paper grades, a range in jet to wire velocity difference of 15 to 70 m min^{-1} is run. If the jet is not directed exactly in the machine direction, this angular deflection is magnified on the wire many times over (Section 6.4.2). The main fiber orientation is then no longer in the machine direction, which can lead to problems (diagonal sheet stress) in certain types of paper (e. g., copying paper).

The properties of the wire, which acts as a filtering auxiliary layer, influence the surface properties of the web (wire mark), fiber orientation, retention, dewatering velocity, and machine operation. Important parameters are the topography of the wire surface, resistance to fluid flow, free volume, cross stability (so that the wire remains level), and the wear characteristics of the wire. Therefore high requirements are put on the design and the maufacture of the wires as well as on their uniformity. An example of dimensions will give a good idea of the process during initial dewatering: The wire, as the auxiliary filter layer, has a weft yarn diameter of about 120 µm, the distance between neighboring weft yarn centers is about 150 µm, the “hole” in between the yarns is then 60 µm deep, converging to about 30 × 30 µm. A fiber may have a length of 2000 µm and 30 µm thickness, a clay particle a size of about 2 µm.

Today, mainly multi-layer wires are used. The material now employed is plastic but in some cases bronze or steel are still used (Section 6.3.1). A good wire should have over its whole area and for its whole lifetime

- low resistance to *z*-direction water flow
- low misting (white water entrainment)

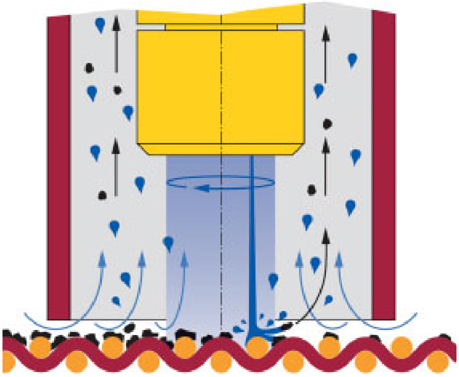


Fig. 6.43 State-of-the-art wire cleaning device (source: Voith).

- flat topography of the paper touching surface
- high wear resistance against wear at the reverse side in contact with the dewatering elements and rolls and against wire cleaning devices.

Thorough wire cleaning is of the utmost importance to ensure uniform dewatering and to prevent or reduce formation interference and sheet breaks as well as fines deposits in the machine. An example of a state-of-the-art cleaning device is shown in Fig. 6.43. It consists of a traversing head with one or more rotating nozzles, operating at a water pressure of up to 250 bar to generate high-impact drops for cleaning the wire. Dirt and water are sucked away.

During the forming process, the suspension is guided between either the wire and air (fourdrinier wire), between the wire and a solid wall (former), or between two wires (twin wire formers). Drainage can occur on one or both sides of the web (Fig. 6.38). Two-sided drainage produces a more symmetrical paper and reduces drainage time and the length of the dewatering zone. Typical figures for fourdrinier wire sections are web forming lengths of about 20 m, at 800 m min^{-1} this means a drainage time of about 1.5 s. A hybrid former 20 m in length and operating at 1200 m min^{-1} has a drainage time of about 1 s, whereas the drainage time for a twinwire gap former of 5 m length at 2000 m min^{-1} operating speed is about 0.15 s. The different principles involved in sheet formation shown schematically in Fig. 6.38 are explained below in more detail.

6.4.3.1 The Fourdrinier Wire Section

The fourdrinier wire (Fig. 6.38A) is the classical method of sheet formation. Speeds up to about 1200 m min^{-1} are achieved with the fourdrinier. This is a reasonable limit due to excessive turbulence on the free suspension surface and dewatering capacity. Normally, the fourdrinier is equipped with a forming board, foils and/or table rolls, suction boxes, wet suction boxes, and suction rolls. Drainage proceeds in the direction of gravity. A dandy roll is often used just in front of the water line to improve formation. This is a wire-covered open roll, with a honeycomb structure, which dips into the suspension and distributes the fibers in the web more uniformly. The dandy roll is also used to produce watermarks in the web through displacement and compression of fibers. These marks are visible in the finished paper in transmitted light. They are generated by a raised pattern soldered onto the roll.

6.4.3.2 Cylinder Former

In the cylinder former family (Fig. 6.38B), web formation occurs on a wire-covered, water-permeable cylinder. The uni-flow and contra-flow former with an immersed mold represents the oldest design. These were later replaced by the non-immersed mold former and finally by the suction former. In suction formers, drainage is further increased by vacuum in the interior of the forming cylinder. The suspension is led between the wire cylinder and a solid wall (lip, former box). Suction formers are employed in the manufacture of single layers of board at speeds up to more than 400 $\mathrm{m\,min^{-1}}$. Higher speeds (up to 1500 $\mathrm{m\,min^{-1}}$) are only achieved with the suction breast roll former in the production of tissue (Fig. 6.38C). A similar forming unit can also be placed e. g. on a fourdrinier wire in multi-ply packaging paper production.

6.4.3.3 Inclined Wire

Sheet formation on an inclined wire section is performed in the area where the wire is covered by a box filled with the suspension and is usually under pressure (Fig. 6.38D). Here the wire is supported by some type of forming board. The pressure under the forming board can be controlled. This type of forming unit is for low machine speeds and operates with low consistencies of down to about 0.01%. It is used for the production of special papers and nonwovens.

6.4.3.4 Hybrid Former

The first section of the hybrid former consists of a fourdrinier, which is followed by a twin wire section in which dewatering also occurs through the top wire (Fig. 6.38E). This increases the drainage capacity of the base forming unit and improves symmetry in the z-direction of the paper web. For good formation results the free suspension height entering to the top wire/fourdrinier wedge has to be optimized by adjusting dewatering conditions ahead. In the past a large variety of configurations of hybrid formers has been developed with applying rolls, foils, blades and suctionboxes in different sequences.

6.4.3.5 Gap Former

In a twin wire gap former (Fig. 6.38F), the suspension from the beginning is led between two wires operating at the same speed, and is drained through one side, or mostly both sides. One of the driving forces in gap former dewatering is the

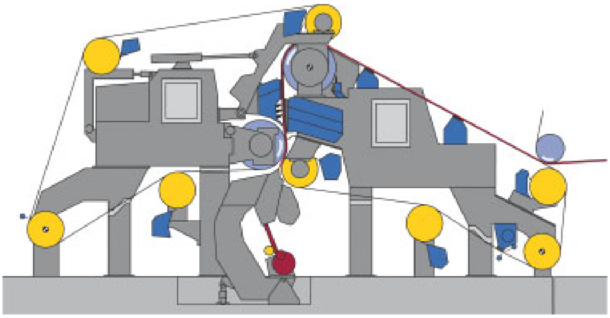


Fig. 6.44 State-of-the-art gap former for high-speed paper production (source: Voith).

drainage force due to wire tension, which counteracts the centrifugal force of the suspension. Open rolls, suction rolls, forming blades, and vacuum shoes are used to increase drainage capacity and improve formation. In the gap former, the jet is injected directly into the gap between the two wires. Also in gap former development a large variety of configurations have been and still are on the market. Todays standard of a high-speed gap former is a roll-blade-roll configuration (Fig. 6.44). This means that the forming roll is followed by a curved forming shoe, usually with counteracting forming blades (counter blades), and by the couch roll. The dewatering zone is S-shaped with the forming roll in contact with the outer wire and the couch roll contacting the transfer wire. This helps to adjust the z-direction symmetry of the sheet. The main direction of the wires in the dewatering zone is vertical. This eases white water handling as well as maintenance and changing the rolls and wires. With machines of this kind or of similar configuration, speeds of more than 1900 m min^{-1} are achieved for newsprint, 1800 m min^{-1} with SC and LWC papers, and 1550 m min^{-1} for wood-free writing and printing grades production.

6.5
Press Section

The purpose of the press section is to increase the dry content of the paper web as much as possible by compression. This kind of mechanical dewatering reduces steam consumption in the dryer section and increases the strength of the web in order to avoid web breaks during production.

The wet paper web is picked up from the wire section and is transported by felts through the press section which contains one or more press nips to be passed. The so-called press nip is formed between two opposing rolls pressed together. The paper web today is usually transported either on one felt in the top or bottom position or between two felts as a sandwich. In some cases, when the paper web is strong enough compared with the applied stress in operation, the web is trans-

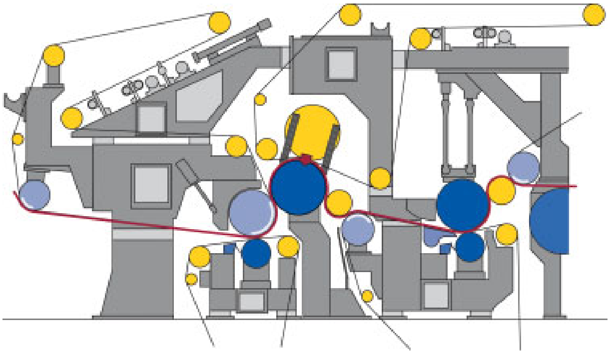


Fig. 6.45 Conventional four nip press section (source: Voith).

ported towards the next press nip or to the dryer section without any felt support. This is called an open draw. The water removed from the web is stored and carried away in the felt and, in the case of high water extraction, also in grooves or perforations in the surfaces of the rolls behind the felt. With suction press rolls, storage and transportation of water are improved and rewetting of the paper web is reduced.

The felt has to be designed to meet high demands as regards large storage capacity under pressure, good water retention behavior on leaving the nip which reduces rewetting of the web, and the smoothest possible felt surface for uniform pressure transfer to the web and to avoid felt marking. For the latter, e.g., the staple fiber diameter at the web contacting felt surface goes down to 20 μm which is even less than the paper fiber thickness (about 30 to 40 μm). Different types of felts are selected for the top or bottom positions in the individual nip as well as for the different press nips, taking into account the press water flow and the target of sheet transfer. The dewatering of the felts is performed with suction pipes. Constant or intermittent treatment with a fine, high-pressure water jet and/or wetting facilities (felt conditioning) keeps the felt clean and maximizes its working life.

A conventional press section usually consists of three to four successive press nips (Fig. 6.45). The rolls are pressed against each other with linear forces of 20–150 N mm^{-1} and up to more than 300 N mm^{-1} in some special designs. For conventional press rolls the magnitudes of the resulting pressure and nip length mainly depend on the diameter of the roll, the elastic characteristics of the material and the geometry of the shell and of the coating (steel, or bronze, rubber or plastic; plain, grooved or perforated), as well as on the felts; for high basis weights the visco-elastic properties of the paper web are also important.

Generally the applied nip pressure must first overcome the fiber structure resistance of the web before it can generate the hydraulic pressure required for web dewatering (see Fig. 6.7 in Section 6.2.4). Fiber structure resistance at the beginning is low and increases with higher dry content which is shown in Fig. 6.46 for static conditions. This means that the dewatering pressure must be elevated with increasing dry content to overcome the higher structure resistance. However,

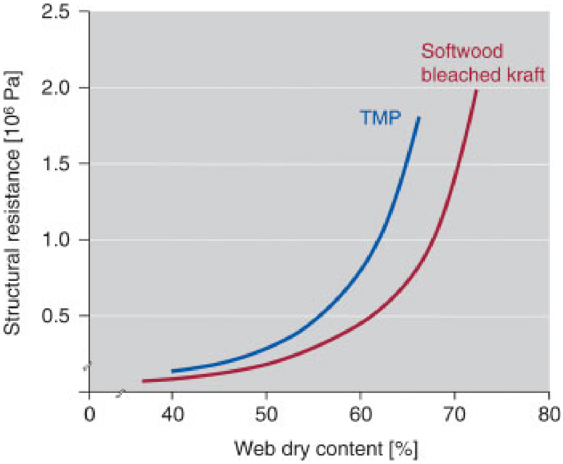


Fig. 6.46 Fiber structure resistance as a function of web dry content under static loading conditions for two different stocks (source: V. Lobosco, see references).

when the hydraulic pressure is too high the paper web may be damaged ("crushing"), especially at higher moisture content. The higher the hydraulic pressure and the longer the time of action (both factors resulting in the "press impulse"), the better the dewatering performance. The flow resistance of the water in the web is determined by the type of stock, the fiber treatment, and the amount of fines and fillers. Increasing the web temperature by steam or infrared heating facilitates dewatering by lowering the viscosity of the water and the structural strength of the web. The actual nip pressure is increased from nip to nip, corresponding to the decreasing water content. For symmetry in both densification and fines and ash content of the top and bottom web surface symmetrical dewatering has to be aimed for.

The time during which the pressure acts on the web can be prolonged up to about tenfold compared to conventional presses by using shoe presses. In this press type, a concave shoe presses a flexible revolving plastic sleeve or belt against the counteracting press roll (Fig. 6.47). The shoe works on the hydrostatic/hydrodynamic lubrication principle. The increase in pressure along the press nip is by far not as steep as in conventional presses, the maximum nip pressure is lower (up to about 90 bar). Furthermore the shape of the pressure curve along the press nip can be adjusted in a certain range. Figure 6.48 shows the total pressure distribution in the machine direction in a conventional two-roll press nip and in a shoe press nip.

Nowadays, the dry content after a shoe press section reaches about 50 to 55%, depending on the product and the raw material used. Because of these high dry contents, less thermal energy is required in the dryer section, and the resulting increased web strength results in fewer breaks.

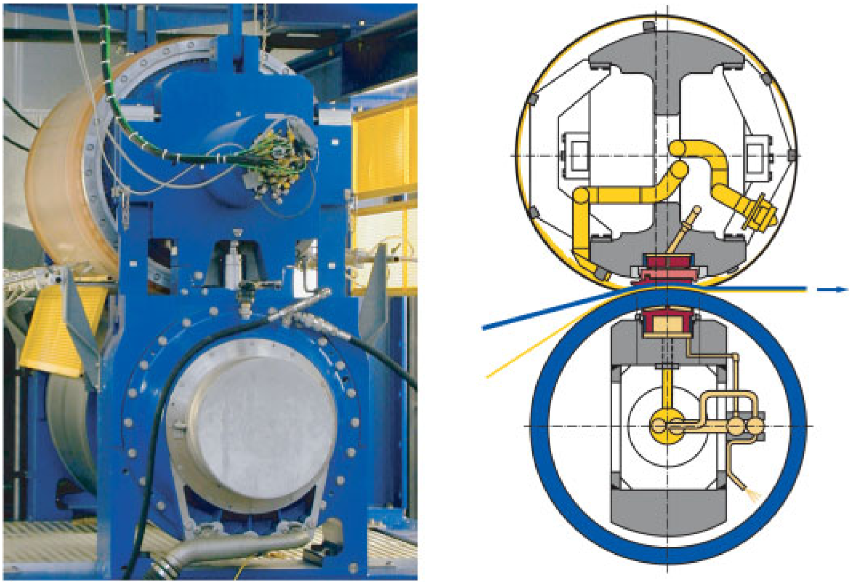


Fig. 6.47 Shoe press consisting of a top roll with sleeve and concave shoe and a bottom roll with iron shell supported by hydrostatic bearings (source: Voith).

Shoe presses have been standard in press sections for board and packaging grades since the 1980s. Later, they have also become state-of-the-art presses for graphic paper machines. Today modern press sections of high-speed paper machines consist of only two nips. They have for instance two double-felted nips or one double-felted nip followed by a second nip with a felt and a transfer belt

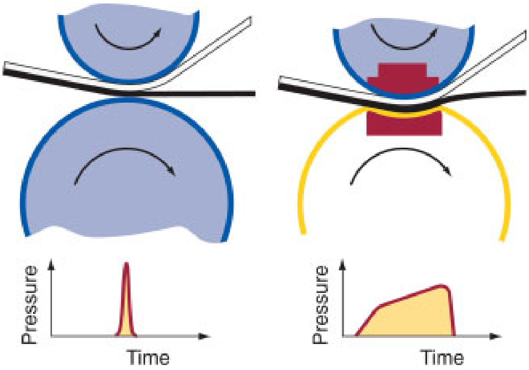


Fig. 6.48 Pressure distribution in the machine direction in a conventional two-roll press nip and a shoe press (source: Voith).

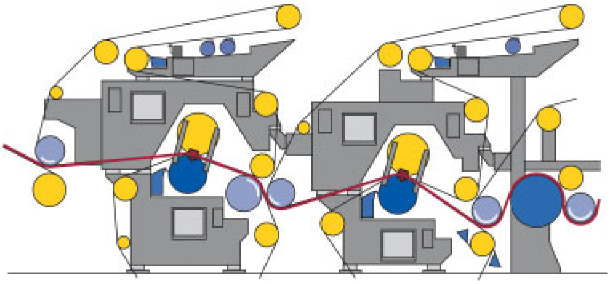


Fig. 6.49 State-of-the-art press section with a double-felted first press nip and a second nip with felt and transfer belt (source: Voith).

(Fig. 6.49). A press system with two single-felted nips is mainly applied for graphic paper production. These types of press operate at line loads of up to 1250 N mm^{-1}. A steam box ahead of the second press nip for enhanced dewatering effect and CD moisture control is optional. The sandwich felt-paper-felt in the press nip assists symmetrical dewatering providing a good *z*-direction symmetry of the sheet. During press dewatering the web layers towards the felt are more densified. So one-sided dewatering means for instance nonsymmetrical surface characteristics such as printability of top and bottom side.

The newest development is a single nip press section where the web is dewatered in just one nip (Fig. 6.50). With a shoe of more than 300 mm length a dryness of about 52% is reached in woodfree paper production at more than

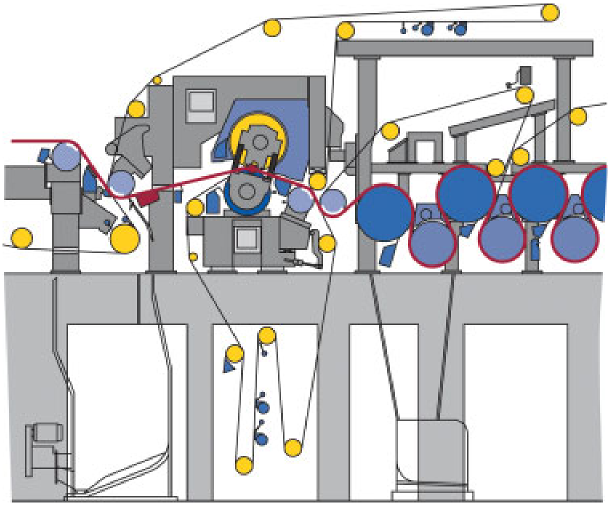


Fig. 6.50 Newly developed press section with a single double-felted nip (source: Voith).

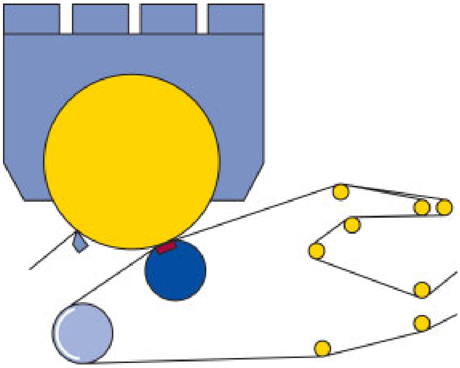


Fig. 6.51 Shoe press in tissue production (source: Voith).

1300 m min^{-1}. The requirements placed on the felt quality and uniformity are correspondingly high. Due to the nonexisting second nip investment costs, energy requirement (vacuum and drive), press sleeve and felt costs as well as machine shutdown time for their changing are lower.

Shoe presses are also used in tissue production. Here the advantages are higher bulk and sheet dryness after the press. In this application the shoe press replaces the suction press roll of a conventional machine acting against the Yankee dryer (Fig. 6.51).

A uniform moisture profile in the cross machine direction on the reel is very important for reasons of quality and economy. This requires a uniform nip pressure as well as a uniform dewatering effect of the felts in CD. Preconditions for that are uniform felt design, structure, and conditioning. For CD moisture profile correction press rolls are in use which can vary the line force selectively across the width (in conventional press sections) and sectionalized steam boxes which heat the web to varying extents across the width.

A reliable web guidance system is important to prevent web breaks, especially at high machine speeds, low basis weights, and at low dry contents of the web, as found after the first press nip. In modern paper machines, especially in the press section, the web is not conveyed freely, but is nearly always supported by a felt, belt or wire, or by the surface of a roll (closed draw).

6.6
Dryer Section

6.6.1
Overview

The purpose of the dryer section is to increase the dry content of the paper web, usually to 90 to 98%, by evaporation. During drying the fibers develop hydrogen bonds which provide the natural strength of the paper. Drying is a coupled heat and mass transfer process so heat has to be transferred from a heat source to the paper and the evaporated water has to be carried off. During drying, the paper web which has been picked up from the press section has to be guided safely throughout the dryer section to the reel where it is wound up. Some dryer sections include a size press for paper strength improvement and/or a breaker stack for pre-calendering. Depending on the type of paper machine different heat transfer and drying principles as well as their combinations are applied.

6.6.2
Drying Principles

6.6.2.1 Contact Drying by Steam Heated Cylinders

With this most common principle in paper drying steam condenses at the inner surface of the cylinder wall, the heat is transferred through the wall to the paper web, the web is heated and water is evaporated. Air flow takes up the evaporated water. The heat transfer rate from the steam to the cylinder shell depends on the flow pattern of the condensate motion. This flow pattern is mainly dependent on the machine speed, and to a lower degree on the amount of condensate volume in the cylinder and on the cylinder diameter. At low speeds of up to about 300 to 500 m min^{-1} a pond of condensate is found in the cylinder. At higher speeds – above the "rimming speed" – the condensate builds up a ring. Acceleration during "ascending" of the condensate ring is against the rotating direction, and in the rotation direction when descending. This results in a swinging condensate motion

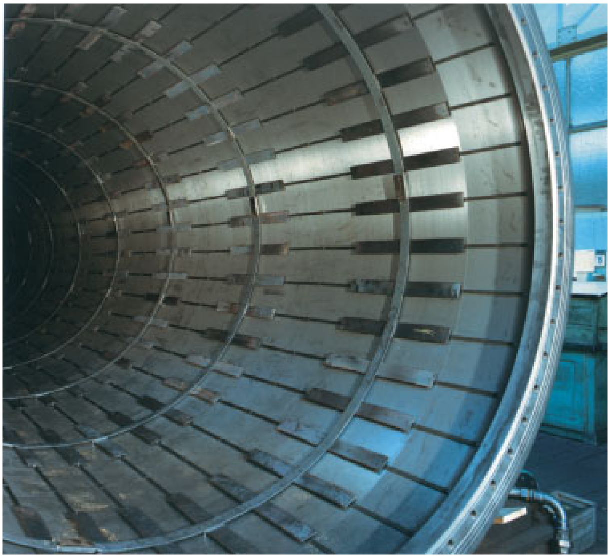


Fig. 6.52 View inside a drying cylinder equipped with spoiler bars (source: Voith).

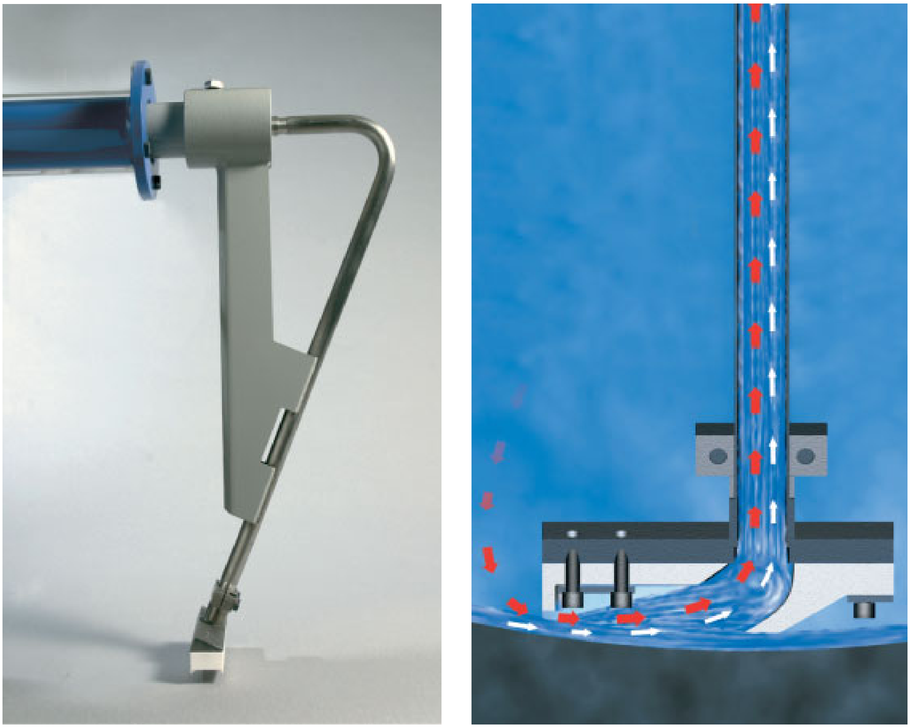


Fig. 6.53 Siphon for condensate removal from a drying cylinder (source: Voith).

relative to the cylinder with the effect that the condensate ring velocity is lowest and thus its thickness is highest at the culmination point and not in the bottom position. For high machine speeds the condensate motion and thus heat transfer decrease. For heat transfer enhancement and uniform drying spoiler bars inducing turbulence to the condensate layer are installed (Fig. 6.52). The condensate is removed from the inner surface of the cylinder to its axis by syphons (Fig. 6.53) in the form of a two-phase flow of steam and condensate. To overcome the high centrifugal forces and to generate the two-phase flow a pressure difference of about 0.3 to 0.5 bar is necessary. The syphons either rotate with the cylinder (for higher machine speeds) or are stationary. Heat transfer through the wall depends on the thickness and conductivity of the cylinder material which is mainly cast iron (in some cases steel). Higher steam pressure increases the temperature difference and thus the drying rates. Accumulation of air in the cylinder has to be avoided as it would reduce the condensing temperature according to the partial pressure. Good heat transfer from the cylinder to the paper web is obtained by pressing the web tightly to the cylinder e.g. by means of dryer fabrics.

6.6.2.2 **Air Impingement Drying**

This drying principle is mainly used in tissue production or in coating machines but also for enhancing the drying capacity of drying cylinders in multi-cylinder dryer sections. Hot air is blown through a nozzle plate at high velocity onto the paper. The impinging air transfers heat to the web and takes up the evaporated water. The air is then sucked back into the hood. Heat transfer in impingement drying increases with increased air temperature and velocity and by reducing the spacing between the nozzle plate and the paper surface.

6.6.2.3 **Through Air Drying**

This method is used in the drying of tissue and nonwovens. Hot air is sucked or blown through the air permeable paper web supported by a heat resistant wire. Heat is transferred directly into the fiber network and the evaporated water is carried off. Through air drying results in the highest drying rates.

6.6.2.4 **Infrared Drying**

This heat transfer method is mainly used to enhance the drying capacity in coaters when the web is wet. Infrared heaters are usually gas fired. The gas heats a mesh to a temperature of about 900 to 1100 °C. The low thermal inertia of the mesh allows fast control of the mesh temperature and the heating rate as well as preventing fires in the case of sheet breaks. In some cases electrical heaters are in use with temperatures up to about 700 °C, exhibiting a fast cool down of the emitter plates. Infrared drying units need sufficient air flow in order to carry off the evaporated water and to prevent coat quality problems.

6.6.2.5 **Press Drying**

This method is a combination of pressing and drying. First the web is dewatered mechanically in a press nip and brought into tight contact with the hot surface on one side. At the opposite side the web is covered by a permeable belt such as a felt or a wire which continues to press the web to the hot surface over a longer distance. The vapour escapes through the permeable cover or is stored therein. There are only a few installations of this dryer type worldwide.

6.6.2.6 **Impulse Drying**

This method is also a combination of pressing and drying. The process takes place in a press nip (for instance with a shoe press) where one surface, which is in direct contact with the web, is heated. The other web side is in contact with a felt. The wet web is compressed and thus mechanically dewatered. The vapor generated at the hot surface pushes the water through the compressed capillaries towards the felt and finally the generated vapor can flow freely through these channels. This kind of process is still in development.

6.6.3
Dryer Sections

6.6.3.1 Multi-cylinder Dryer Section

6.6.3.1.1 Types of Multi-cylinder Dryer Section

Multi-cylinder dryer sections consist of double-tier or single-tier groups or a combination of both. In double-tier dryer sections (Fig. 6.54) the paper web runs around a large number of cylinders (up to about 60 in graphic paper machines and up to 90 for board and packaging paper machines) arranged in an upper and a lower row. The paper is in contact with each cylinder at an angle of about 220 to 240°. Dryer fabrics, one for each top group and one for each bottom group of cylinders, press the paper against the cylinder surface for improved heat transfer. Even together with stabilizers the dryer fabrics can only partly support the paper web during its transfer to the next cylinder. Tail threading in conventional dryer sections is usually done by means of ropes.

The state-of-the-art dryer section for a high-speed paper machine has a single-tier configuration with steam heated cylinders in the top row and suction rolls in the bottom row. The paper web is always supported by the dryer fabric and runs jointly around the drying cylinders and suction rolls (Fig. 6.55). In the top row the paper web is pressed against the drying cylinders by the dryer fabric. In the bottom

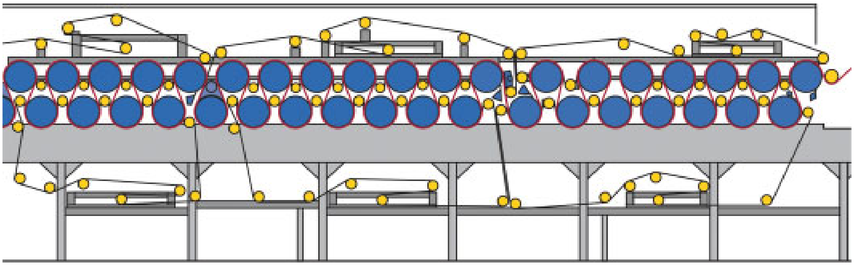


Fig. 6.54 Double-tier dryer section (source: Voith).

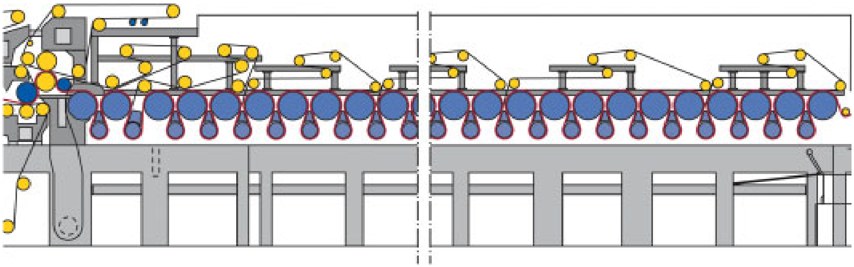


Fig. 6.55 State-of-the-art single-tier dryer section for high-speed paper machines (source: Voith).

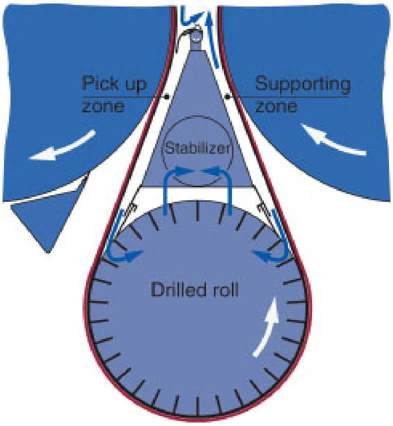


Fig. 6.56 Stabilizing elements for web guiding in single-tier dryer section (source: Voith).

row it is held on the fabric by reduced pressure in the suction rolls. Stabilizing elements ensure a safe web run along its path between cylinder and suction roll where the web is not in contact with the drying cylinder (Fig. 6.56). For high speed paper machines tail threading with only doctors and air jets is standard (Fig. 6.57). Many paper machines have some single-tier groups for runnability reasons followed by double-tier dryer groups. Cylinder diameters today are usually 1.8 m, in older machines they are also 1.5 or 2.2 m.

The dryer section is split into several drive groups to control web tension and to account for web stretch and shrinkage. Each group has its own dryer fabric and separate drive. The steam and condensate system is also split into groups to control the heating curve. Temperature and steam pressure in the different heating groups have to follow an ascending curve so, usually, a steam cascade system is applied, supplying the blow through steam of the last drying group to the last but one etc. The remaining steam from the first group is condensed and any air extracted from the steam-condensate system.

In the field of dryer fabrics excessive air entrainment at high machine speeds had to be reduced without losing drying capacity by decreased air permeability of

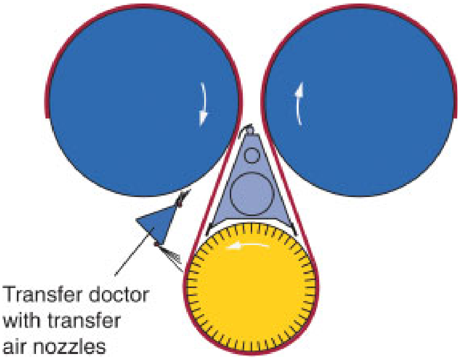


Fig. 6.57 Ropeless tail threading system for single-tier dryer section (source: Voith).

the fabrics. Modern dryer fabrics provide high contact area, low caliper, high stability and abrasion resistance. Good cleaning of the dryer fabrics ensures uniform evaporation, less sheet picking and improved effectiveness of the web run stabilizers. Shutdowns for cleaning can be avoided or cleaning intervals increased by appropriate cleaning devices as mentioned in Section 6.4.

6.6.3.1.2 **Web Handling**

In order to reduce the forces acting on the web at high machine speeds a single-tier dryer section is applied where the paper web is continuously supported by a fabric. In the critical areas where the web has to be released from the drying cylinder surface stabilizers support the safe web run. Stabilizers are also used in double-tier dryer sections. In the most sensitive areas of low strength or low stretch potential the size and speed of the dryer groups have to be adjusted according to the strength, stretch potential and web shrinkage. This enables fine-tuning of sheet quality and improves machine runnability.

6.6.3.1.3 **Dryer Hood**

The whole dryer section is enclosed in a drying hood with doors which can be opened e. g. for inspection. It allows controlled flow of the hot and dry make-up air as well as of the vapor laden exhaust air. The pressure inside the hood should be balanced in such a way that a minimum of air is blown from the hood into the machine hall or sucked from the machine hall into the hood. For effective pocket ventilation the hot air enters via blow boxes or blow rolls and flows to both sides of the machine where it is sucked off. To prevent condensation the hood walls are insulated and make up air is supplied along both hood sides from underneath. These measures allow a low amount of make-up air, a high air dew point of the exhaust air and effective heat recovery.

6.6.3.1.4 **Paper during Drying**

The web strength increases with increasing dryness due to build up of hydrogen bonds between the fibers. The increase in strength from about 50% to 95% dryness is about a factor of 10. Stretch before rupture decreases with drying and also depends on the web structure and how far the web was allowed to shrink.

The paper web shrinks during drying. The extent of shrinkage depends on the type of stock, degree of beating, the fiber orientation, and on forces that restrain the shrinkage. The shrinkage in the machine direction can be controlled by stretching the web. CD shrinkage is nonuniform and is higher at the sides than towards the center of the web. The single-tier dryer configuration changes the CD shrinkage profile compared with a conventional double-tier one (Fig. 6.58). The profile is now flatter over a large part of the sheet between the drive and tender side with low shrinkage, accompanied by less stretch potential and higher dimensional stability in this area. On the other hand there are distinctly steeper slopes in the shrinkage curve with high shrinkage numbers at the edges.

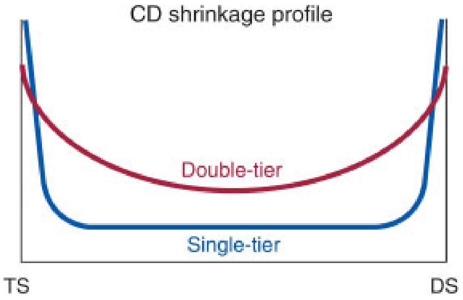


Fig. 6.58 CD shrinkage profile for single-tier and double-tier dryer sections.

Paper curl is an undesirable effect when paper undergoes heating or moistening, e. g. in copy machines or in printing. Curl is due to nonsymmetrical residual stresses in the z-direction of the web which date back to nonsymmetrical drying of its top and bottom sides. The amount of curl is influenced by the degree of nonsymmetrical drying. The impact increases towards the end of the drying process. The direction of curl (MD, CD or diagonal curl may occur) is defined by the paper and fiber structure. Curl can be overcome by varying the operation of the top and bottom drying cylinders if there is a conventional double-tier after-dryer section. With a pure single-tier dryer section curl can be controlled by additional tools such as by moistening (water, steam) or by additional drying (air impingement drying).

A uniform CD moisture profile of the web at the end of the dryer section is an important quality requirement so the heat transfer of the cylinders to the web as well as the vapor exhaust conditions close to the web have to be uniform. Additional CD moisture control tools such as sectioned cylinders, blow boxes or moisturizers are also used.

6.6.3.2 **Tissue Dryer Section**

Conventional tissue drying is a combination of contact and impingement drying. Today a combination with through drying is often used. So a tissue drying system consists either of a tissue cylinder wrapped by a hood or of a system with an additional through air dryer section ahead of the tissue cylinder. In some cases only through air dryers are used.

6.6.3.2.1 **Tissue Cylinder**

Tissue cylinders (Fig. 6.59), also called Yankee dryers, have a width of up to 8.2 m and a diameter of 3.6 to 5.5 m, and in special cases even up to 6.3 m. The inside of a tissue cylinder shell is usually ribbed for maximum drying rates. The drying rate is further enhanced by turbulence generators. Condensate removal is performed by two-phase flow through a sodastraw syphon system. The cylinder shell, made of special cast iron, is the most sensitive part as regards safety against catastrophic failure. It undergoes a mainly two-dimensional combined static and dynamic

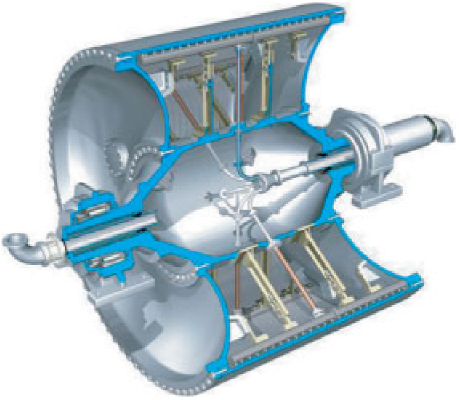


Fig. 6.59 View inside a ribbed tissue cylinder with soda straw siphons for condensate removal (source: Andritz).

stressing. This is due to inside steam pressure, high temperature gradient across the shell thickness, high centrifugal forces and dynamic stress due to press roll loading so the admissible steam pressure has to be limited. For good creping effect a coating consisting of hemicellulose and/or synthetic agents has to be established on the cylinder shell surface. This also reduces wear; prolonged cylinder lifetime can also be achieved by covering the surface with a metal spray coating. One (or two) press roll(s) dewater the web and bring it into good contact with the cylinder for intense heat transfer. The shell shape in CD depends on the operating conditions. These must be defined in advance in order to grind the adequate crowning on both cylinder and pressure roll(s) for uniform web pressing and dewatering in CD. As operating conditions may vary in a certain range, the cylinder shape and in CD the moisture profile may also show some deviations. To end up with a uniform moisture profile and creping quality modern tissue drying includes a press roll which can better adjust to cylinder shape deviations as well as a dryer hood with a CD moisture profiling system.

6.6.3.2.2 **Tissue Dryer Hood**

The dryer hood spans the tissue cylinder by about 220 to 260° and consists of two halves both of which are retractable. The nozzle plate is concentric to the cylinder and includes exhaust openings. The diameter of the nozzles is about 5 to 7 mm depending on the spacing between the nozzle plate and the cylinder. The ratio of nozzle diameter to spacing has to be optimized with regard to minimum fan energy consumption and maximum drying rate. The minimum spacing is limited for runnability reasons to about 20 mm. Air temperatures of up to 700 °C and air blow velocities of up to 160 m s^{-1} are used. For CD moisture profile control the hood is divided in several sections across its width. The hood is insulated. Its design has to account for the large temperature differences when heated up. The air system with burners, fans and heat exchangers for heat recovery is located in a

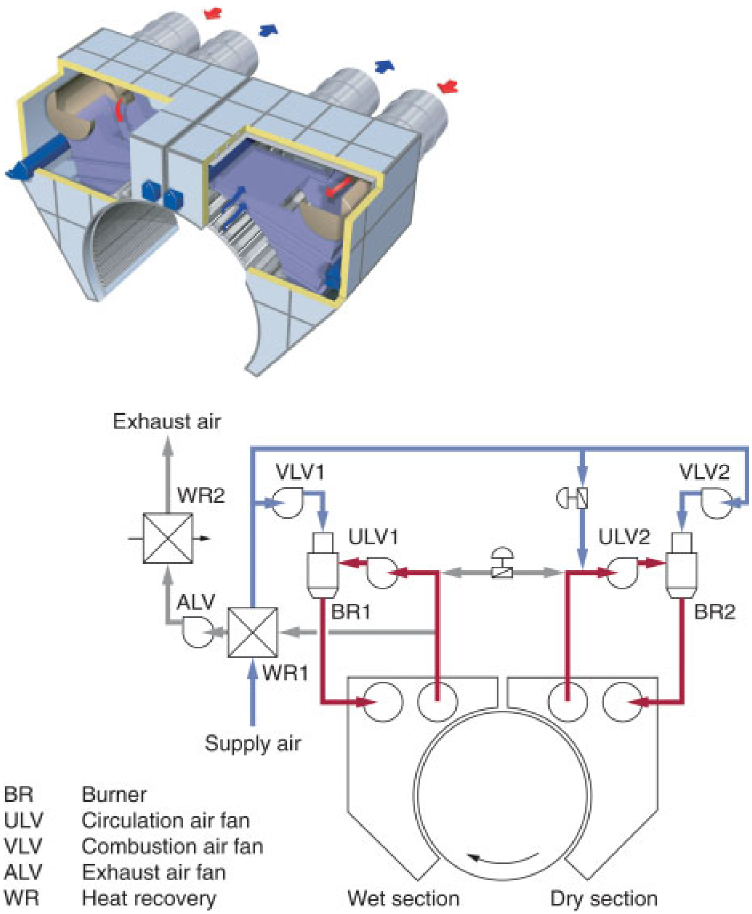


Fig. 6.60 Schematics of a tissue dryer hood and an air system (source: Andritz).

separate place outside the hood. A tissue dryer hood and its air system is shown in Fig. 6.60.

6.6.3.2.3 **Through Air Dryer**

This type of cylinder can be built with diameters up to 5.5 m, or in special cases up to 6.7 m, and widths of up to 9 m. It has a free outside surface area of up to 96% in order to have a uniform air flow through the paper web. During its contact with the cylinder the paper web is supported by a revolving wire. The cylinder can run at speeds of up to 3000 m min^{-1}. Air is usually sucked into the cylinder by reduced pressure and is supplied by a hood wrapping the cylinder by about 250°. The temperature can be up to 300 °C. The design has to withstand the heat up and cool down cycles during its operational life and always has to ensure a uniform geome-

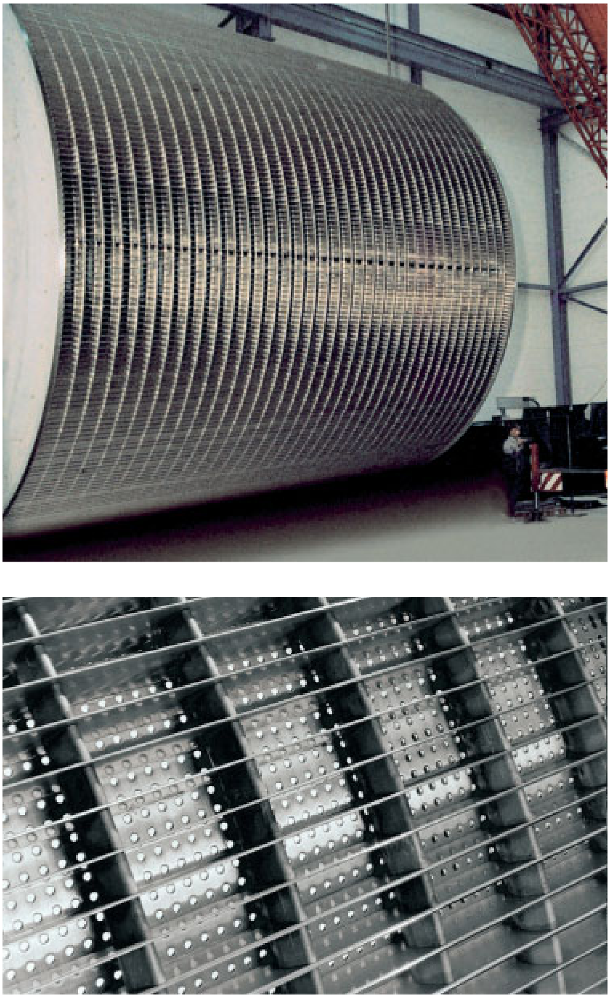


Fig. 6.61 Overall view of a cylinder for through drying with a highly open surface and some construction details (source: Fleissner).

try and drying conditions. Figure 6.61 gives an overall view of a through air drying cylinder and a closer look at the construction.

6.7
Surface Sizing

Martin Tietz

Some paper machines contain a unit for the application of certain liquid media to the web surface. When applying a starch solution, a sizing agent, or a mixture

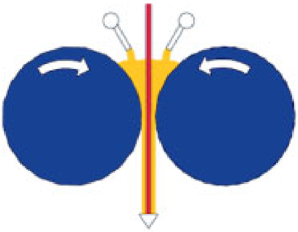


Fig. 6.62 Size press (source: Voith).

thereof, this process is called sizing. The main objectives of sizing are to increase the strength of the paper and to modify the surface properties with respect to liquid uptake during writing, printing, or coating.

Sized papers show a considerably higher strength. This is, for instance, important for liner and corrugated media, but also for other packaging papers as well as for graphic papers. For tensile strength increase, penetration of the size into the paper is desired. If the main objective is to increase surface strength, for example for printing, the size should remain on the surface.

Sizing also reduces the penetration of liquids into the paper. This limits, for example, the ink spread when writing or printing onto the paper. The same effect is desired for coating base papers, since sizing improves the coating hold-out in the subsequent coating process.

Sizing is usually performed in a size press or a film press. In a size press (Fig. 6.62), the web is passed through a pond of the sizing agent, which is located above a roll nip. As a result of both capillary action in the pond and the hydraulic pressure in the roll nip, the paper web absorbs the sizing liquor.

The amount of size pick-up and the degree of penetration depend upon the pond height, the concentration and viscosity of the size, the absorption behavior (porosity, moisture content, temperature, etc.) of the paper web, and the nip pressure and nip length. Control of the size pick-up is mainly by variation of the size concentration, but also by variation of the pond height or nip pressure.

Typical size concentrations lie between 5 and 12%. The pick-up is usually 0.8–3 g m^{-2} dry substance in total. The size press is limited in speed due to pond turbulences, which become unacceptable above approximately 1000 m min^{-1}. Size concentration and pick-up are also limited.

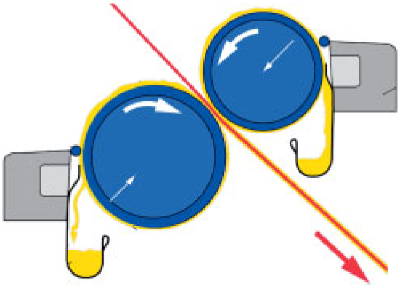


Fig. 6.63 Film press (source: Voith).

The modern film press overcomes these limitations (Fig. 6.63). In a film press a film of the application medium is formed on the rolls and is then transferred to the paper web in the roll nip.

To meter the applied film, a profiled (or grooved) rod is usually used. Different profile geometries allow for different film thicknesses. Therefore, variation of the size concentration for pick-up control is no longer needed. With a given rod profile, an additional but limited variation of the size pick-up is possible by adjusting the rod pressure.

Today's size presses do not limit the speed of the production line, 1700 m min^{-1} has been achieved and even higher speeds seem possible.

A size concentration of 8–15% is typical, 25% or more can also be reached. Typical pick-up amounts are 1–4 g m^{-2} dry substance, and 7 g m^{-2} and more are possible.

The water applied in the size press or film press increases the moisture content of the paper web from around 2–4% to 60–75%. The water is evaporated in the after-dryer section. The first cylinder in particular must be protected against the build-up of coatings.

6.8
On-line Coating

Papers of high surface quality receive a pigment coating. For graphic papers, the application of this coating was traditionally performed off-line in a separate coating machine. The coating process, including the different types of applicators and the coating media, is discussed in more detail in Chapter 7.

In a paper machine with on-line coating, the same applicators as in off-line coaters can be used. Refer to Chapter 7 for a more detailed description of these applicators.

On-line coating has the advantage of a considerably reduced total machine size compared with off-line coating, because a winder and an unwind station as well as a re-reeler can be omitted. This reduced size has a direct impact on investment and personnel costs. Paper losses due to the additional winding and unwinding process in an off-line process are also avoided.

However, the coating process is susceptible to web breaks due to the forces acting on the paper or board. If a web break occurs in an off-line coater, the paper machine can continue production and the off-line coater will keep up with a higher machine speed. With an on-line coater, however, the entire line has to discontinue production during a web break at a coater station. Therefore, the time efficiency of an on-line machine is lower than that of a paper machine with a separate off-line coater.

On the other hand, off-line operation gives additional material losses due to the rewinding processes. Each unwinding, splicing and winding is associated with certain losses. These can add up to 1% of the entire production.

It depends strongly on the paper grade and on the coating concept, whether on-line or off-line coating is more economical.

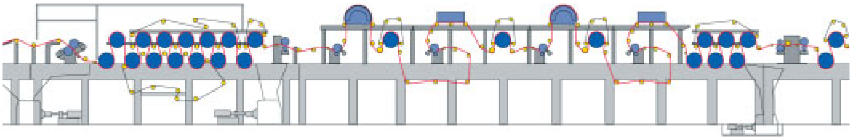


Fig. 6.64 On-line coating section of a board machine (source: Voith).

6.8.1
Board

Board has, because of its high basis weight, a relatively high absolute strength. Furthermore it is produced at much lower speeds than packaging or graphic papers. Therefore, it is much less sensitive to web breaks than the fast machines producing lower basis weights. Hence, the coating of board is mostly done on-line.

Figure 6.64 shows the coating section of a typical board machine. It comprises four blade coater stations, two per side, following the pre-drying section. The bottom side is pre-coated first and then the top side is pre-coated. The covering layer (called the top-coat) is applied in the same sequence. The web run for the bottom-side coating is relatively straight in the machine direction. In order to coat the top side, however, the web has to pass the blade coater against the machine direction, because the coat application is always from the bottom. Therefore, the web has first to be guided beneath the coater. After coat application, the web is turned into the machine direction again, with infrared dryers and air dryers placed above the coater followed by a short after dryer section.

6.8.2
Graphic Papers

Coating of graphic papers is more often performed off-line. Some machines with on-line blade coaters are in operation, but usually at moderate machine speeds.

In the 1990s, the film press was introduced as an on-line applicator for graphic single-coated papers at elevated speeds (Fig. 6.65). In film presses, the forces acting on the paper are considerably lower than in a blade coater, therefore the risk of web breaks is reduced. The benefit of higher material efficiency as well as lower investment and operating costs more than compensates for the reduced time efficiency. The roughness of a film-coated paper is greater than that of a blade-coated paper, therefore it is more difficult to reach the same gloss level. Nevertheless, the economic advantages together with a more uniform print image make the on-line film-coated papers very competitive.

Film coating is more suitable for an on-line process than blade coating due to the lower risk of web breaks. Therefore, it is also used for the pre-coat of multiple-coated products. There are in operation some machines – especially those operat-

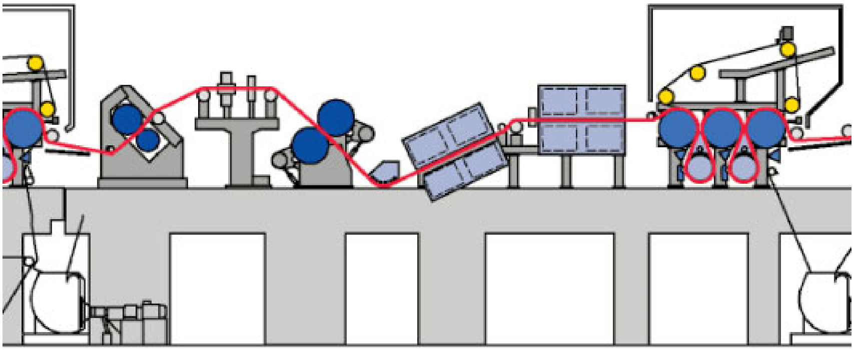


Fig. 6.65 On-line film press of a modern LWC machine (source: Voith).

ing at low speeds – incorporating pre- and top-coat on-line but in most production lines for multiple-coated graphic papers an off-line coater is included. A film precoat is then very often part of that off-line coater. However, there exist also on-line/off-line combinations where pre-coating is done in the paper machine. All further coats are applied off-line.

6.9
Calendering
Rüdiger Feldmann

6.9.1
Objective and General Description of the Calendering Process

The objective of calendering is to modify the surface characteristics of paper with regard to its further use, e. g. printing. Depending on the individual grades, the focus is put on different technological properties. These are mainly
- gloss
- smoothness/roughness
- density
- blackening
- brightness
- opacity.

Printed gloss and printing smoothness are the major prerequisites for a good print quality. Both are generally dependent on the gloss of the paper and its smoothness/roughness as well as its levelness and compressibility. High printed gloss gives the printed product the desired shiny appearance, while high (printed) smoothness is decisive for the evenness of print and print density, e. g. reduced number of missing dots.

As to the theoretical basis of calendering, a series of explanations exist. Some scientists hold the view that smoothness and gloss result from slipping of the paper in the nips. Others maintain that calendering is a flattening process where the smooth surface of the hard rolls is replicated on the side of the web that contacts the hard roll. Still others argue that it is the shearing action in the nip which causes gloss and smoothness by "aligning" the surface particles of the web. Not in dispute is the influence of heat: thermal energy transferred to the web softens the cellulose fibers (glass transition point) and thus enhances the development of gloss and smoothness.

Smoothing the surface and increasing gloss are accompanied by reduction in caliper, strength properties, brightness and opacity to a certain degree.

The strength properties of the paper are peremptory for the runnability of the web in the printing machine. Brightness and opacity have a distinct impact on the print quality. Blackening is found when parts of fibers have collapsed under pressure. Under transmitted light the respective areas appear glassy, whereas under incident light they appear as darkened areas. This is still intensified by the printing process, i. e. the light full tone areas turn murky gray.

Calendering is done by pressing the paper web in one or more "rolling" nips formed by rolls with special properties.

The main factors in calendering – apart from furnish and paper properties such as moisture, temperature and coating – that influence the above-mentioned technological result are:

- nip pressure/load
- nip dwell time
- roll elasticity
- roll surface temperature and smoothness.

Details concerning the rolls and roll covers, the roll configuration and other important components of the calenders will be treated below.

6.9.2
History of Calendering

From the very beginning there was a desire to glaze the rough surface of paper. The procedure then was to lay each hand-made sheet on a smooth surface and treat it with an agate or pumice stone. Nothing changed in this tedious procedure for centuries. Later, water-driven hammers came into use for smoothing. These hammers were superseded in the course of the 17th century by roll presses like those that had been used since the late Middle Ages for copper rotogravure printing. This was the first step toward smoothing in the "rolling press nip", i. e. calendering. Today, this method still determines the surface treatment of paper.

In 1798, Nicolas Louis Robert invented the paper machine. It took more than fifty years, however, until calenders were installed in the paper machine. These calenders – also called machine calenders – consisted of at least two hard rolls. A decade later the supercalender appeared with a large number of alternating hard

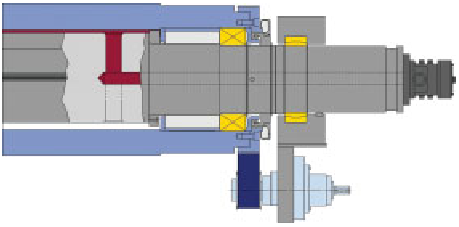


Fig. 6.66 Overall control roll, swimming roll (source: Voith).

and resilient rolls. The resilient rolls were often termed filled or paper rolls since rounds made of fibrous material (cotton, wool) were pushed onto the roll shafts where they were pressed together under high pressure and secured with closure elements. Paper rolls are highly prone to marking. They must therefore be replaced at regular intervals and finish-turned. This is why these supercalenders could only be operated off-line.

Conventional rolls deflect under the influence of the load and their dead weight, which would result in a nonuniform distribution of linear load in the press nips. To avoid this, the rolls had to be crowned, i. e. ground with a camber. The selected crown does, of course, only apply to a certain load. If it were desired to alter the load, the rolls had to be re-crowned.

Hence, the introduction of the “Swimming Roll” in the 1950s by Küsters was of decisive importance for the further development of both the machine calender and the supercalender. This roll consists of a fixed shaft with a shell rotating around it. Between the shaft and the shell is an oil-filled chamber. By adjusting the oil pressure in this chamber the shape of the roll shell can be changed (Fig. 6.66). Thus the “operating window” of calenders was suddenly expanded.

The swimming roll allows control of the linear load distribution across the width only in a given overall shape. This limitation was overcome with the next generation of nip control rolls introduced in 1974 by Escher Wyss, the Nipco roll (Fig. 6.67). Here the load distribution can be controlled locally zonewise. On this roll the rotating roll shell is carried by a large number of hydrostatic supporting elements, which in turn are supported on a fixed shaft. The hydraulic control unit combines several supporting elements into one zone. In all, there are six to eight effective hydraulic zones. As they can be controlled individually, the linear load can be specifically adjusted across the width of the calender. It is therefore possible not only to uniformly distribute the linear load across the roll width but also to increase or reduce it locally. Zone-controlled deflection rolls are meanwhile available

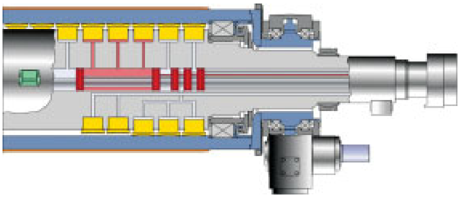


Fig. 6.67 Zone-control roll, Nipco roll (source: Voith).

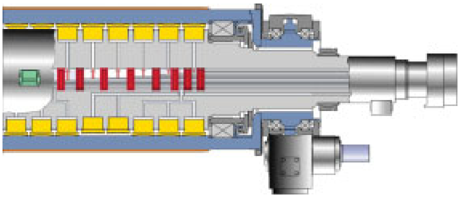


Fig. 6.68 Multizone roll, Nipcorrect roll (source: Voith).

in the marketplace under different names and designs by Küsters, by Metso and by Voith.

Since 1994 multi-zone control rolls have been in operation with up to sixty supporting elements arranged horizontally close together. These can be individually controlled so that even more precise profile corrections can be made (Fig. 6.68).

Machine calenders and supercalenders with width about 5000 mm and above are today equipped with zone-controlled rolls as standard. Narrower machines still use the simpler overall control type rolls.

Supercalenders are classic off-line machines as they have downtimes of 25–30% due to the filled roll change. To be able to keep pace with a high-speed paper machine at least two, sometimes even three, supercalenders were therefore required. This disadvantage of the supercalender led, at the beginning of 1980, to the development of the soft calender. The soft calender consists of at least one heated roll and one resilient roll covered with synthetic material. Because synthetic rolls are much more resistant to marking than the filled rolls of the conventional supercalender, the soft calender was also able to be used on-line. In many cases, the online soft calender was very successful. However, not all quality demands on the paper surface could be met with it. For demanding papers, the supercalender equipped with filled rolls and which could therefore only be operated off-line remained the only alternative.

Things changed in the middle of the 1990s with the emergence of improved synthetic covers. In 1994 the first calender of the new type (Janus Concept calender of Voith Paper) was built with all resilient rolls covered with special synthetic materials. At a first glance, this new calender looks like a conventional supercalender. In reality, it differs in many respects, e.g. by the reduced number of nips, less energy input and – most noteworthy – suitability for on-line operation. Thanks to a suitable combination of pressure, roll surface temperature, roll surface quality and number of nips, it was now possible to calender even highly demanding paper qualities on-line. Other machine builders followed (Küsters and Metso). The latest development is a calender (Voith's Janus MK 2), on which the roll stack is no longer arranged vertically but at an angle of 45°. The modern online-capable multi-nip calenders have extensively ousted the classic supercalenders. The few cases in which it is still used for technological reasons are treated in Section 6.9.4

6.9.3
The Different Calender Types

6.9.3.1 Machine Calenders

Machine calenders consist of two or more hard rolls and are practically always installed on-line. They are primarily used for paper that only requires moderate finishing or for pre-calendering grades that need further finishing treatment in order to obtain higher gloss and/or smoothness. Machine calenders are equipped with overall deflection or zone-controlled deflection rolls (Fig. 6.69).

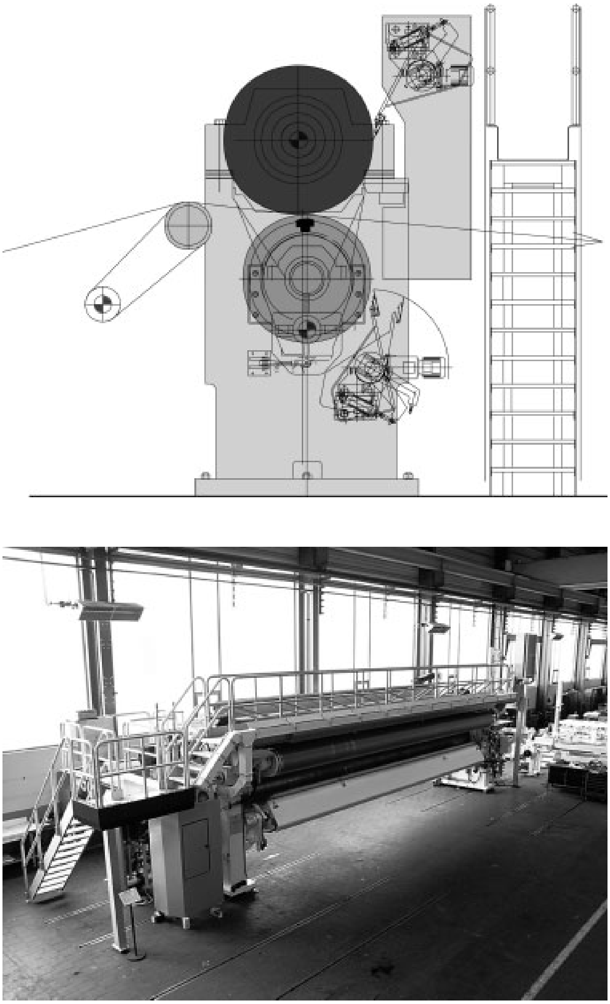


Fig. 6.69 Machine calender, schematic and photo of mounting (source: Voith).

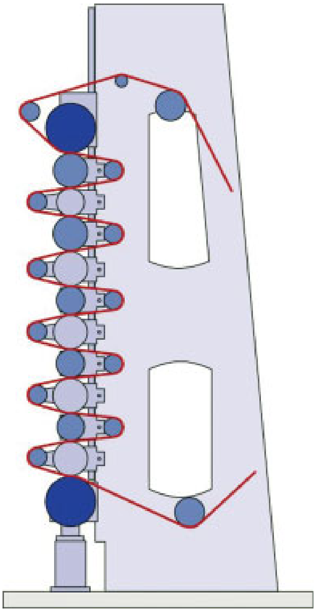


Fig. 6.70 Supercalender (source: Voith).

6.9.3.2 Supercalenders

Supercalenders are off-machine multiroll-calenders consisting of an unwind stand, a roller stack and a rewind stand. The usual number of rolls is 9–12. For specialty papers – such as silicon based papers for instance – the number can reach 18. The rolls are hard and elastic in turn. When the number of rolls is even, there will be a so-called “reverse” nip having two adjacent elastic rolls. The elastic rolls are filled rolls. The filling consists of a multitude of specialty paper sheets slid onto a steel shaft, compressed to the required hardness and then locked by nuts. The hard rolls are steel or cast chilled iron rolls and are often heated. The top and bottom roll are either overall deflection or zone-controlled deflection rolls. To prevent the filled rolls from getting marked by the web following a web break, the stack is equipped with a device for quickly opening the nips. Further important features are the spindle system, the overhanging load compensation system, doctors, web cutting and oscillating devices, flying splice devices, inner and outer lift platforms etc. The maximum working speed of supercalenders is approximately 800 m min^{-1} and the maximum line load approximately 450 N mm^{-1}. However, maximum speed, line load and maximum surface temperature cannot be applied at the same time because of the delicate nature of the filled rolls (Fig. 6.70).

6.9.3.3 Softcalenders

The basic version of the softcalender is the two-roll softcalender. Its main components are the soft covered deflection control roll and the heating roll. The linear pressure of a softcalender ranges from approximately 10–350 N mm^{-1} and the

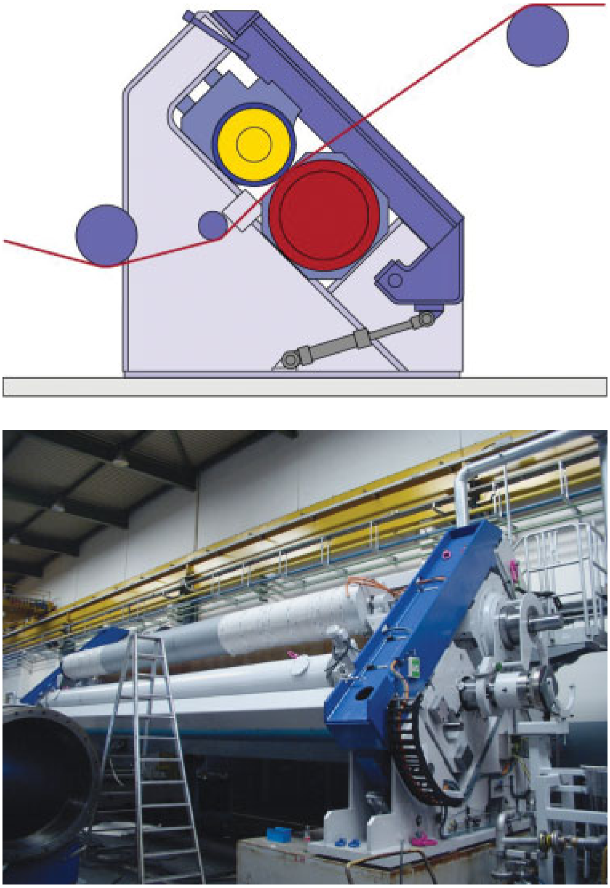


Fig. 6.71 Softcalender, schematic and photo of mounting (source: Voith).

surface temperature of the heated roll can be up to 230 °C. For two-sided calendering, two stacks with an inverted roll configuration are combined. In cases where one hot calendering nip per web side is not sufficient to obtain the desired finishing result, more calendering capacity is achieved by adding further soft nips. In contrast to supercalenders, softcalenders can also be installed on line because the soft covers can withstand line loads, load cycles and temperatures that are much higher than witnessed with conventional filled rolls (Fig. 6.71).

6.9.3.4 Modern Multinip-calenders

Modern multinip-calenders are similar in function to supercalenders. The main difference is that the filled rolls are replaced by polymer covered rolls. As a result, modern multinip-calenders can be installed on-line and can be run more than

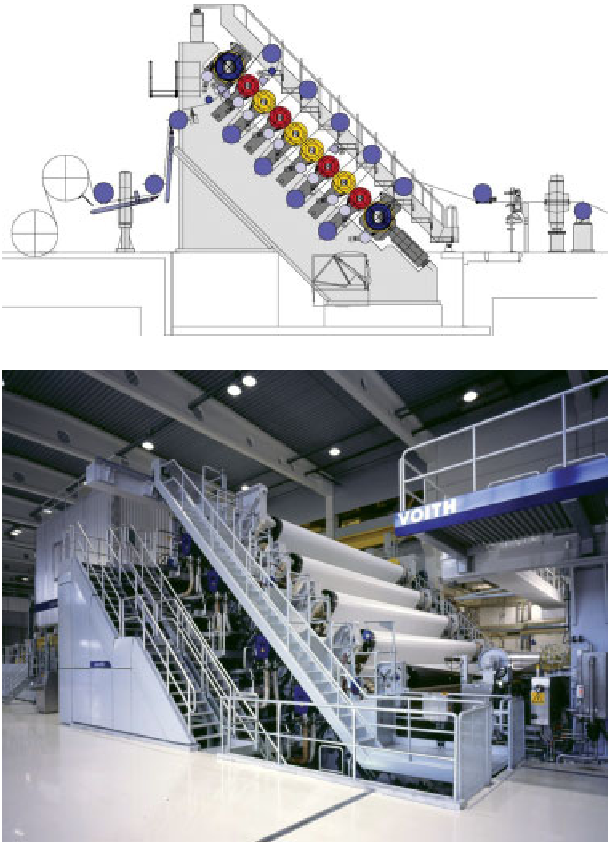


Fig. 6.72 Multinip-calender with inclined layout, schematic and photo of mounting (source: Voith).

twice as fast as supercalenders and with much higher surface temperatures and line loads.

Today, there are three calender designs which make use of the new technology (Janus MK 2 calender of Voith, ProSoft calender of Küsters, and the OptiLoad calender of Metso).

Voith's Janus Concept calender was the first multinip-calender that could be integrated into a fast running paper machine. Various roll configurations were possible, i. e. 6–10 rolls in one vertical stack, 2 × 5-rolls in two vertical stacks etc. As the polymer cover of the elastic rolls is less thick than the filling of the conventional paper rolls, no slideways and spindles are necessary. The intermediate rolls are supported by loading arms that incorporate the overhanging load compensation function. Depending on their design, the heated rolls can produce surface temperatures of up to 170 °C. Line loads in the range 250–500 N mm^{-1} are possible. When installed in-line with a paper machine, the Janus calender is featured

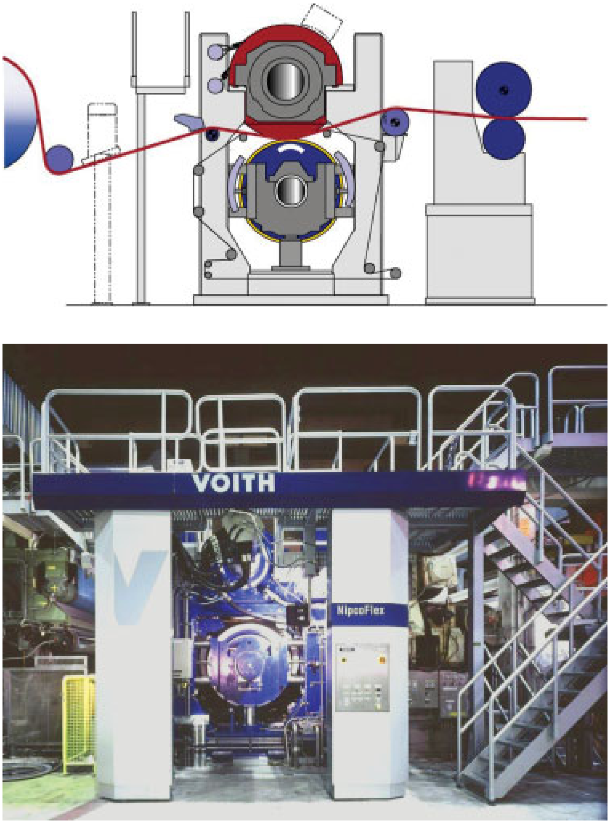


Fig. 6.73 Extended nip calender, schematic and photo of mounting (source: Voith).

with a special tail threading device. Similar parameters are found in the OptiLoad calender of Metso and Küsters's ProSoft calender.

Based on the Janus Concept calender, Voith developed the Janus MK 2. This latest multinip-calender version is mainly characterized by the stack being no longer arranged vertically but inclined at a 45° angle offering operational and technological advantages (Fig. 6.72).

6.9.3.5 Extended Nip Calenders

Certain board grades have traditionally received their final surface properties by means of a Yankee cylinder, i.e. a heated cylinder having a large diameter and a highly polished surface, or by soft calenders. This technology is about to yield to extended nip calendering which provides two advantages, namely a speed that is much higher than that possible with the Yankee cylinder and a better relationship of smoothness versus bulk than can be obtained on a soft calender.

The extended nip calender is based upon the well-established shoe-press technology. The machine consists of a heated metallic roll acting against a soft sleeve rotating around a shoe roll and a moistening device directed against the side of the web to be surface-treated. When passing the elongated nip, the web is calendered on the side contacting the heated metallic roll. Typically, the heated roll is operated at surface temperatures far above 200 °C. The nip length is determined by the length of the concave shoe. For board, the length varies between 130 and 250 mm. Technologically, extended nip calendering can be described as moisture and temperature gradient contour calendering on the basis of reduced line loads and leads to improved micro-roughness (PPS) and high bulk preservation (Fig. 6.73).

6.9.3.6 **Embossing Calenders**

The objective of embossing is to give the paper a three-dimensional pattern. This is achieved by means of a single nip calender.

There are three different embossing methods, namely “matrix” embossing, “flat-back” embossing and “union” embossing.

Machines for “matrix” embossing consist of an engraved ridged heated and sometimes chromium plated top roll and a soft covered bottom roll whose diameter is exactly double that of the top roll. By pressing both rolls together and running them at low speed, the pattern of the top roll is imprinted on the bottom roll. As a result, a paper web passed through the nip will have an embossed laid pattern on both sides. Matrix embossing is applied for graphic papers, wallpapers etc.

Flat-back embossers are similar to the a. m. calenders for geared embossing except that the diameter relation of the top and bottom roll is bigger or smaller than 1 : 2. With this type of calender, only the top side of the web receives a pattern. If both sides require a three-dimensional structure, the web has to be passed through the nip again with the former bottom side now turned against the top roll and with a reduced nip pressure. Flat-back embossing is applied for writing and printing papers, photographic papers, car body boards etc.

Union embossing calenders differ from the a. m. machines in so far as they consist of two rigid rolls of the same diameter. The rolls mesh. The distance between the two rolls is always adjusted in such a way that it is identical with the thickness of the web to be embossed. The result of union embossing is a web having a corrugated shape.

6.9.3.7 **Friction Calenders**

The purpose of friction calendering is to impart glazing to the paper. Friction calenders are single or double nip machines in which all rolls are driven separately at speeds that differ by 10–30 %. They are mainly used for glazing playing cards.

6.9.4
The Main Calendering Methods for Various Paper and Board Grades

6.9.4.1 Wood-containing Paper Grades

6.9.4.1.1 Newsprint

Newsprint belongs to the group of uncoated, woodcontaining printing papers. Nowadays it consists of up to 100% DIP (deinked pulp), basis weight around 45 g m^{-2}. These papers are produced on machines at speeds of up to about 1900 m min^{-1} and are equipped with machine calenders or on-line soft calenders. Modern paper machines equipped with just two double-felted press nips produce a base paper whose top side is slightly rougher than the bottom side. If a soft calender is used, its heated roll is always installed in the top position, since the contact of this roll with the rougher top side reduces the two-sidedness. The shrinkage-preventing, single-tier dryer section of a modern newsprint machine causes a more or less pronounced upward curl. To eliminate this curling, a steam moisturizer is installed in front of the first calender nip. Since optimal CD caliper profiles are a basic prerequisite for a smooth-running printing process, particularly with lightweight newsprint, deflection control rolls are used in calenders that allow zone-controlled, short-wave caliper profiling and insure 2-sigma values of below 0.5 μ in the caliper. As far as the printing process is concerned, offset printing is becoming more and more popular. A differentiation is made between cold offset and heat offset. Each method places a different demand on the paper.

For cold offset printing, Bendtsen roughnesses of the order of 150–200 ml min^{-1} are required. This roughness level can easily be achieved on a two-roll online soft calender. The linear loads here are between 40 and 100 N mm^{-1}. The calendering temperature corresponds approximately to the web temperature.

For heat offset printing, lower roughness is required, i.e. Bendtsen values of approximately 100 ml min^{-1}. To meet this requirement, on line soft calenders with a total of two nips are used, so that each side of the web contacts a heated roll once. With a suitable layout – linear load, roll surface temperature – even rotogravure-capable SC-B papers (see below) can be produced.

6.9.4.1.2 SC-B/Offset and Rotogravure

SC papers can be subdivided into two main grades, SC-B with a high percentage of recovered paper (up to 100%) and SC-A with a high percentage of woodpulp (TMP or groundwood; up to 80%).

In contrast to SC-A top grades (see below), SC-B papers with a partially 100% DIP portion are already being calendered on-line today on 6, 8 or 10-roll calenders. The large percentage of DIP means that the papers are very quickly prone to increased black calendering. This trend continues with increasing web moisture. For this reason, cooling rolls are indispensable here. These reduce the moisture losses and therefore allow running into the calender at approximately 9% moisture. On line calendering of course places special demands on the availability of the machines, especially on the service life of the resilient rolls and thermorolls and presupposes a properly functioning tail threading system.

6.9.4.1.3 **SC-A/Offset and Rotogravure**

SC-A top grades are calendered on 10–12-roll multi-nip calenders in the off-line process, allowing speeds of up to 1500 m min^{-1}. Due to the much higher calendering temperatures compared to the supercalendering process, the web running into the calender must be significantly moister. To achieve approximately 5 % end moisture after the calender, ingoing moistures of 8–10 % are necessary. Still higher web moistures do not produce any additional increase in the effect, on the contrary, they even worsen the optical properties. The moisture losses between the calender and the rewind should therefore be kept as low as possible. The use of cooling rolls has proven useful in these cases. These are installed shortly after the last nip. In this way, the web temperature is suddenly cooled down by approximately 20 °C and the moisture loss is reduced accordingly.

Due to the previously mentioned high calendering temperatures in conjunction with significantly higher steam rates – up to five steam moisturizers are used – offset papers can be produced that already come very close to the LWC grades and are characterized by high gloss, a very uniform surface – no more "print mottling"! – and greatly reduced black calendering.

The calendering of rotogravure-capable SC papers proves to be more difficult, because rotogravure calls for very smooth paper surfaces in order to minimize the number of missing dots. A certain compaction is necessary for this, which is produced by the number of nips, linear load, temperature and addition of steam. With increasing calendering speed it is of course more and more difficult to achieve the desired compaction. For high quality rotogravure papers the maximum possible calendering speed is therefore around 1100 to 1200 m min^{-1}.

6.9.4.1.4 **Blade-coated LWC/Offset and Rotogravure**

LWC papers are either blade-coated or film-coated. In both cases it is recommended to calender the base paper before coating. The objective of this pre-calendering is to optimize the CD caliper profile, to compact the sheet structure and to easily smooth the web surface. In this way, the end result of calendering can be improved in Gardner gloss by up to 5 percentage points and in PPS-10S roughness by up to 0.2 µm. The pre-calendering mostly takes place on a two-roll machine calender, i.e. in a hard nip. It is, however, also possible to use a two-roll soft calender. Both types of calender are equipped with a deflection control roll. The calendered LWC papers go either to offset printing or to rotogravure printing.

LWC papers with a typical basis weight of 50–70 g m^{-2}, which are blade-coated on off-line coating machines, are still calendered off-line today. The extreme demands made on the smoothness of these papers provided with coating of only 6–8 g m^{-2} per side – the PPS-10S roughness values are around 0.7–0.8 µm – have until now prevented on line calendering at high speed. For the off-line calendering of these papers generally modern 10 to 12-roll multi-nip calenders are used. The calendering temperatures are up to 130 °C. The linear loads range between 300 and 400 N mm^{-1}.

6.9.4.1.5 Film-coated LWC Offset

On LWC offset grades of typically 45–70 g m^{-2} basis weight, the on line-capable two-sided simultaneous film coating method is becoming more and more popular, even at the highest speeds. Due to film splitting, the surface of the paper is distinctly rougher than with the blade coating method and hence harder to smoothen. As offset papers do not require such high smoothing as rotogravure papers, they can today already be calendered on-line. Modern 6, 8 or 10-roll multi-nip calenders are used for this purpose. The calendering temperatures partially lie above 160 °C. The linear loads can reach 450 N mm^{-1}. Gardner gloss values of 55% are not infrequent. The PPS-10S roughnesses are between 1.4 and 2.0 µm. Today's base papers for LWC offset may contain up to 90% recovered paper. It should be noted that greater efforts are also being made to produce LWC rotogravure grades by the film-coating method. These film-coated LWC rotogravure papers can then be calendered on line.

6.9.4.2 Woodfree Paper Grades

6.9.4.2.1 Woodfree Uncoated Papers

Woodfree uncoated papers include, above all, office papers, which are in turn subdivided into writing and printing papers as well as copy papers. In the past, these papers were not supercalendered. Simple machine calendering was considered satisfactory. However, the demands made on the surface quality of these papers have now increased considerably.

Besides the standard copy papers with a Bendtsen roughness of 220–280 ml min^{-1} there is also a smooth paper for color copies with a roughness of less than 80 ml min^{-1}. For standard copy papers a low-loaded machine calender with two hard rolls continues to be sufficient. As these papers require only a low sheet compaction, calendering in the hard nip does not lead to detrimental mottling. In the case of copy papers with a Bendtsen roughness of below 150 ml min^{-1}, sheet compaction by a two-roll machine calender is already so high that distinct mottling occurs here. To avoid this, a 2 × 2-roll on line soft calender is required. As, in this case, each side of the web contacts a hot nip once, the roughness values are low for the top and bottom sides. It has been found that linear loads of 150–250 N mm^{-1} and roll surface temperatures above 140 °C provide the optimal calendering conditions. Copy papers are cut-size papers, therefore uniform calipers are of special significance. Thus, irrespective of whether a machine calender or a soft calender is used, it is recommended to equip the calender with a multi-zone deflection control roll to optimize the caliper profile.

6.9.4.2.2 Woodfree Coated Paper Grades

With these papers a differentiation must be made between single-coated, double-coated and triple-coated papers. In addition, it is also of significance whether the papers are to be used in rolls or as cut-size sheets.

Single-coated, woodfree papers are generally calendered on-line. The machines used for this are mostly 2 × 2-roll soft calenders. At speeds up to 1300 m min^{-1}, Gardner gloss values of 55–65 % can be achieved. To insure good flatness – this applies above all to cut-size sheets – the papers must be subjected to only moderate linear loads.

Up to the mid-1990s, double or triple blade-coated woodfree high-gloss papers with coating per side of 20–30 g m^{-2} were calendered on supercalenders. Even today, they are still calendered off-line. However, 8–10-roll multi-nip calenders, whose resilient rolls are covered with synthetic material, have ousted the classic supercalenders. In contrast to conventional supercalenders, these new types can be operated at higher temperatures, i.e. temperatures of 100–130 °C. Consequently, the desired calendering parameters – PPS-10S roughness 0.7–0.9 µm and Gardner gloss 75–85 % – can now be achieved at much higher speeds, around 700–1000 m min^{-1}. A further increase in speed would theoretically be possible, but presupposes an increase in the linear load. With rising linear load, however, the flatness, which is particularly important for cut size paper, would be negatively affected. Linear loads of 200–300 N mm^{-1} have proven to be optimal. Usually, these calenders are equipped with two cooling rolls.

It goes without saying that in this premium segment there is, in addition to high-gloss paper, always a certain portion of matte or satin papers. Two different calendering processes exist for these. Either an on-line soft calender with two synthetic-covered rolls is built into the coater – by this soft/soft calendering the matte character of the paper is hardly changed, but the abrasion resistance is significantly improved – or the a.m. multi-roll off-line calender is used by calendering the web in its uppermost and lowermost nips while the intermediate nips are "run through" – in this case both the gloss and smoothness of the web are increased.

6.9.4.3 Specialty Papers

6.9.4.3.1 Silicone Base Paper

Silicone base papers are used as carrier papers for the later application of a one-sided or two-sided layer of silicone, onto which, in the following operations, further layers, e.g. adhesive in combination with label paper, are applied. Silicone base papers presuppose special quality features. These include, above all, high compaction, uniform caliper and moisture, high transparency, strength, good flatness and a low surface roughness which ensures that the later application rates of the cost-intensive silicone are minimized. The basis weight of the silicone base paper is between 60 and 160 g m^{-2}. As in the past, these papers are calendered off-line on special supercalenders with at least 15 rolls. The resilient rolls consist of a cotton/linen mixture. The surface temperatures are around a maximum of 150 °C and the linear loads around 450 N mm-1. The operating speed is 600 m min^{-1}. It is only in instances where not such high demands are made that modern off-line multi-nip calenders with synthetic-coated resilient rolls are taken into consideration.

6.9.4.3.2 Laminated Base Paper

Laminated base papers are highly absorbent papers for the production of layered materials saturated with synthetic resins. The basis weight of these papers with an extremely high percentage of fillers – up to 40% – and correspondingly low strength, lies between 40 and 80 g m^{-2}. Laminated base papers are very dry. Their moisture content is only 1–2%. Characteristic of the production process of laminated base papers is that the trim widths change frequently and to a great extent. The base papers must be opaque and require one-sided smoothing to Bekk smoothness values of 400–600 sec. For this purpose, 5-roll on-line multi-nip calenders with a linear load of 300 N mm^{-1} are used. The roll surface temperatures of the heated rolls are around 150 °C. The resilient rolls are covered with synthetic materials. A steam blow box is also used.

6.9.4.4 Board

6.9.4.4.1 Uncoated Board

Uncoated boards include a large variety of sub-grades like test liner, kraft liner, white top liner, liquid container board etc. Some of these grades need no calendering at all. Where calendering is required to achieve better surface properties, Yankee cylinders and soft calenders have been used. As with coated grades, this traditional technology is about to be superseded by extended nip calendering – see Section 6.9.3.5.

6.9.4.4.2 Coated Board

Coated board grades range from one- to five-ply boards and can consist of virgin fibers and/or recycled fibers. The most important properties are high bulk, stiffness and smoothness. The board is usually one-side coated. In some cases, however, it can also be two-sided.

Traditionally, calendering has been performed with Yankee cylinders or soft calenders. In view of the bulk saving, this classical technology is increasingly being replaced by extended nip calendering – see Section 6.9.3.5.

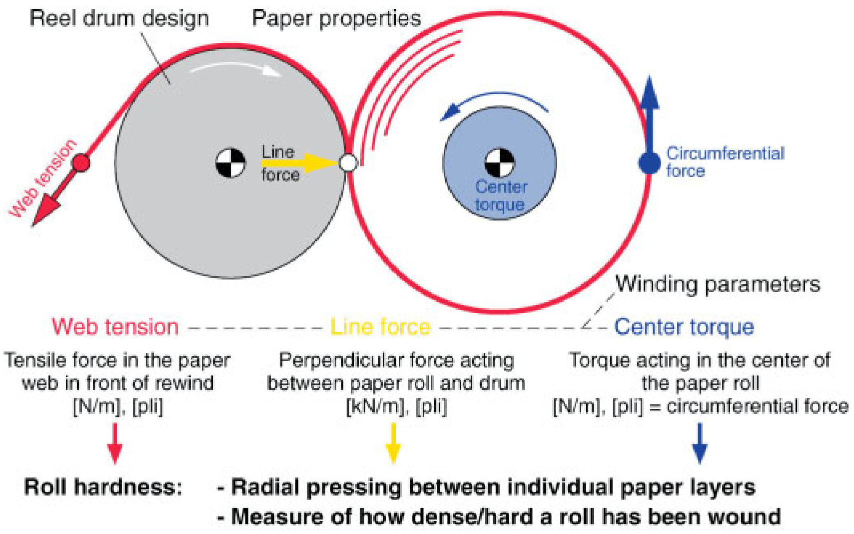


Fig. 6.74 Variables influencing the structure of a roll (source: Voith).

6.10
Reeling
Matthias Wohlfahrt

6.10.1
Objectives and Basics

The purpose of reeling is to wind up the continuously produced paper web on reel spools building up paper rolls of up to 4.5 m diameter. The paper rolls have to fit the requirements of any following process steps. These mainly concern the paper roll structure such as hardness and overall shape. As reeling is a discontinuous process economic aspects as regards broke due to roll change/turn-up are important as well. This concerns the so-called top broke at the outside of the finished parent roll and the bottom broke at the inner layers of the spool.

There are only a few key parameters which influence the hardness of a roll (Fig. 6.74). These are web tension, line force and center torque. As, for example, some paper grades only allow low web tension to avoid breaks at the winder this parameter often cannot be used for optimization of roll hardness. So the main parameter is the line force which usually varies between 1 and 6 kN m^{-1}. Line force can be applied either by the reel drum or the paper roll. The center torque applied on the reel spool is the third tool to build a good roll structure. There are different reel types combining these parameters in different ways depending on the special requirements of the individual paper grades to be reeled.

Table 6.3 Influence of winding parameters on roll hardness for constant velocity.

Factor for $v = 1200\ \mathrm{m\ min^{-1}}$	Unit	Heavy weight coated paper	Light weight coated paper
f_{const}	$\mathrm{N\ mm^{-2}}$	–0.6	–0.26
f_{WT}	$\mathrm{N\ mm^{-2}/N\ m^{-1}}$	8.2×10^{-4}	7.4×10^{-4}
f_{CF}	$\mathrm{N\ mm^{-2}/N\ m^{-1}}$	5.8×10^{-4}	3.7×10^{-4}
f_{LF}	$\mathrm{N\ mm^{-2}/kN\ m^{-1}}$	3.0×10^{-1}	9.6×10^{-2}

For certain ranges roll hardness can be described by a linear equation as

$$s_{\mathrm{rad}} = f_{\mathrm{const}} + (f_{\mathrm{WT}} \times \text{web tension } (\mathrm{N\ m^{-1}})) + (f_{\mathrm{CF}} \times \text{circumferential force } (\mathrm{N\ m^{-1}})) + (f_{\mathrm{LF}} \times \text{line force } (\mathrm{kN\ m^{-1}}))$$

with the radial pressure s_{rad} defined as a positive value.

The f-factors can be determined e. g. by trials on a pilot reeler, where the same paper roll is wound several times varying the above parameters and measuring the resulting roll hardness.

As Table 6.3 shows, the f-factors depend on paper grades which can be explained by their individual quality parameters.

The negative value of f_{const} signifies, that for every paper grade and velocity the combination of the parameters web tension, circumferential force and line force has to reach at least a minimum value below which the roll could not be wound.

The main influencing paper properties in winding are porosity, smoothness, Young's modulus, density, friction coefficient and cross machine (CD) caliper profile. The reel drum is a design parameter which cannot be changed during winder operation. On the other hand its design has to be reviewed and possibly adapted when the paper grade produced is changed fundamentally as regards the above quality properties.

6.10.2
History

During reeling the paper quality cannot be improved any more. This why over several decades the simple pope reel (Fig. 6.75) was used with nearly no modifications. This type of reel only applies a line force system in the primary and the secondary arm and has no center drive. The primary arm handles the spool at the beginning of the winding process and turns the spool around the center of the reel drum. The secondary arm guides the spool on the horizontal rail. The line force system in the arms has to produce the nip load and has to compensate for the growth of the roll.

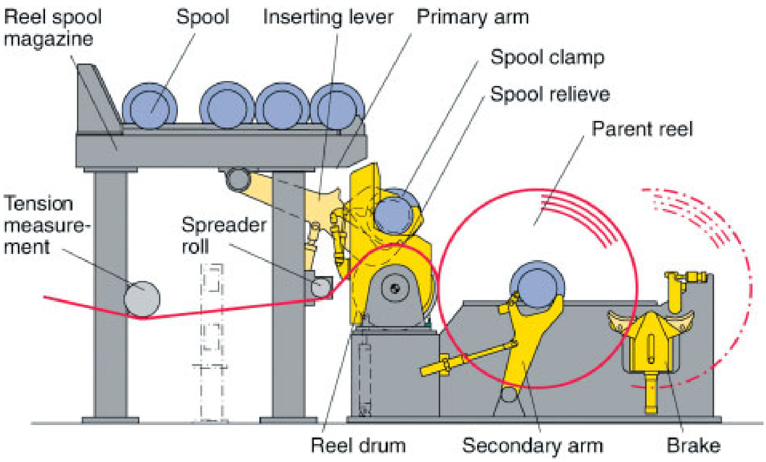


Fig. 6.75 Standard Pope reel (source: Voith).

Some other reels, e.g. for special papers have no nip for line force application, but a drive at the spool center. This was necessary for example for sensitive papers like noncarbon required (NCR) grades. Without a nip the speed is limited to about 700 m min^{-1}.

In the 1990s demand increased dramatically. For example in LWC production coating has been changed from an off-line to an on-line process. This means, that paper grades with critical properties (very high smoothness and high density) have to be wound on the reel at high machine speeds. Furthermore the reel diameter has been increased from e.g. 2.8 m to more than 3.2 m for better efficiency of the paper machine. This required the development of new reel types.

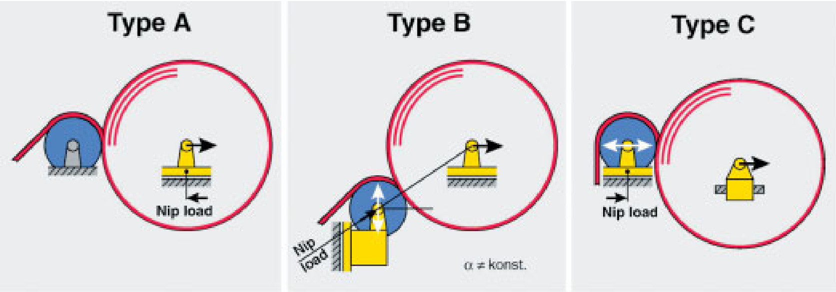
6.10.3
New Generation reels

6.10.3.1 Center Drive

A common characteristic of the reels of the new generation is the center drive in the reel spool applied during the whole winding process. Especially for paper grades with sensitive surfaces the center drive allows one to reduce the nip load and generate sufficient roll hardness at the same time.

6.10.3.2 Nip Load System

In modern, wide machines the nip load system uses hydraulic cylinders. Here the nip load system is still a distinguishing factor. Type A in Fig. 6.76 has a nip load system in the primary and secondary arm. When the nip load is applied by the parent reel, which may have a weight of up to 120 t the friction forces can no longer be neglected, so type A reels sometimes use a low friction linear guide for the parent roll to reduce these forces. As a further possibility the nip load may be



	Type A	Type B	Type C
Reel drum	Stationary, fixed	Vertically movable	Horizontally movable
Parent roll	Horizontally movable	Horizontally movable	"Stationary"
Line force system	2 systems: primary arm for spool clamp, secondary arm for transfer	1 system: reel drum carriage Angle not constant	1 system: reel drum carriage
Spool weight	Influence on line force in primary arm operation	No influence on line force	No influence on line force

Fig. 6.76 Comparison of new generation reels (source: Voith).

controlled by force sensors as part of a force controlled system instead of the pressure in the hydraulic cylinders. One disadvantage is still given: the change of nip load application from the primary to the secondary arm.

The next two reel types have a movable reel drum to generate the nip load. The advantage is that there is no change of nip load system as in type A. Type B has a drum movable in the vertical direction. Here the weight of the drum has to be compensated as there is a large load component in the vertical direction but only a small part of it is used for nip load control. This reduces the accuracy of this kind of control system. Type C has a drum movable in the horizontal direction. Here the force direction of the nip load is orthogonal to that of the drum weight. Using low friction carriages, line force deviations due to friction are low.

With this system very low line forces can be realized with high accuracy. For example, now the sensitive NCR papers can be wound up with a nip allowing about double the speed.

6.10.3.3 **Oscillation**

The reel spool in the secondary arm is way-controlled. It has to compensate for the growth of the roll diameter. The reel drum is force controlled and follows the movement of the nip. When the secondary arm gets an overlay of a sine movement in the machine direction counteracting at FS and DS, the drum follows without changing the nip load and its CD uniformity. This requires a vertical web run before the reel drum, in order not to influence web tension over the width. The result is an oscillated paper roll (Fig. 6.77), realized with only a few small further hardware components. This feature is very useful for "hard" paper grades with

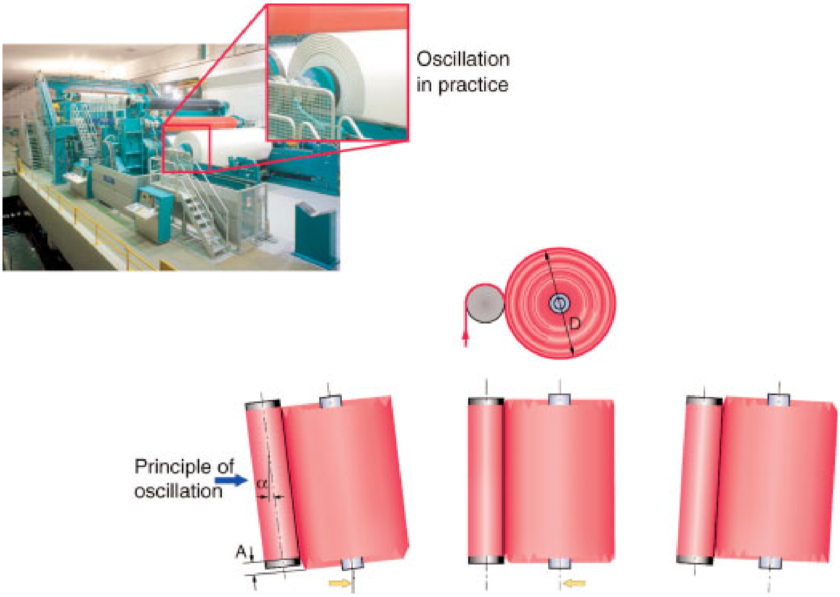


Fig. 6.77 Oscillation in reeling (source: Voith).

high Young's modulus. Deviations in CD caliper profile cannot accumulate so easily which allows one to wind larger diameters without winding defects.

6.10.4
Reel Drum Design

The structure of the wound paper roll is also influenced by the design of the reel drum. As shown in Fig. 6.78, two kinds of air bubbles may occur at the reel. The boundary layers below the web and on the reel drum are mainly influenced by the

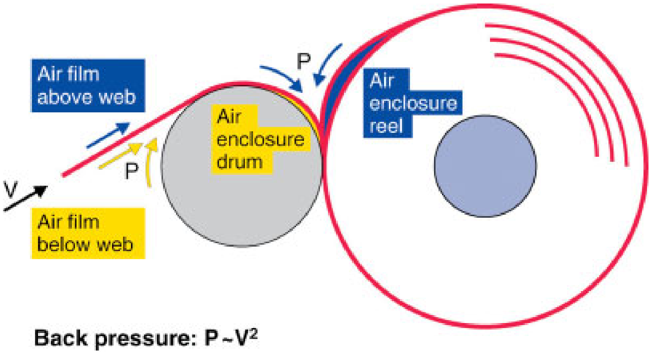


Fig. 6.78 Influence of air boundary layers on winding result (source: Voith).

web speed. Low paper porosity leads to air accumulation (air bubble) between the web and the drum before the nip. The web is no longer firmly fixed in the cross machine direction and can float in CD which will lead to uneven edges. A critical situation occurs when the air bubble gets too big and even goes through the nip. The resulting wrinkles cause broke. The air bubble problem can be avoided or reduced by two measures. First, narrow grooves in the drum surface allow the air to pass the nip. Practical experience has shown that for higher speeds and lower paper web porosity through-drilled drums have the highest efficiency. Here the air is not compressed as it goes through the drills into the drum and can leave below the drum.

Deviations in the CD caliper profile lead to a noncylindrical roll shape. This means, that the nip is not closed over the whole width and air can be easily wound into the roll between the outermost two layers. When paper porosity is high, the air can escape before coming again through the nip. If not, the air will also accumulate between two layers of the paper web in the parent roll before the nip. Sometimes there exist more bubbles between several layers. If the bubbles are almost stationary and not too large, then generally no problems occur but when they are pulsating irregularly in the cross machine direction, they can cause wrinkles and broke.

With the groove design on the reel drum the wind-in of air cannot be avoided, but the air can be moved steadily to the edges resulting in a stable balance of air in the roll. Here a pressure relief groove or wide grooves will be applied. The groove has to be a spiral, changing its direction in the middle of the drum. The arrow of the groove has to show in the web run direction otherwise the air would be transported towards the machine center.

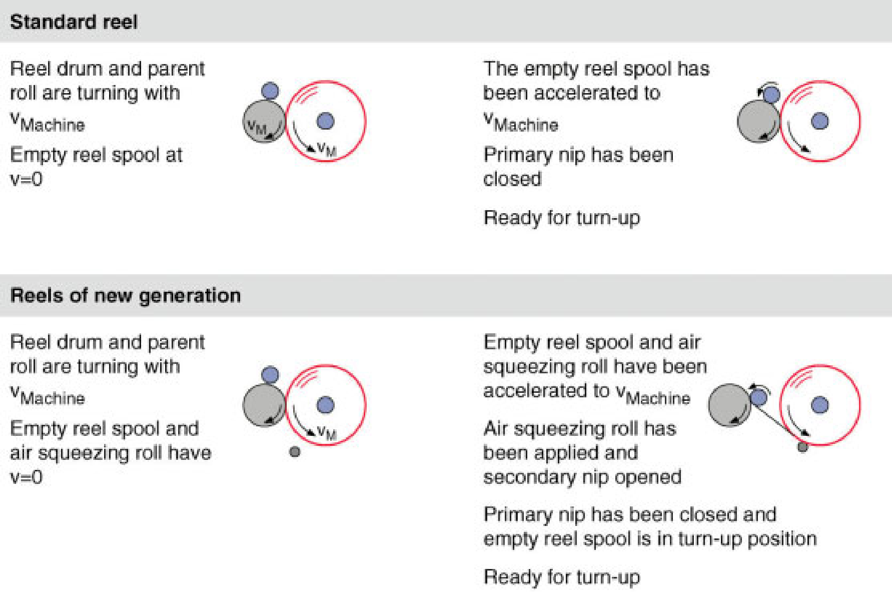
A possibility to reduce the amount of wound-in air in the parent roll is to use a rubber covered reel drum. This drum can adapt to the uneven surface of the roll to a certain degree and thus close the nip over the whole width. At the same time line force distribution with the rubber covered drum is more even over the whole machine width thus avoiding the high pressure areas that can occur with a steel drum.

6.10.5
Turn-up Systems

6.10.5.1 General

The continuous process of paper production is interrupted at the reel, when the required roll diameter or web length has been reached. Now the paper web has to be cut, a fresh reel spool started and the finished parent roll discharged. So first the empty reel spool has to be accelerated to machine speed. With a standard Pope reel, the empty reel spool will now be lowered, till the nip is closed (Fig. 6.75). The reel is now ready for the turn-up which will be described separately.

Some new generation reels show a different sequence. They first open the nip by moving the parent roll (Fig. 6.79). In order to avoid too much air being wound in an air squeezing element like a small roll or a brush on the parent roll is applied.



Standard reel

Reel drum and parent roll are turning with $v_{Machine}$

Empty reel spool at v=0

The empty reel spool has been accelerated to $v_{Machine}$

Primary nip has been closed

Ready for turn-up

Reels of new generation

Reel drum and parent roll are turning with $v_{Machine}$

Empty reel spool and air squeezing roll have v=0

Empty reel spool and air squeezing roll have been accelerated to $v_{Machine}$

Air squeezing roll has been applied and secondary nip opened

Primary nip has been closed and empty reel spool is in turn-up position

Ready for turn-up

Fig. 6.79 Turn-up preparation for two kinds of reel types (source: Voith).

After the parent roll is in its end position, the primary arm can be lowered to the turn-up position and the primary nip is closed. The turn-up position of the primary arm can now be varied between the position of a standard Pope reel and the position on the rails, depending on the demand of the turn-up system and the paper grade. The turn-up is easier and faster with self-threading concepts when the empty spool is already partly wrapped by the web.

6.10.5.2 **Nordic Turn-up**

The most simple and oldest system is the nordic turn-up. The parent roll opens the nip a little and then is decelerated. Thus a web loop is formed between the reel spool/reel drum running at machine speed and the decelerated parent roll. Because of the vacuum between the outgoing web and the empty reel spool, the paper web starts to wrap the spool. When it reaches the nip, at low basis weights the web will be cut by the suddenly induced acceleration. For high basis weights, the web will be cut by the high tear forces, because the paper on the parent roll and on the new reel spool moves in different directions. For heavier paper grades wrapping of the empty spool can be supported by an air stream from below. The disadvantages of this system are the high amount of top broke and the high load of all components, when the paper is torn in the nip, especially at higher basis weights.

6.10.5.3 **Web-wide Cutting Knife**

With the winding concepts, where the nip between drum and finished roll is opened, the web can be cut with a web-wide knife operated in the open draw. As the new spool is already wrapped by the web, the system is self-threading. The system has a very high turn-up efficiency and is mainly applied for lower and medium basis weights up to about 120 g m^{-2}.

6.10.5.4 **Air-supported Turn-up Systems (Gooseneck, Cobra)**

The air-supported turn-up systems have their main applications at basis weights up to 100 g m^{-2}, or in special cases up to 150 g m^{-2}. A blowpipe formed like a gooseneck gave the name to one of these turn-up systems. A small cut of a few centimeters in the cross machine direction will be created, e. g. with a needle, in the middle of the web before the drum. The thus weakened web can be blown by the gooseneck blowpipe to the empty reel spool. The tear in the cross direction will be supported by two nozzles blowing from the middle to the edges between the primary and the secondary nip.

For very small paper machines one or two blowpipes in the cross direction, positioned at the edges after the primary nip, are sufficient. They cut the web from the edges and transfer it to the empty spool. The so-called Cobra system can also be used to support the gooseneck for large paper web widths.

The air-supported systems only need compressed air as a medium and they have a quite simple design. As web cutting is not clearly defined the turn-up quality depends on the paper properties and the machine speed. As a further consequence some bottom broke may occur.

6.10.5.5 **Tape Turn-up System**

For higher basis weights and board and packaging grades the tape turn-up system is often used. Here a tape of sufficient strength is placed before the drum, below the web, across the machine width. One end of the tape is provided with an adhesive which will connect the tape to the edge of the empty spool as soon as it reaches the nip. A brake on the end of the tape builds up adequate strain in the tape so that it can tear the web when it is wound as a spiral on the empty spool. This system can provide defined tear forces acting on the web at the tape edge. Although several tape types with different thicknesses are available, there are still bottom losses due to the marking of the tape.

6.10.5.6 **Turn-up with High-pressure Water Jet**

One of these kinds of turn-up system has two high-pressure nozzles before the reel drum which can be moved very quickly in the cross direction. These nozzles start in the middle of the web at a distance of about 20 to 40 cm. The high-pressure water jet thus cuts a center strip which is transferred to the empty reel spool after the primary nip. After its successful turn-up, the two high pressure nozzles are

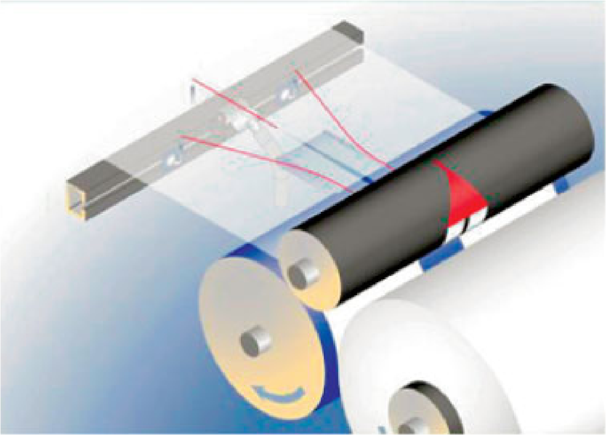


Fig. 6.80 Turn-up system with high-pressure water jet and cutting form sheet (source: Voith).

moved at high velocity towards the edges of the paper web which finishes the turn-up of the full web width. The kind of center strip cutting and transfer to the empty spool is the main difference in the existing systems.

On a new generation reel, where the secondary nip is opened, the next step is to cut the center strip in the open draw after the primary nip with an air nozzle or a small knife. The stripe is then self-threading and the turn-up can be finished as described above.

Another high-pressure water jet system is similar to a gooseneck which only turns up the center strip. This system can be used both with a closed and with an opened secondary nip. With these systems the beginning of the center strip is not immediately fixed at the empty reel spool, which can lead to considerable bottom broke especially with the gooseneck-type system.

Figure 6.80 shows a newly developed system. A center strip is cut by two high-pressure water jets as described before. For about one second a thin strip in the middle of the center strip is cut by means of two further high-pressure water jets. This thin strip is sucked before the reel drum and blown into the pulper. Now a form sheet with an adhesive at one end can be connected to the empty reel spool through this thin slot from underneath the web. This form sheet picks up the separated center strip parts on the right and left side. As soon as the form sheet is on the empty spool the turn-up is finished by moving the two other high pressure nozzles to the edges. With this system every step in the turn-up is clearly time-defined, and no component depends on the paper properties or the machine parameters. So high turn-up efficiency is given with almost no bottom broke as the web is fixed on the empty spool accurately from the beginning. There is also no limitation for higher basis weight applications.

6.11
Paper and Board Machines
Herbert Holik

Since the earliest times of industrial papermaking fourdrinier and mould formers have been used for the production of all kinds of paper and board. In the last century the machines started to be more customized to the special requirements of the individual product grade, based on quality, economy and operational requirements. When planning today a new machine or a major rebuild requirements have to be defined and decisions made relating to e. g. capacity, furnish, essential product properties, frequency of production changes, multi-ply, multi-layer or single-layer production, machine width and speed, machine equipment, etc. The variety of machines and their layouts are mainly related to the five main classes of paper and board grades with their varying requirements and can be defined as:
- graphic paper machines
- packaging paper machines
- board machines
- tissue machines
- specialty paper machines

6.11.1
Graphic Paper Machines

The majority of paper machines worldwide produce graphic paper grades on fourdrinier wire sections or on hybrid formers. These kinds of conventional forming section usually satisfy the quality requirements. Their disadvantages are the limitation in machine speed of about 1200 m min^{-1} and for some paper grades the nonsymmetry in the web z-direction.

Modern paper machines for graphic paper production are – except for tissue machines – the fastest paper machines. They comprise a gap former, a closed-draw press section and a single tier or combined single/double tier dryer section and, in certain cases, a size press or a coating station. The technological progress as well as increased cost pressures have led to in-line multi-nip calendering positioned between the dryer or coater section and the reeler in SC and LWC papermaking lines.

The paper machine layout and operating conditions differ according to the special requirements of the grades produced as regards
- woodfree paper such as copy paper or base paper for coated paper
- wood-containing paper such as newsprint and SC or LWC paper grades

with
- off-line or on-line coating and
- off-line or on-line calendering.

An example of woodfree paper is copy paper. The most important properties are high bulk at a certain roughness, and good formation. Here the whole papermaking process has to be considered to meet the high bulk requirements of the

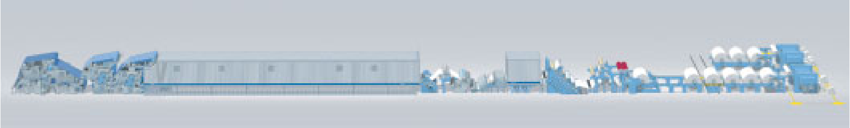


Fig. 6.81 Schematic of a state-of-the-art paper machine for LWC paper production (source: Voith).

market. In particular the wet pressing impact has to be limited in favor of a bulky sheet. The trade-off between dry content, speed potential, energy consumption, and paper quality is a matter of continuous research and development activity. As a consequence, single-nip presses have been recently introduced for copy paper production. The single nip press employs one shoe nip and is double-felted. This design enables a no-open-draw web run into the dryer section. Despite the lower web dryness the speed limit is currently well above 1400 m min^{-1}. With increasing machine speeds formation quality decreases. Here the application of lamellas in the headbox nozzle can improve the formation quality to a certain extent. The upcoming tendency for hard fine flocs in look-through is counteracted by optimization of the lamella geometry. With the lamellas the MD/CD ratio of strength parameters is reduced, which results in higher strength in CD but also lower strength in MD. These papers are in general single-layer products with one paper machine producing copy paper with a three-layer headbox. Today's speed limit in copy paper production is about 1600 m min^{-1}. The dryer section is a single tier with a double tier part after the size press or the film coating. Double tier is required in order to produce a paper which does not curl in the copy machine. For coating base paper production a single tier dryer section is possible as the non-symmetrical "frozen tension" during drying in a single-tier dryer section is eliminated during coating by wetting.

Machines for wood-containing papers aim for high dry content after the press section. This not only reduces energy consumption in the dryer section but also improves machine runnability due to the resulting higher web strength at the first free draw. High demands regarding surface smoothness such as for SCA paper grades require a press section where both web sides come into contact with a smooth roll surface without a felt in between. High surface smoothness has to be aimed for, starting from forming and followed during pressing. Smoothness generation by excessive calendering results in blackening, especially when recycled fibers are used and at lower basis weights. The dryer section is single tier for high runnability at maximum machine speeds which are today up to 1950 m min^{-1}.

Optimized fabrics support the efforts of the paper maker towards high quality and economy. E. g. the wire design has to assist high filler retention in the forming section and the design of the press felts has to ensure good surface smoothness and long lifetime at constant quality production and high machine runnability.

Figure 6.81 shows a schematic of a modern paper machine for LWC paper production started up in 2004. It includes a gap former wire section, a press section with a double-felted first press nip and a second press nip with felt and transfer belt, a pre-dryer section followed by a soft calender for preliminary calendering, a coating station, an after-dryer section, a ten-roll multi-nip calender and the reeler. A winder follows which converts the large parent rolls into suitable-size rolls.

6.11.2
Packaging Paper Machines

The main products of packaging paper machines are grades which are the base for corrugated board. Corrugated board consists of two outer layers (testliner or kraftliner) which are glued to a corrugated inner layer (corrugating medium or fluting) to obtain high bending stiffness. Testliner and corrugating medium are made from recycled fibers, kraftliner and fluting from virgin fibers. Corrugated containers must safely transport the packed product e. g. from the origin to the super market. Here they inform the customers, and the staff, about the content and its characteristics, and therefore should allow an appealing printed display on the surface. So the main quality requirements are the box compression resistance (ability to pile the boxes) and good printability. As a result the raw paper must show sufficient strength, measured as SCT (short span compression test) or RCT (ring crush test) for liner and CMT (Concora medium test) for corrugating medium or fluting.

The various applications require a wide basis weight range of about 70 to 450 g m^{-2}, to be run on one single machine. In Europe emphasis is put on 70 to 130 g m^{-2}. Here the main furnish is recovered paper. By its adequate treatment in stock preparation and by thorough cleaning of the fabrics and rolls in the paper machine good paper quality as well as good machine runnability at high machine speeds are achieved. Machine speeds were 500 to 800 m min^{-1} in the 1970s and 1980s. Today the maximum operating speed is about 1450 m min^{-1}, with design speeds of up to 1800 m min^{-1}. The driving force for the speed increase is the emphasis on lowered basis weights and low cost production.

High machine speeds require a twin wire gap former to ensure high uniformity of the product and sufficient dewatering capacity. Twin wire gap formers are available in different configurations. One is shown in Fig. 6.82 which depicts a state-of-

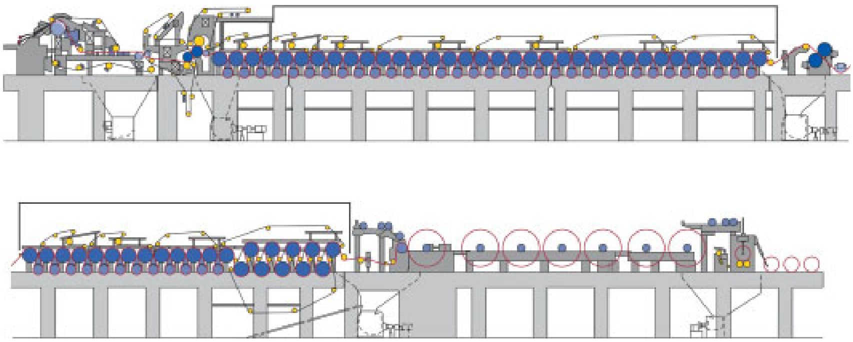


Fig. 6.82 State-of-the-art paper machine for packaging grades (source: Voith).

the-art packaging paper machine with the headbox of the gap former in an upper position. Lamellas in the headbox nozzle help to optimize fiber distribution. A two-layer headbox with different fiber fractions in the two layers is an option to increase paper strength properties.

The press section with three nips ensures high dry content of the web on entering the dryer section. As the paper web is always supported during its transfer from the wire to the dryer section, without any free draw, machine runnability is high, even at the elevated machine speeds and lowered basis weights. For runnability reasons the pre-dryer section is single tier. Safe web run is supported by airflow based stabilizers. For high machine speeds a film press replaces the pond size press as the latter starts to encounter unacceptable pond turbulences at speeds above 800 to 1100 m min^{-1}. Surface sizing increases the strength properties of the final sheet significantly. However the web strength in the machine is reduced dramatically by rewetting during sizing. For low basis weights, high moisture pick up at the size press and high speed production an air-float dryer may be used after the film press, followed by single tier and double tier dryer groups.

In reeling one main requirement is a large paper roll diameter, for two main reasons: First to reduce paper loss. A certain loss at each reel is unavoidable, so less reels with larger diameters for the same production reduce the overall loss. Secondly, to allow one single winder to cope with the paper machine output. This can be reached by reducing the nonproductive time for parent roll change in this noncontinuous process step. Today Jumbo rolls with diameters of up to 4.5 m are produced.

There are other packaging products on the market, e. g. white top liner and sack paper. White top liner has a white surface to cope with the high demands for an appealing display. For its production two webs are formed in two separate forming units – one white and one brown layer and then couched together ahead of the press section.

In the case of sack paper high strength and sufficient elongation at rupture in both directions (MD and CD) of the paper are required. These special properties are important for instance during the filling of the sacks. Other applications are all kinds of wrapping. For the highest elongation of this kind of packaging material the “Clupak process” introduced in the 1960s is applied. Here the still wet web is pressed in a nip where a compressible belt runs with the web. The belt deformation in the nip and the shape regain of the “extensible unit” after the press nip results in micro-creping with up to about 12% elongation (MD) at rupture. Micro-creping can also be obtained by passing the web through a nip with a hard and a soft covered roll.

6.11.3
Cartonboard Machines

Cartonboard is a product with a wide range of basis weight of about 160 to more than 600 g m^{-2}. Cartonboards have the highest share, about 80%, of the total paperboard production. Cartonboard is mainly used for production of carton boxes to pack e. g. food, cigarettes, pharmaceuticals or cosmetics. Additionally a wide range of specialty boards exists like artboard, gypsum board, playing-card board, bookbinders board etc. As the requirements for these board grades vary a lot the furnish and the board machine design may differ accordingly. Some of the basic required properties are:

- Mechanical properties like bending stiffness (bulk, Young's modulus), to protect the packed goods against damage.
- Flatness, plybond, creasability, punching, to ensure good runnability in converting and packaging lines.
- Resistance against moisture, gas and flavor, to protect the goods from quality changes.
- Freeness from impurities like micro-organisms, toxic or mutagenous substrates, taint or odor, to protect the goods against contamination.
- Brightness, gloss, roughness, printability of the surface, to ensure appealing information, identification and promotion of the packed goods.

Paperboard mainly has a multi-ply structure to achieve the different product requirements in the most economical and environmentally friendly way e. g. by applying various furnishes in the different plies. The surface plies (top and back plies) have to ensure the strength properties (bending stiffness) and, together with the coating, the required surface quality. With the inner plies (undertop and filler plies) the bulk is optimized (affecting bending stiffness). Most cartonboards are on-machine coated and calendered to obtain appealing surface characteristics.

Depending on the product and the geographic location of the board producer, virgin or recycled fibers or both fiber types are used as raw material. In multi-ply production the individual plies are formed on separate forming units and couched together in wet condition. Forming of two layers in one forming unit is also done. Different forming principles as described below have been and are applied either uniquely or in combination with others.

In suction formers 3 to 11 cylinder formers in series with suction chambers produce webs of about 25 to 100 g m^{-2} each which are couched on a transfer felt, thus building up the baseboard. The maximum speed is about 350 m min^{-1}, the maximum width is about 5 m. Cylinder formers without vacuum application are limited to a maximum speed of about 150 m min^{-1}.

In fourdriniers and hybrid formers each ply is formed on a separate fourdrinier wire. Hybrid formers are used e. g. to produce the filler ply with the widest basis weight range and highest basis weights which require extended dewatering capacity. The headbox and wire section have to be adapted to the high throughput ratio and to the high surface quality requirements for coating and printing. The maximum speed of a fourdrinier and of hybrid formers is about 1000 to 1200 m min^{-1}.

As the fourdrinier wire sections have sufficient speed potential gap formers are seldom used in cartonboard production. Nevertheless gap former installations can be found for certain applications of specialty board like gypsum board.

The press sections of modern machines for cartonboard are designed for high dewatering capacity, high bulk, smoothness and good runnability. This leads to press concepts with typically three press nips, e.g. a first double-felted suction press nip followed by a double felted shoe-press nip and finally an unfelted smoothing press or a single felted roll press to enhance surface smoothness. Between the nips a closed web run ensures stable sheet transfer, independent of speed and basis weight.

The dryer section consists of up to 100 drying cylinders in the pre-dryer section and about 16 in the after-dryer section. One or two single-tier groups are followed by double-tier drying groups. For good flatness of the finished product the top and the bottom cylinder rows are heated separately to control curl tendency.

Starch or size can be applied in a film press or a pond size press to enhance surface strength and bending stiffness. In this case an after-dryer section is required for baseboard drying.

Before coating, the roughness of the baseboard has to be reduced by calendering. In modern board machines this is done by a heated hard-nip calender. As an alternative soft-nip calenders can be used for reduced densification. The latest development is the shoe-nip calender which combines long dwell time, low specific pressure and high roll surface temperature to achieve minimum roughness at lowest densification. In Europe for machines below about 650 m min-1 the use of a MG (machine glazed) cylinder is state of the art for high bulk, low roughness board production. As the entering web dryness (about 60 to 70%) and exiting (about 70 to 75%) web dry content is crucial for smoothness and bulk of the baseboard the MG cylinder is often the bottle neck for machine speed increase. Most likely it will be replaced in future by the shoe-nip calendering technology (Section 6.9).

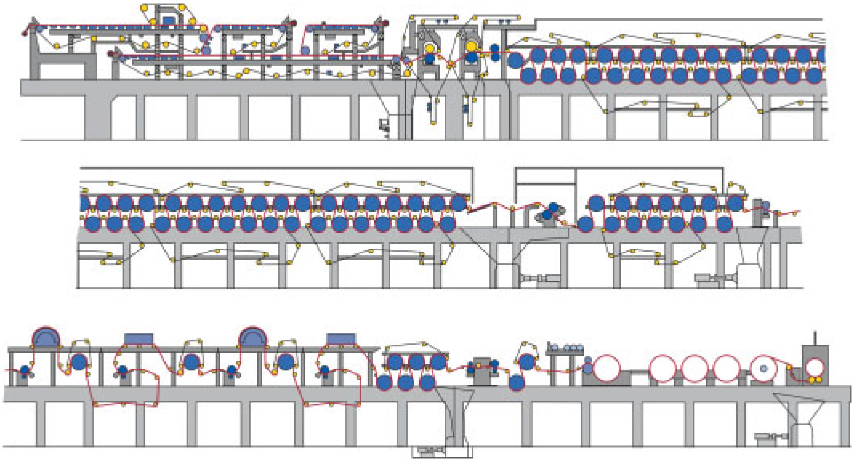


Fig. 6.83 State-of-the-art machine for board production (source: Voith).

Virgin-fiber based cartonboard is mainly double coated on the top side and uncoated or single coated on the back side. White-lined chipboard made of recycled fibers is mainly triple-coated on the top side and uncoated or single-coated on the back side, each layer with special tasks and coating formulations. Coating is done by roll applicators or by free jet applicators for highest surface requirements and machine speeds.

Final cartonboard post-calendering is mainly done with soft-nip calenders. The Pope reeler can be used for reeling up to 3.5 m diameter, reelers with center torque are applied for diameters of up to 4 m. A state-of-the-art board machine (Fig. 6.83) with on-line coating and final calendering has a length of up to 350 m.

6.11.4
Tissue Machines

The bases for hygienic products are tissue grades with basis weights of 5 to 35 g m^{-2}. Consumer demands drive the tissue industry to ever more softness and absorbency of the tissue grades used e. g. in the bathroom (toilet, facial) or in the kitchen (towels). Softness can be increased by the proper selection of fiber furnish and chemical additives or the proper machine concept and operation e. g. by low or no wet pressing. On the other hand sufficient paper strength and economy of production have to be regarded.

In former times tissue was made – and is still made in many places – on fourdriniers, later followed by suction breast rolls (Section 6.3.4) and since the 1970s by gap formers. Since the 1990s the so-called crescent former is the most accepted system. Today's tissue forming section is a roll former where the headbox jet is deposited in the wedge between two converging fabrics. One-, two- or even three-layer headboxes are used, the latter for stratification of the tissue. The converging fabrics can be either two forming wires or a forming wire and a felt (crescent former). In this case the felt transfers the web directly to the dryer section. Web formation is completed during the contact of the wire(s) on the forming roll. The wire run in the forming section may be designed as a C-wrap or an S-wrap with the headbox placed at the top or bottom position in both cases.

The dryer section in tissue machines consists of
either

- one large diameter tissue cylinder with an air impingement hood, where the web is completely dried within less than half a second, and creped
  or
- a tissue cylinder with air impingement hood where the web is only dried up to about 70 to 80 %, then wet creped and finally dried in a conventional after-drying section
  or today for high quality tissue production
- a through air dryer, which dries the web up to about 70 %, followed by a tissue cylinder.

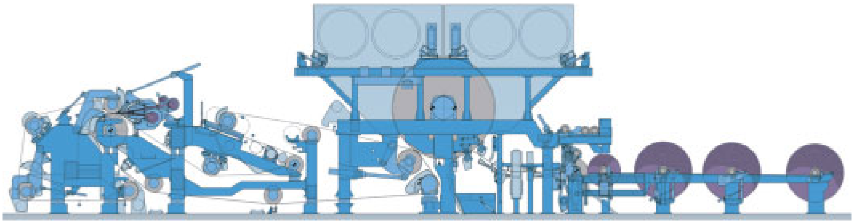


Fig. 6.84 Conventional tissue machine (source: Andritz).

In a state-of-the-art conventional tissue machine (Fig. 6.84) the web is formed in a gap former (wire plus felt), transferred (at a dry content of about 12 to15%) by the felt to the dryer section where it is first pressed and mechanically dewatered (up to about 38 to 40% dry content) by a shoe press acting against the tissue cylinder. In older machines dewatering is done by one or two press rolls, one of them being a suction press roll. The web is dried, by intense contact and impingement heating, to about 95% dry content. Here the hood contributes up to about 60% of the overall drying capacity. The web is then creped by a creping doctor and wound up. During creping the web is reduced in length by about 10 to 20%.

In a tissue machine for premium soft tissue production (Fig. 6.85) the formed web is first dewatered and pre-dried (to about 70 to 80% dry content) in a through air dryer without mechanical pressing. Here the through dryer replaces the press nip dewatering in order to preserve the bulk. On the other hand this results in substantially higher energy consumption for drying. The web is then transferred, pressed and glued to the drying cylinder. The pressing impacts the web, mainly locally, according to a special surface pattern of the transferring wire. Coating agent application ensures good sticking of the web to the cylinder surface to obtain the required characteristics at creping. Web length decrease by creping in this case is only about 5%.

Finally the web is calendered off line for web caliper control and for surface smoothness. The line load is low in order not to lose too much bulk.

Compared to other paper machines tissue machines are compact as regards their widths (maximum 7.9 m) and lengths which are about 45 m for conventional machines and about 60 m for a machine equipped with a through air dryer. Tissue

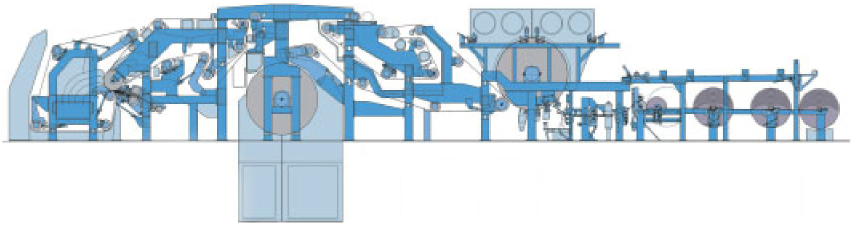


Fig. 6.85 Tissue machine with through air dryer for extra soft tissue production (source: Andritz).

machines are the fastest paper machines with a maximum speed today of about 2200 m min^{-1} (in the forming section). Maximum production capacity is about 100 000 tpa.

6.11.5

Specialty Paper Machines

Peter Mirsberger

The category of specialty papers defines a very wide range of different paper grades with a wide variety of specialized end uses and thus different and particular quality demands. These require special production technologies and specific know-how. Some of the required properties are very common and similar to commodity papers, but they are usually more distinct or with a closer tolerance. Such characteristics include profile quality, formation, smoothness, strength, thickness, porosity, and absorption. Some are very particular characteristics, such as wet strength, electrical conductivity, pore size distribution, resistance to certain chemicals, chemical reactivity, light proofness, heat resistance, and cleanliness.

Often specialty paper grades like photo, cigarette or label papers are cut into small formats. Here the basis weight profile as well as the fiber orientation must be as uniform as possible across the width so dilution water technology in the headbox for CD profile control is standard on most paper machines for specialty paper grades. Other important quality characteristics of specialty papers are MD/CD tensile ratio and dimensional stability. Decor, inkjet and label papers for example absorb a large amount of water during laminating, printing or gluing. Fibers, however, swell in width more than in length when wetted. To achieve the best dimensional stability the fibers of the sheet should be randomly oriented to obtain a “square sheet”, i. e. the lowest possible MD/CD tensile ratio is required.

Not only are the quality requirements various but also the production of specialty papers covers a wide range of speed and basis weights. The basis weights extend from 12 g m^{-2} for tea bag paper up to 300 g m^{-2} for specific photo base papers. The speed range extends from 40 m min^{-1} for banknote papers up to 1400 m min^{-1} for thermal base paper, for example. Often, different grades are produced on the same paper machine. Further characteristics are small tonnages per grade, many grade changes and a dynamic grade development, i. e. new grades are developed which can cope with new market demands, other grades disappear from the market due to lack of demand. So flexibility is a key word – not only for the production of these papers but also for the paper machine concepts.

The base sheet forming concept for specialty papers is the fourdrinier. It can be used for the whole basis weight range and up to a machine speed of about 1200 m min^{-1}. In order to achieve best results concerning formation and dimensional stability Dandy rolls or hybrid formers and effective wire shaking units are frequently used. New machines however can exceed the speed limit of fourdriniers, so gap former concepts are used in this case.

The basic raw material for specialty papers is wood pulp. There are however grades like tea bag, plug wrap or filter paper where the required porosity, absorb-

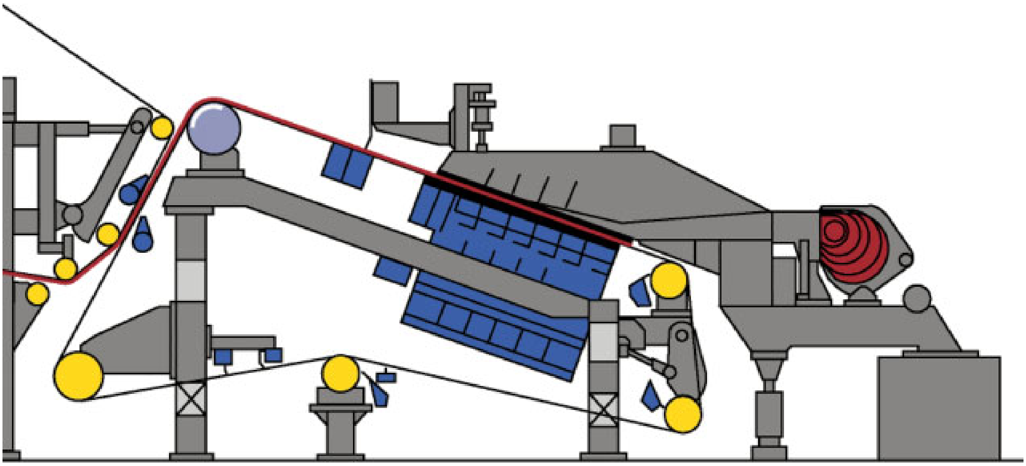


Fig. 6.86 Inclined-wire forming technology (source: Voith).

ency or bulk can only be achieved by using special plant fibers like abaca, sisal or hemp or even synthetic fibers like rayon. These fibers are much longer than wood pulp fibers. Due to their length and the demand for best formation and uniformity, even at lowest machine speeds, the inclined wire sheet forming technology is used for theses grades (Fig. 6.86). Extreme dilutions are necessary in order to avoid reflocculation of the fibers and headbox consistencies even below 0.01% are run. Overlay papers for high abrasion resistant surfaces such as flooring laminates are produced with embedded fillers (up to 30% aluminum oxide) on a three-layer former.

Another "old fashioned" well proven sheet forming technology which is found in specialty paper production only is the cylinder mould former (Fig. 6.87). This sheet forming technology is still used for the production of cotton based banknote paper. The paper production on a cylinder mould former enables the application of three key security features:

- The use of cotton as raw material gives the paper a unique feel.
- The multi-tone watermark has a wide tonal range going from light through a number of shades to dark.
- The security thread can be fully embedded or windowed, i. e. the thread appears at intervals in the surface of the banknote.

These security features together with more than a 200 years old tradition and know-how make the cylinder mould former and cotton-based paper still the best choice for banknotes.

The press sections in specialty paper machines need to be highly flexible. For paper grades where only one smooth side is required, multi-roll press concepts with two or three press nips and a closed sheet run can be used. For increased dryness and improved runnability these press concepts can be equipped with a

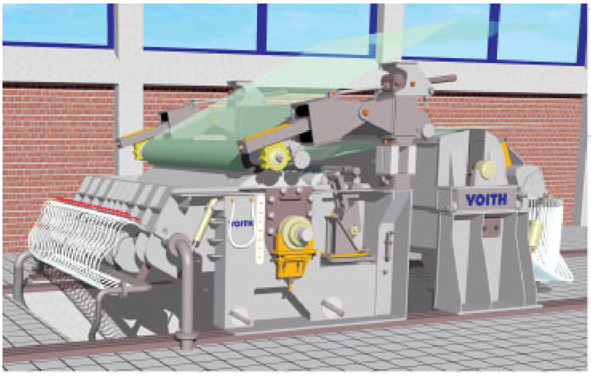


Fig. 6.87 Cylinder mold forming technology for banknote paper production (source: Voith).

shoe press. For grades like inkjet or bible paper low roughness figures on both sides are required so a bottom-felted straight through press is added in order to reduce the roughness on the top side and to control the roughness two-sidedness.

Depending on the requirements, all available drying concepts are used for the production of specialty papers. The most common concept is the double tier arrangement. Fast machines are equipped with single-tier dryer groups for improved runnability. When highest smoothness and gloss values on only one side or low CD elongation at rewetting for best dimensional stability are required, the wet web is dried on a Yankee cylinder. If high bulk or high porosity is a must, as it is for filter or tea bag papers for example (Fig. 6.88), the web is dried on a through air dryer.

Specialty papers can be divided into uncoated and coated grades. The uncoated grades are either machine finished, like cigarette papers or base papers for sub-

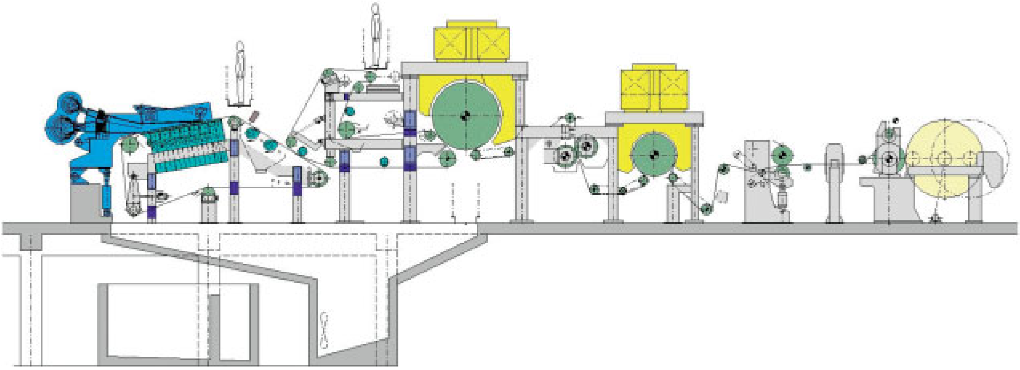


Fig. 6.88 Machine with inclined wire former and through air dryer for tea bag paper production (source: Voith).

sequent value adding off-machine process stages such as for photo base paper. Coated grades can be subdivided into two groups:

1. Where the coat is needed for a certain special function, such as thermal or carbonless papers.
2. Where the coat is needed for improved printability, such as label or cast coated papers.

In both cases the base sheet is normally pre-coated on one or on both sides. By precoating, the functional coat weight can be minimized or the final surface quality can be improved. The most suitable and economical applicator for the pre-coat is the on line film press. Both sides of the sheet can be coated simultaneously and different applications are possible.

The application of the functional coat is more demanding. For coated commodity grades, the quality generally increases with increasing coat weight. For coated specialty papers like thermal or carbonless paper, however, the quality does not improve further once a certain coat weight for the functional coat is reached at any point. The optimum concerning uniform coverage and minimum coat weight is achieved with the curtain coater: a perfect layer of coating color is applied on the surface without any mechanical impact on the paper. Since the first commercial installation in the mid-1990s the significant advantages of curtain coating have led to more than 20 units being installed within the last 10 years. Due to better flexibility and time efficiency the functional top coat is applied off line.

There is no typical calender concept for specialty papers. Each of the different specialty paper grades has its own demands with regard to surface properties, smoothness, densification, caliper, porosity, transparency, etc. Calendering of specialty papers, therefore, requires specific customized calender concepts. Thermal base paper, carbonless and label paper are pre-calendered usually with one soft or hard nip calender. For coated inkjet papers, two soft nips are necessary – one for each side. The smooth surface of decor papers is achieved using calenders with two or four soft nips. Here the printed side of the decor paper is in contact with the heated roll surface up to four times, supported by steam application as well. A combination of one hard nip for pre-calendering and a multi-nip calender stack for the final calendering is used for photo base paper. Silicone base paper has the highest demands concerning densification. The paper has an initial moisture of up to 16% before running through 14 nips of a supercalender, the rolls of which are heated up to 180 °C and loaded up to 400 N mm^{-1}.

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7
Coating of Paper and Board

Werner Kogler† *and Werner J. Auhorn*

7.1
Objectives of Coating [1]

The main purpose of coating is to improve the surface quality of paper or board. The quality improvement can be aimed at optical properties such as brightness, gloss or opacity, at tactile properties such as smoothness, but, most importantly, at printability and print image quality.

The application of (usually white) pigments to the base paper surface enhances the brightness of the paper. In addition, the opacity increases due to the high light scattering of the pigments. This improves the optical appearance, because the shine-through of the back side printing is reduced. Also, the coat layer evens out the surface topography of the sheet, resulting in an improved smoothness, which in turn gives a better gloss.

The coat layer reduces the penetration of ink into the paper sheet. Therefore, the ink does not spread as much and the print image is clear and sharp. The print density and the print gloss are enhanced, and the ink demand is reduced compared to uncoated papers.

For specialty papers, the coat layer can have functional properties. Examples are the thermosensitive layer of thermal papers or the capsule-containing coat layer of carbonless papers.

The benefits of applying a coating layer become very apparent when comparing paper surfaces with different coatings. The SEM (scanning electron microscope) micrograph of an 80 $g\,m^{-2}$ woodfree base paper shows multiple layers of intersecting fibers (Fig. 7.1). The paper surface is characterized by hills and dales formed by the fiber mesh. The voids between the fibers impair the smoothness and uniformity of the paper surface. The next micrograph shows a precoated paper at the same magnification for comparison. A precoating of just 10 $g\,m^{-2}$ per side suffices to cover up the majority of voids and fiber crossings. This helps to smooth and even out the paper surface. Paper surface quality can be further enhanced by the application of a top coat. Coating the paper with another 12 $g\,m^{-2}$ per side distinctly enhances the existing precoated surface quality, with a number of dominant fiber structures and valleys still remaining visible. Subsequent calendering

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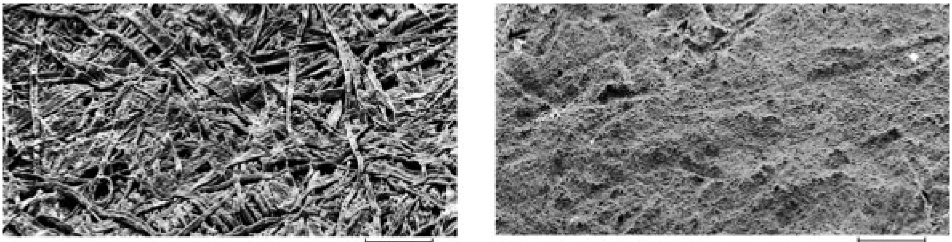
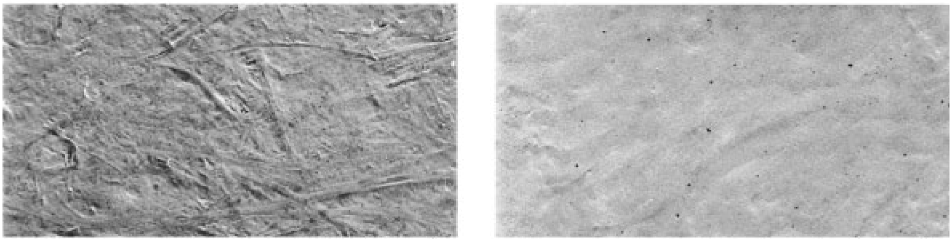


Basepaper: 80 g/m² woodfree

Precoating: 10 g/m² per side



Double coating uncalendered: 22 g/m² per side

Double coating calendered: 22 g/m² per side

Fig. 7.1 Comparison of base paper, precoat, topcoat uncalendered and topcoat calendered (source: Omya).

achieves an additional quality gain by enhancing smoothness and gloss. The resulting surface is flat, with a minimum of irregularities. An electron microscope picture of a microtome cut from a coated paper sample is shown in Fig. 7.2. In the center of the sheet, the fibers can be seen. The lighter and more densely packed structure on the outside of the paper sheet is the pigments of the coat layers. The

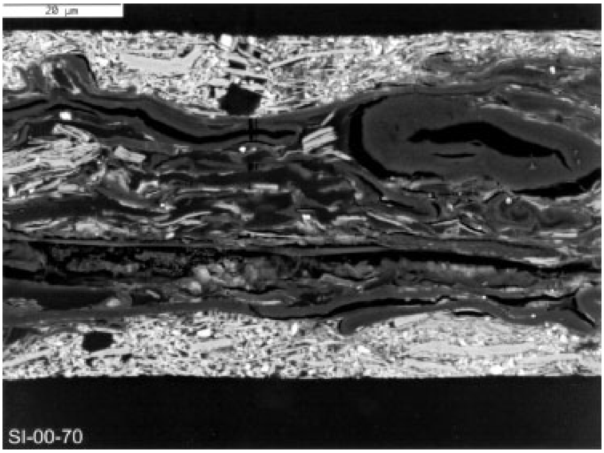


Fig. 7.2 Microtome cut of a coated paper sheet (source: Voith).

caliper of the coat layer varies according to the changing thickness of the base sheet. The surface is smooth so, by coating, paper and board can be upgraded to a higher quality level with added value. Furthermore, raw material costs are also an important factor of coated papers and coating colors are in most cases cheaper than chemical or mechanical pulp. So an optimum ratio of coating layer/fiber web has to be found.

7.2
Requirements of Coated Papers for the Printing Process [1, 2, 4, 7–10]

Printed matters are used for advertising, news and information, transactions, education, and entertainment. Here they are in competition with other communication media, such as radio and television, and the internet. Printing on packaging paper and board has the functions of advertising, delivering information, and showing data such as barcodes. So paper and board have to maintain their competitiveness through continuous product development strongly supported by coating technology as a prerequisite for excellent print quality.

7.2.1
Printing Methods and Printing Ink Properties

For the various printing methods and the press constructions the major press variables are paper feed, paper take-off, and drying. Table 7.1 shows the major classes in different types of printing for different types of presses with the primary product categories for each type of press. Offset printing methods comprise newspaper offset, heatset offset and sheet fed offset. Newspaper offset printing today is mainly coldset offset which needs no drying capacity in the presses. Web fed magazine offset is heatset. Here drying is done by hot air. The type of paper feed relates to the scale of printing and the paper or board basis weight. Large scale printing and printing on low basis weight substrates is web fed.

The type of drying correlates to the demands that the printing method places on the ink properties and the desired quality level of the final product. Inks that contain a large proportion of solvent such as gravure, flexographic, and heatset offset inks are typically dried through evaporating the solvent by air flow. Depending on the air temperature, drying may be done by “hot air” as in heatset offset, “warm air” as in gravure, or “cold air” as in flexographic printing. The drying mechanism can also be a function of the ink, as in oxidizing and polymerizing inks. Polymerizing inks are mainly used in sheet fed offset, but it is likely that their use in web fed printing will increase. News inks do not really dry during the one day lifetime of newspapers.

The steps during printing include transfer of the ink to the plate, its transfer to the receiving substrate or paper, and print drying. Mechanical printing uses the rotary principle. This means that printing ink is transferred to the paper in a nip between two rotating cylinders (Fig. 7.3.). Ink transfer between flat surfaces or a

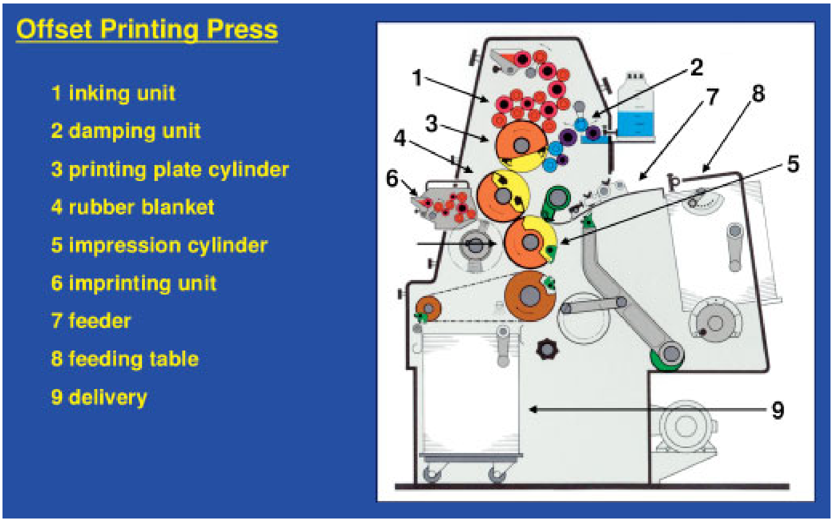
Table 7.1 Different types of printing processes (source: P. Oittinen, H. Saarelma, Lab. of Media Technology, Helsinki University of Technology).

Printing method	Paper in	Paper out	Drying
Letterpress (newspaper printing)	Web	Newspaper	No drying
(books, business forms)	Sheet Web Web	Sheet Form Book	No drying No drying No drying
(small scale utility printing)	Sheet	Sheet	No drying
Newspaper offset (books, directories, business forms)	Web	Newspaper, book, form	Cold set; no drying (normally)
Heat-set offset (magazines, catalogs)	Web	Cut & folded sheet (= signature)	Hot air drying
Sheet fed offset (special interest magazines, advertising, books)	Sheet	Sheet	No drying or UV-drying or IR-drying
Gravure (magazines, catalogues, packaging)	Web Web	Signature reel (Packaging)	Warm air drying
Newspaper flexo	Web	Newspaper	No drying
Packaging flexo (solid board, corrugated board, paperback books, plastic films)	Sheet Web	Sheet Web	No drying (Absorbent substrates) Warm/cold air drying
Silk screen	Sheet Web Object	Sheet Web Sheet Object	Different drying methods; no drying/UV/IR

flat surface and a roller has also been used in the past. As the achievable speed is less than in rotary printing this kind of printing has become obsolete.

In *offset printing* the ink is transferred to the paper from the printing plate using a separate transfer cylinder – the offset or blanket cylinder. The characteristic of an offset plate is, that the printing areas (image areas) and nonprinting areas (non-image areas) are in the same plane. The printing and nonprinting areas are generated via the different wetting properties of two coatings on the printing plate (Fig. 7.4.). Before applying the ink, the printing plate must be evenly wetted with the fountain solution. The printing areas attract the fatty ink and the nonprinting areas attract the water.

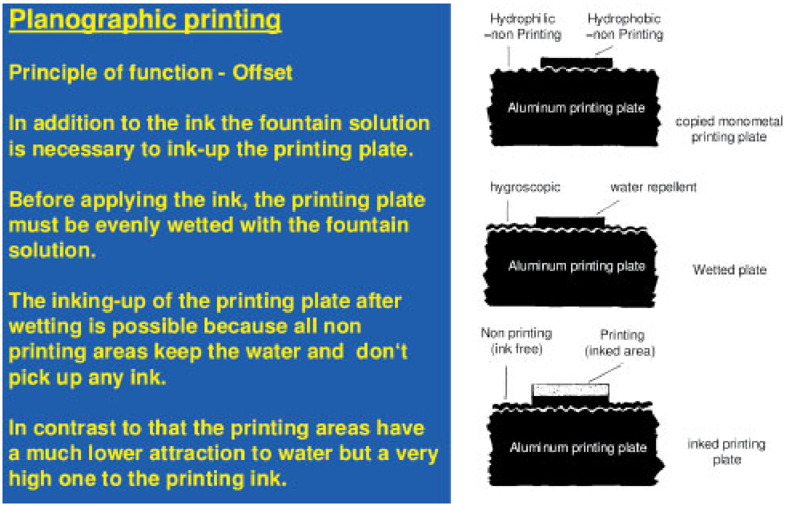
In *letterpress, flexography,* and *hot stamping,* the printing and nonprinting areas form a geometrical profile in the *z*-direction of the plate surface (Fig. 7.5.). The printing areas are above the mean depth of the profile, and the nonprinting areas are below. Letterpress and flexography ("flexo") differ in the characteristics of the



Offset Printing Press

1 inking unit
2 damping unit
3 printing plate cylinder
4 rubber blanket
5 impression cylinder
6 imprinting unit
7 feeder
8 feeding table
9 delivery

Fig. 7.3 Offset printing press (source: BASF).



Planographic printing

Principle of function - Offset

In addition to the ink the fountain solution is necessary to ink-up the printing plate.

Before applying the ink, the printing plate must be evenly wetted with the fountain solution.

The inking-up of the printing plate after wetting is possible because all non printing areas keep the water and don't pick up any ink.

In contrast to that the printing areas have a much lower attraction to water but a very high one to the printing ink.

Fig. 7.4 Planographic printing – principle of offset process (source: BASF).

plates and the inks. In flexo, the plate profile is higher, and its polymeric material is softer than in letterpress. Flexographic inks are two orders of magnitude less viscous than letterpress inks. Under nip pressure, a softer plate conforms more easily and achieves more contact with a rough printing substrate. This process is necessary for ink transfer actually to occur. Squeezing of the inks toward the edge of dots or characters allows one to recognize flexography and letterpress.

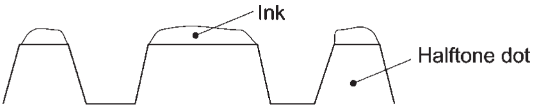


Fig. 7.5 Principle of letterpress and flexography (cross section of a printing plate surface) (source: P. Oittinen, H. Saarelma, Lab. of Media Technology Helsinki University of Technology).

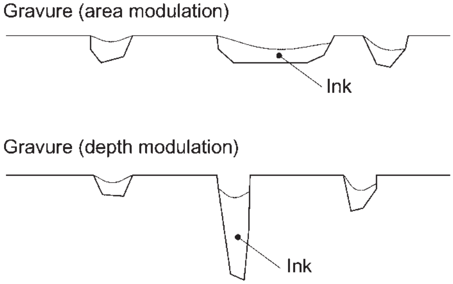


Fig. 7.6 Two principles of gravure printing plates: area modulation and depth modulation (cross section of the printing cylinder surface) (source: P. Oittinen, H. Saarelma, Lab. of Media Technology Helsinki University of Technology).

In the *gravure technique*, cells – a negative relief engraved or etched in a copper layer on the printing cylinder – form the printing area. For better durability, copper cylinders receive a subsequent chrome plating. Figure 7.6 shows that different levels of darkness result in halftone image printing by varying the area of the cells or by varying the depth of the cells. The two principles of gravure – area modulation and depth modulation – are shown in a magnified cross direction view of the printing cylinder.

Electronic printing – also synonymous with digital printing – consists of nonimpact processes. The printing methods differ considerably in the principles they employ. Electrophotography is the most mature black-and-white nonimpact technology. In color technology photocopying was the impetus for early development. Today high end color electrophotography challenges sheet-fed offset printing. At the low end, higher complexity prevents color electrophotography from competing with color ink-jet. The inks in electrophotographic printing are so called toners, which are commonly powdered materials. The particle size is typically 5–10 μm with a narrow size distribution. With an increase in resolution, particle sizes had to be decreased. Approximately, the particle size is a fifth of a pixel size. Liquid toners are applied when high resolution is required. Toner particles dispersed in a carrier such as a kerosene-like solvent can be smaller than 1 μm. After transfer to the paper, the carrier phase becomes superfluous. Toner particles consist primarily of pigment to impart color, thermoplastic resins to bind the pigment to the paper, and charging additives to enhance the charging capacity. Powdered toners are transferred by adhesive, electrical, and magnetic forces.

In *ink-jet printing*, a drop is the basic imaging element. Its principle is the generation of ink drops from a continuous stream of liquid emanating from a nozzle. It needs very small nozzles through which the ink emerges in order to reach high resolution. The ink should not clog the nozzles or form a crust when in the standby state. In thermal DOD (drop on demand) ink-jet, rapid thermal gradients in the heating period impose high demands on the thermal stability of the inks. A characteristic of ink-jet inks compared with inks in other printing methods is that they are very fluid. This is especially true for the continuous stream ink-jet method where rapid drop formation requires viscosity near 1 mPa s. In thermal jetting, viscosity is commonly less than 5 mPa s, 10 mPa s is the upper limit.

7.2.2
Properties of Coating Layer Surface versus Printing Method

The composition of the coating color is largely determined by the demands put on the paper surface by the particular printing process. In the press room a faultless runnability of the paper is demanded and the publisher asks for an excellent print quality (printability).

Offset printing requires an especially well bound coat because considerable forces in the *z*-direction (surface strength/pick strength plus internal bond) are exerted by the highly viscous inks at the high printing speeds of today. To meet these strength demands a high amount of coating binder is necessary. At the same time, the coating must be sufficiently porous to permit fast, controlled absorption of the printing ink without reducing the print gloss. Two further requirements are high water resistance, and sufficiently fast absorption of the fountain solution. In general, the coated paper must have adequate stiffness, resistance to blistering, good dimensional stability, high brightness, no or low yellowing tendency, and good aging resistance. The coated and printed paper has to be without waviness, mottling and ink strike-through. Additional important printability properties are high print gloss, even halftones, detailed tonal gradation, low ink consumption (high density), sharp dots (controlled dot gain), fast ink drying for immediate processing, controlled water/ink interference and low fiber roughening by the moistening and the following drying process.

The importance of *letterpress printing* today is very much reduced by the cold-set offset process, whereby most of the newspapers are printed. Conventional newspapers are uncoated papers, based on recovered and deinked printing papers and/or mechanical pulps. However, a coated surface of such a newspaper or another base paper made from a relatively cheap furnish opens new applications for the cold-set web-offset process with significant improved print quality and cost-performance (Fig. 7.7).

Flexographic printing requires good ink absorbency, even fulltones without pattern, high dot definition (no “shadow”), fast ink drying and good ink adhesion.

In *rotogravure printing*, the tensile forces between the printing cylinder and the surface of the paper are very small, as solvent-containing, low viscous inks are used. So rotogravure printing requires only very little pick strength of the paper

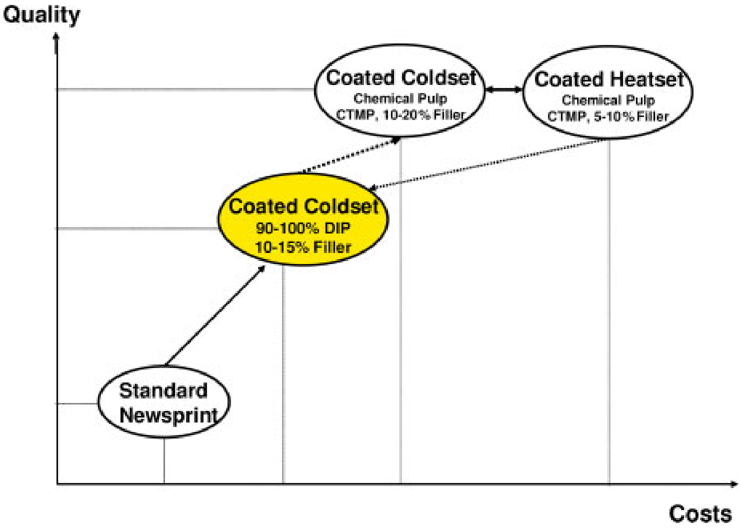


Fig. 7.7 Upgrading of printing papers and improving cost-performance by selection of base paper furnish, coating and printing method (source: BASF).

surface. For this reason, only a relative low amount of coating binder is needed. For rotogravure printing good paper compressibility, a high degree of smoothness, and adequate receptivity for the ink solvent are important.

Further important criteria for paper and board grades used for packaging include low odor, flexibility, fold crack stability, glue-ability, and grease resistance. Coated specialty papers require specific properties, such as alkali resistance (labels), washability (wallpaper), and solvent resistance (silicone release paper).

In *electronic printing* the runnability of a paper is critical, because of the electricity involved. The electrical conductivity of the paper should be sufficient so that excessive accumulation of electricity on the paper does not occur despite charge removal conductors in printing devices. Accumulation of charges causes sheets to adhere to each other leading to jamming. Image quality requires electrical resistivity in the paper, because the paper must hold the electrical field during transfer of the toner. These two factors determine the tolerance range for paper resistivity. All toner particles should be transferred to the paper from the photoconductor to prevent accumulation after the erasure step. Accumulation would cause a ghost image on the next print. With the rise in moisture content, resistivity drops exponentially. If the paper is too conductive, the toner spreads sideways causing loss in detail. The moisture content of paper is critical, as is friction. Friction must be within a specific range since the transportation occurs commonly by friction. The thermal conditions in fusing determine the requirements on the dimensional stability of the paper and the strength of the surface. A lack of dimensional stability can cause curl, cockle, and image depletion in duplex printing.

Softening of the paper surface in fusing may cause adhesion on the counter roll, loosening particles from the surface and leading to accumulation on the rollers of the printer. Good toner adhesion requires surface-chemical compatibility of paper and toner. With an increase in the resolution of printing and the related decrease in toner size, the smoothness requirements of the paper surface become increasingly important.

In ink-jet printing, ink and paper interact very strongly. Because of the fluidity of the inks and their high velocity of impact on the paper, ink-jet papers require characteristics that are matched with the inks and the drop volumes. This is especially true at the higher end of the quality level. Ink-jet papers must be smooth so that drops impacting on the paper spread evenly. Sufficient and even porosity composed of small pores is necessary to absorb the solvent quickly and to counteract the spreading tendency. Dyes are trapped close to the surface of the paper. This can be aided by cationic dye fixatives in the paper which capture the anionic dyes and allow the colorless vehicle to be absorbed into the paper or coating. The use of aqueous inks places demands on the dimensional stability of ink-jet papers. Cockling and curling tendencies are critical factors. The impact of drops on paper causes enlargement in area, typically by a factor of two. This, as well as the need to decrease drop size, constrain efforts to raise resolution, although the commercially implemented levels keep going up and have exceeded 1000 dpi. Printed pixels are most visible in light tones where they are far apart. The use of more than three colored inks helps to reduce the solvent that is transferred to the paper in multicolor printing. This means supplementing the three process colors cyan, magenta, and yellow with additional color inks such as orange and green which also brings the advantage of a wider color gamut. Further requirements for ink-jet printability are fast ink drying, good tonal stability (no color shifting), no bleeding and no feathering.

7.3
Requirements of Base Papers/Board for Coating [4, 7, 8]

7.3.1
General Aspects

Coated papers are classified as wood-containing or mechanical papers, and fine papers, which are also called woodfree, or WF papers. Wood-containing papers are made of a fiber furnish such as groundwood or other mechanical pulps. Recycled fibers (RCF) are also currently an important and steadily growing raw material for coated base papers. Woodfree papers are made of a fiber furnish of only chemical pulp, or only very little mechanical pulp (no more than 10% of the fiber material). Typical mechanical coated papers are LWC papers (light weight coated) and ULWC papers (ultra light weight coated), MWC papers (medium weight coated) and HWC papers (high weight coated). Art printing papers are typical woodfree coated paper for the highest printing quality (Fig. 7.8). Coated folding boxboard (FBB) is

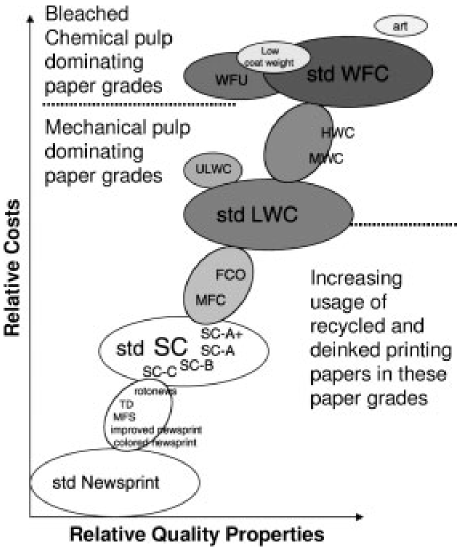


Fig. 7.8 Range of printing papers (quality versus cost) (source: Metso).

an example of coated board, which is used in selling packages for goods. In North America and Japan there exists a classification system that is based on the brightness of coated papers.

The base paper in coating must ensure trouble-free running of the coater, provide an optimal basis for paper finishing, and form a base for fixing the coating layers demanded by the end users. The lower the basis weight the more important are the properties of the base paper. Generally, the best coated paper surface is achieved with the best and most uniform base paper. Variations in formation, absorption, thickness, moisture, and roughness of the base paper have a great influence on the properties and the uniformity of the coating layer. Nonuniform coat weight distribution is the most important factor in generating uneven print image, called mottling.

Further critical properties are paper web profiles in the machine and cross machine directions as regards basis weight, filler distribution, caliper and moisture. The paper web has to be free from faults, holes and impurities, and have low fiber roughening potential (for web offset grades), low porosity with a uniform pore distribution, high smoothness, opacity and brightness, minimal two-sidedness, sufficient tensile and tear strength, as well as sufficient stiffness. Stiffness is related to the bulk of the coated paper. Stiffness especially becomes a critical property with low basis weights, high filler content and high coat weight, and in sheet printing. By choosing coarse, bulky fibers, careful wet pressing and by calendering as little as possible, bulk can be improved. In sheet-fed printing, the stiffness in the cross machine direction is more critical. This can be influenced with fiber furnish and by controlling fiber orientation with the jet:wire ratio in web forming.

Good internal bond strength is required both in heat-set web-offset (HSWO) and sheet-fed offset. If the internal bond strength is good in HSWO, the blistering temperature increases. In this printing method, printing ink is dried by external heat, while at the same time the remaining water in the base paper starts to evaporate. If the internal strength and formation are poor, steam pressure inside the paper web can rise locally causing bubbles, which is called "blistering". No cracking in the fold is very important in high-quality printed jobs with colorful printing. The cracking tendency is higher with stiff mechanical pulp fibers (e. g. TMP) than with chemical pulp fibers, but it remains a problem in WF papers – especially those with high basis weights. Folding properties can be affected by pulp refining, by pulp and pigment types, and by the amount of starch used in the coating formulations.

The base sheet of board mostly consists of several layers (multiply), therefore sufficient ply bond and crack fold are additional important parameters, besides a uniform and bright surface, to achieve a good quality of coated board.

7.3.2
Specific Base Paper Properties Affecting Coating

Base paper characteristics have a strong effect on the quality of coated paper and board and process economy. The main properties are as follows:

Strength Properties: To guarantee a good runnability of paper web in coating different strength properties are needed. Because base paper is wetted in coating units, it requires good temporary wet strength. *Wet tensile strength*, in principle, is measured using similar methods as for measuring tensile strength, but the sample is prepared differently. Other strength properties related to coating are *tear strength* and *edge tearing resistance* as well as *bursting strength*

Basis weight, caliper, and moisture profiles in the cross and machine directions: These have a strong influence on the uniformity of coating, e. g., calendering very often controls caliper, which means that in the cross direction some parts of the web are pressed more than others to reach a uniform caliper profile. These more compressed parts will differ in porosity and smoothness of base paper, which affects the coating amount. *Caliper* before coating can be measured on-line for control. *Basis weight* variations usually cause caliper variations, they can be seen as streaks in the machine direction. *Moisture* variation will affect coating amounts with risks of wrinkles if moisture variations across the web are high. High moisture before coating can affect coating color penetration and the gloss of coated paper and, subsequently, ink settling in printing.

Porosity: If porosity is very high, absorption of coating is also high and coating weight can increase dramatically and drying problems may also occur.

Formation: This property refers to small-scale basis weight variations in paper. There are areas that are denser and less absorbent to the coating than other areas. To reach uniform coating penetration, base paper requires even formation, otherwise mottling may occur in printing.

Smoothness: Smooth base paper gives a uniform and closed coated surface. The various coating processes have slightly different smoothness requirements. Air knife coaters require a relatively smooth surface because, in that method, coating is applied in a layer of rather uniform thickness, regardless of the base paper contour. The blade coaters' coating film fills the cavities and leaves the high spots uncovered.

7.4

Principles of Coating Techniques for Paper and Board [1, 3, 4]

Historically, papers used to be coated in much the same way as painting a wall: the color was applied and distributed with a brush, then dried and smoothed. The process has remained essentially unchanged to the present day, although it has undergone major improvements over time. Today, roll or jet applicators are employed instead of a brush, and the color layer is leveled out using either a pneumatic or mechanical system, such as a blade or a metering bar. The moist sheet then passes between infrared dryers before being conveyed to high-temperature air floats and/or drying cylinders.

In principle, coating can be divided into different phases:

- Application of the coating color onto the base paper. Surplus of coating color is applied in several coating methods (existing coating systems are shown in Section 7.10).
- Metering of the coating (metering may take place before, during or after the application).
- Drying of the coating.
- Smoothing of the surface e. g. by supercalendering or soft calendering.

Pre-metering, or metering before application takes place, e. g., in the metered size press (MSP) and in the gate roll press. Simultaneous metering or metering and application take place at the same time in the short dwell time applicator (SDTA) and in the conventional size press. Post-metering, or metering after application takes place in the blade coater, in the rod coater, and in the air knife coater. Figure 7.9 depicts a schematic arrangement of backing roll, roll applicator and doctor together with the coating base. The applicator roll runs at a slower rate than the paper sheet and applies a generous amount of color (20–30 times in excess) to the base paper. After wetting the base paper, the waterline migrates into the coating base. This penetration is assisted by hydrodynamic pressure building up in the nip as a result of the web speed. Consequently, the kinds of application and metering characterize the various coating methods. In both the metered size press (MSP) and in the gate roll press, metering takes place on the surface of a roll, and the coating film is then transferred onto the paper in the nip between two rolls.

Coating can be done double-sided, i. e., both sides of the paper are coated simultaneously (e. g., MSP), or on only one side at a time. Printing papers are usually coated similarly on both sides, and boards often on one side only.

Single coating means that only one coating layer is applied per paper side, in multiple coating several coating layers are applied per paper side. The most common multiple coating is double coating. So-called art papers may be triple-coated, i. e., three coating layers per paper side.

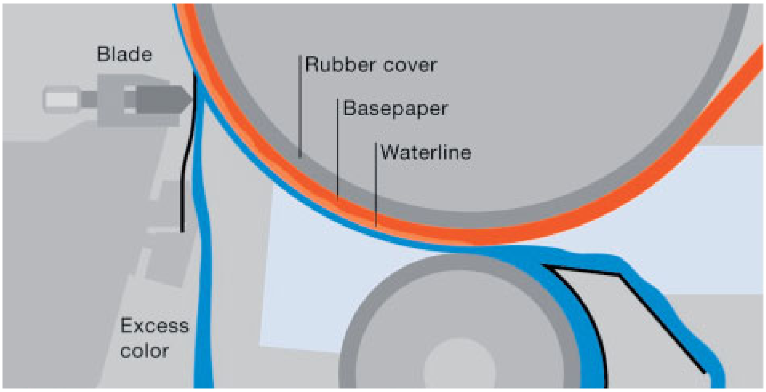


Fig. 7.9 Principle of coating color application (source: Omya).

If coating is done on-machine, then the coating will immediately follow the manufacturing of the base paper without intermediate reeling. Off-machine coating means that the paper is reeled after the paper machine and coating is done in a separate machine. Web defects may be removed during re-reeling.

During coating the following effects occur:

Liquid is removed from the color, which then adheres to the base paper. As the liquid phase strikes into the base paper, water containing dissolved substances and other color components (mainly binders, cobinders and additives) migrates into the base paper. Actually, filtration of the coating components takes place in the z-direction, i. e. perpendicular to the sheet plane. This anchors the color to the paper surface. If color strike-in is too intense the coating layer may become depleted of binder. This may in turn give rise to undesirable phenomena like dusting or picking. If the color is dewatered extremely quickly, solids content and hence viscosity will increase. This increases e. g. the blade pressure in blade coating, so the coating color needs dilution – a measure that may result in poorer surface quality. Another key phenomenon is the mechanical shear stress experienced by the color in the clearance between the stationary doctor and the paper sheet as it passes by. The shear rate D (rate of application of strain) on the color may be calculated from the velocity v of the paper and the clearance d between paper and doctor as follows:

$$D = v/d\ [\mathrm{s}^{-1}]$$

The clearance d is difficult to measure due to the flexible cover of the backing roll and the compressibility of the base paper. The shear rate D may attain a multiple of $10^6\ \mathrm{s}^{-1}$. This value plays a crucial role in coating color rheology and runnability. More recent analysis shows that at high speed, the above simple shear generation model may no longer be applicable. Boundary slip conditions can occur, leading to a pseudo-plug flow under the doctor nip initiated by the rapid change in shear rate upstream from the nip. Under these circumstances, the coating color behaves partially elastically, in contrast to the classical viscous flow described here.

Appropriate absorbency of the coating base paper, water retention (WR) of the coating color as well as its rheology or viscosity ensure good coating quality and runnability. These mechanisms take place within fractions of a second: at a coater speed of 1500 m min^{-1}, e.g. the paper web reaches the doctor just 0.04 s after the moment of color contact. Under adverse drying conditions, binder may distribute nonuniformly into the coating surface. Along with local variations in surface porosity caused by nonuniform coating consolidation during drying, this is a typical cause of print mottle as a result of irregular ink absorption.

7.5
Components and Properties of Coating Colors [1, 3–6]

Coating colors have a very simple composition, although the interactions between ingredients are far from simple. A coating color consists primarily of pigments dispersed in water, plus binders, cobinders and additives (see also Section 3.6.9.). Calculations are, as a rule, based on the dry product, even if the actual ingredients deployed are mainly liquid commercial products with differing dry contents (proportion of active substances). The basis of calculation is 100 parts of pigment, to which all additions are referred (Table 7.2). As an example 24 kg of commercial product binder must be added to 100 kg of dry pigment to obtain 12 parts of dry binder in the formulation if the synthetic binder has 50 % dry content.

Table 7.2 Example of an offset coating formulation.

Parts[1]	Substance
100.0	Coating pigment
12.0	Binder
0.5	Cobinder
0.5	Additives (e.g. calcium stearate, wax, optical brightener) pH is set to 8.5 by adding sodium hydroxide solution (NaOH), and the solid content to 65 %–70 % by adding water.

[1] The term parts refers to the parts by weight addition of a component based on 100 parts by weight of pigment

7.5.1
Pigments

Pigment is the most abundant component in the coating, so pigment is naturally the most important factor affecting the properties of the coating (see also Section 2.2.2). An ideal pigment would have the following properties:

- appropriate particle size and narrow particle size distribution
- free from impurities

- good dispersibility for easy mixing with water and low water absorption
- high chemical stability and low solubility in water
- good compatibility with other coating components
- good light reflectivity at all wavelengths for high brightness
- high refractive index for good opacity
- good glossing properties for eye-pleasing coating gloss and high print gloss
- low binder demand
- lood flow properties in an aqueous suspension and low abrasiveness
- cheapness.

There is of course no pigment that could meet all these requirements, however, different pigments meet different combinations of them. The main coating pigments are clay (kaolin), ground calcium carbonate (GCC), precipitated calcium carbonate (PCC) and talc.

7.5.2
Binders

Binders serve as pigment-pigment bonders, and to anchor the pigments to the base paper surface. They are also expected to control the coating color viscosity and water retention, and to prepare the coated papers for printing and converting stages. Today, synthetic binders are preferred in coating kitchens. They are polymerized petroleum products that are available in the form of dispersions in very fine distributions, often with 50% solids. Some typical starting materials are monomeric styrene, butadiene, acrylic acid, and their derivatives from which products such as styrene butadiene latexes, acrylic acid esters and polyvinyl acetate are obtained. Besides synthetic binders, natural binders are also used. They are often multifunctional in that they contribute to bond strength, water retention and improved runnability. Natural binders include starch and derivatives, and with some restriction carboxy methyl cellulose (CMC, see Section 7.5.3.1). These products are normally supplied dry and need to be dissolved during color preparation (see Section 3.6.9.3.3).

Among binders, styrene-butadiene latexes dominate beside modified starches. Styrene-acrylate dispersions are specialties and of high importance for impressive prints. Additionally acrylate dispersions have an excellent brightness and ageing resistance and are less odorous. Future requirements of coating process conditions, on paper characteristics and printing technologies forced the production of tailor-made binders with very specific property profiles.

7.5.3
Other Coating Additives

Coating additives are either production additives required for the coating process (see also Section 7.7), or product additives that contribute towards specific paper properties (see also Section 7.8).

7.5.3.1 Production Additives

Coating additives which primarily influence the production process are

- dispersants for pigments, alkalis for pH control, such as sodium hydroxide solution (NaOH) or ammonia solution (ammonium hydroxide, NH_4OH)
- products for controlling viscosity and water retention, and for optimizing runnability, (co-binders, thickeners)
- products that aid lubrication/smoothing of coated paper surfaces, such as calcium stearate or waxes
- defoamers, deaerators and preservatives (biocides).

The purpose of using dispersants is to prepare a pigment dispersion where neither agglomerates nor aggregates exist and only primary particles are present. Primary particles are to be evenly distributed in water, and the system is to stay stable for a certain period of time (see also Section 3.6.9.3.2).

Synthetic co-binders and thickeners are both used for the same purpose in coating colors, i.e., adjusting rheological properties (shear viscosity), and water retention. Most of these products have additional binding power and also act as acceptor chemicals for optical brightening agents (OBA) (see following sections). Products belonging to this group are carboxy methyl cellulose (CMC), polyvinyl alcohol (PVOH, or PVA), acrylic copolymers, and associative thickeners (see Section 3.6.9.3.4). Thickeners need to be able to interact strongly with water molecules when they are to increase the water retention of coating colors. They also need to interact with other ingredients of coating formulations, especially pigments, in order to display a thickening effect. The nature and strength of these interactions depend on the chemical composition of the polymer.

Coating consolidation is the process during which the liquid coating color on the base paper is transformed into an immobilized coating layer. The runnability of a coating color is determined by the properties of the liquid color, i.e., wet coating

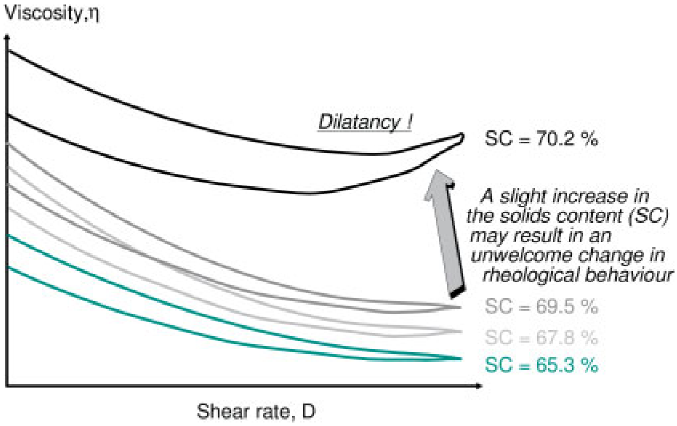
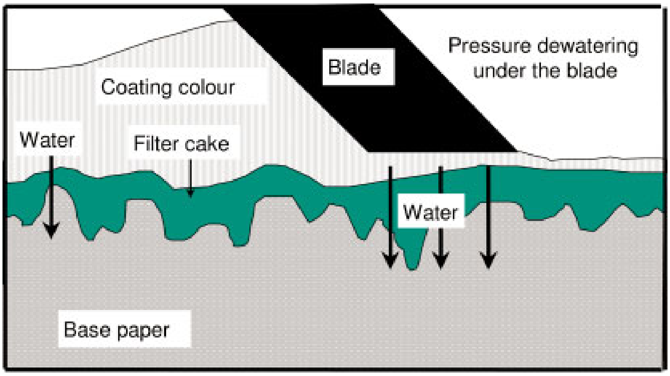


Fig. 7.10 Influence of dewatering on the rheology of coating colors (source: BASF).



The water retention of the coating colour influences the thickness of the filter cake together with the absorbency of the base paper.

Fig. 7.11 Influence of water retention on coating color application (source: BASF).

structure. Modern coating processes with high solids contents and high coating speeds demand coating colors with pronounced pseudoplasticity, i.e., low viscosity under high shear. The increase in the color viscosity by an increase in the shear rate is called dilatancy or shear thickening (Fig. 7.10). The final quality of the coated paper depends on the dry coating structure. The transfer from wet to dry coating structure is a result of the aqueous phase penetration from the coating color into the base paper (influence of water retention; Fig. 7.11) and, later, due to evaporation during drying.

Air/gas has a negative effect on the rheology of coating colors. If the coating color contains large amounts of air/gas bubbles, the extreme consequence can be skip coating, i.e. occurrence of uncoated spots, so physical and chemical aids have to be applied to reduce the air content (see Section 3.6.9.3.4.5). Preservatives, respectively biocides or microbiocides, are chemicals used in the pigment slurry and/or in the finished coating color to prevent the growth of microbes (see Section 3.7.4).

7.5.3.2 **Product Additives**

Shading dyes, optical brightening agents (OBA) and their carriers, cross-linking agents for natural binders and wet strength agents for offset papers, belong to the group of product additives which influence primarily the properties of the coated paper surface. The last two product classes are also called insolubilizers (see Section 3.6.9.3.5).

The brightness of pulp, fillers and coating pigments is often not high enough to reach today's brightness targets. Therefore there is a need to use blue/violet *shading dyes* and especially so-called *optical brightening agents* (*OBA*) as coating additives (see Sections 3.6.9.3.5 and 3.6.2). Optical brighteners work only when they are fixed to a carrier. A good carrier is linear and contains OH- or other hydrophilic groups. Linearity increases the contact between the carrier and OBA so physical bonds (such as hydrogen bonds and van der Waals forces) can be formed between the OBA and the hydrophilic groups of the carrier. Carriers in a coating color are, among others, starch, CMC (carboxy methyl cellulose), PVA (polyvinyl alcohol), or PVFA (polyvinyl formamide) derivatives.

There are many chemically different types of *insolubilizers* or *crosslinkers*. They all have the same function – to increase water resistance (see also Section 3.6.9.3.5.2). Water resistance is particularly important in offset printing, but also for wallpaper and in the storage of board packages. In double-coated boards, crosslinkers are used in the precoating to impart water resistance against the topcoat. The water resistance can be measured as wet rub and wet pick or is seen as less pick, print mottle, or binder migration. The water sensitivity of paper and board coating originates from the fact that water-soluble binders tend to lose their binding power in contact with water and dissolve. This water sensitivity of binders can be described as the amount of O-atoms in the molecule (in hydroxy and carboxy groups). The water sensitivity can be decreased by crosslinking the soluble binders together with insolubilizers or by building an insoluble net around the binders. Traditional insolubilizers in paper and board coating are based on formaldehyde and its amino compounds (melamine, urea) or on glyoxal. Imidazoline derivatives are also used as crosslinkers. Another class of insolubilizers are based on zirconium; the product most widely used is ammonium zirconium carbonate (AZC).

Lubricants improve the runnability of the coating color by reducing the friction between the machine part and the coating color. This can be seen for example as fewer scratches in the coating and longer lifetime of coater blades. Lubricants enhance the plastic deformation of the dry coating in the supercalender by preventing the cracking of the soluble binder film that would lead to dusting. It also improves gloss. During calendering, lubricants migrate from the coating onto the hot calender rolls and form a monolayer on the rolls, thus preventing sticking of the coating to the rolls. Dusting at printing machines has been a problem in LWC, especially when delaminated kaolins are used. Different kaolins have different dusting tendencies, dusting can often be reduced or eliminated by using a lubricant. The most commonly used lubricant is calcium stearate. Wax emulsions (mostly emulsions of paraffin waxes, microcrystalline waxes, or polyethylene waxes) are the oldest group of lubricants in paper and board coating. These emulsions give good runnability but have less effect as antidusting agents than has stearate. A new group of substances used as lubricants are soy lecithin/oleic acid blends. Polyethylene and polypropylene glycols are used in blends with calcium stearate or alone as a lubricant with additional influence on rheology and flow properties of the coating color (see also Section 3.6.9.3.4.4).

7.6
Coating Color Formulations [1, 4, 8]

The main driving forces to develop new or improved coating color formulations are:

- customer needs for improved coated paper quality such as higher brightness, print gloss and bulk, better coating coverage
- requirement of high uniformity of paper quality which calls for accurate process control during coating color formation, color application, and drying
- trends in printing technology such as higher printing speeds or digital color printing
- new developments in coating technology such as new coating methods or higher coating speeds requiring good coating color runnability and uniform coating color quality at the same time
- need for less energy consumption in drying which means higher solids content of coating colors
- environmental requirements including recirculation and reuse of coating colors.

However, coating color formulations, in any case, must be cost competitive.

Coating color application requires its special formulation:

1. The solids content greatly influences the runnability of the coating color in the coating machine. The solids content basically influences the viscosity of the color and its flow behavior at varying shear stresses in the coating machine.
2. The various components of the coating color determine the highest possible solids content attainable for the target viscosity. The highest possible solids content is aimed for to save energy for drying of the coating color.
3. Most coatings are processed in the pH range 7.5–11.5. The alkaline range is preferred because most of the color components are anionic in character and, from a colloidal chemical viewpoint, form considerably more stable systems at higher pH values than at low pH values. In addition, the drying time in offset printing is greatly reduced with increasing pH, because of the oxidative drying system mostly used.
4. For nearly all coating processes, the water retention capacity of the coating color is most important; i. e., the ability of the coating color to retain water in spite of the sucking action of the coating base paper. If the water retention capacity is too low, the coating color may be too strongly dewatered between application and levelling. This leads to an increased solid content of the coating color before it comes into contact with the levelling blade which causes streaking and an uneven coat surface.

Coating color formulations and their solid content and properties differ according to the kind of application and coating process. Typical ranges of coating weight applied to the paper as well as solids content of the coating color for the various principles of pigmenting and coating are shown in Table 7.3.

Table 7.3 Coat weights and solid contents of coating colors for different coating methods.

Coating Method	Coating Color solid content (%)	Coating Speed (m/min)	Coat Weight	Remarks
Size Press	20–30	100–1000	2–5	Pigmented surface sizing
Film-Press	35–68	100–2000	6–12	
Blade Coater	45–72	100–3000	7–20	
Metering Bar Coater	40–65	100–800	3–12	Pigmented surface Sizing or coating
Air Knife	30–50	100–500	8–12	Mainly Board coating
Spray Coating	45–55	100–2000	5–12	
Curtain Coating	45–68	100–2000	8–12	

Another crucial factor in coating color formula design is the intended use, i.e., the envisaged paper type and printing process. Formulations differ between matt and glossy grades, as well as for single or double coats with pre- and top coats, and triple coats with precoat, intermediate and topcoat. All coating color formulations aim for maximum solids content for quality and economic reasons. The coating color formulations presented in Tables 7.4 to 7.12. are examples commonly used in Europe at present. However, they must usually be adapted to suit the particular conditions in the individual paper and board mills. All formulations are in dry parts of the individual substances. In many cases coated web offset paper has to have high stiffness of paper and freedom from blistering and creasing, the latter especially for heat-set web offset. Manufacture of higher-weight papers like MWC and HWC involves formulations similar to those used for woodfree grades.

Table 7.4 Woodfree offset printing paper – single-coat, matt quality.

Amount (parts)	Component
80	natural ground calcium carbonate (GCC, 60–90% < 2 μm)
20	kaolin
10–12	synthetic binder
0.5–1.0	co-binder, thickener
0.5–0.8	optical brightener (as received)
65–68%	solids content

Table 7.5 Woodfree offset printing paper – double-coat, matt quality.

Precoat **Amount (parts)**	**Component**	**Topcoat** **Amount (parts)**	**Component**
100	GCC (60–75% < 2 μm)	80	GCC (90–99% < 2 μm)
8	starch	20	high glossing kaolin
6–8	synthetic binder	10–12	synthetic binder
		0.5–1.0	co-binder, thickener
		0.5–0.8	optical brightener (as received)
65–68%	solids content	66–70%	solids content

Table 7.6 Woodfree offset printing paper – single-coat, gloss quality.

Amount (parts)	**Component**
70–80	GCC (60–99% < 2 μm)
20–30	high glossing kaolin
12	synthetic binder
0.5–1.0	co-binder, thickener
0.5–0.8	optical brightener (as received)
65–70%	solids content

Table 7.7 Woodfree offset printing paper – double-coat, gloss quality.

Precoat **Amount (parts)**	**Component**	**Topcoat** **Amount (parts)**	**Component**
100	GCC (60–75% < 2 μm)	80	GCC (60–90% < 2 μm)
8	starch	10	kaolin
6	synthetic binder	10	talc
		12	synthetic binder
		0.5–1.0	co-binder, thickener
		0.5–0,8	optical brightener (as received)
65–68%	solids content	66–68%	solids content

Table 7.8 Wood-containing light weight coated (LWC) paper for rotogravure printing (51–72 g m^{-2}), gloss quality.

Amount (parts)	Component
70–100	kaolin
30–0	talc or GCC (90–99% < 2-μm)
4.5–5.5	synthetic binder (sole binder)
0.5–0.8	stearate (sodium, ammonium or calcium stearate)
50–60%	solids content

Table 7.9 Wood-containing light weight coated (LWC) paper for rotogravure printing (51–72 g m^{-2}), matt quality.

Amount (parts)	Component
45–50	GCC (75–90% < 2-μm)
20	kaolin
30–35	talc
5.0–5.5	synthetic binder (sole binder)
0.5–0.8	stearate
50–60%	solids content

Table 7.10 Wood-containing light weight coated (LWC) paper for web offset printing (50–70 g m^{-2}).

Amount (parts)	Component
50–70	GCC (90–99% < 2 μm)
30–50	kaolin
10–12	synthetic binder
0.5–1.5	co-binder, thickener
2–4	natural co-binder
60–70%	solids content

Table 7.11 Solid bleached board (SBS–100% bleached chemical pulps) – double coated.

Precoat Amount (parts)	Component	Topcoat Amount (parts)	Component
80–100	GCC (60–90% < 2 µm)	60–80	GCC (90–99% < 2 µm)
0–20	kaolin	20–40	kaolin
12–14	synthetic binder	12–15	synthetic binder
0.5–1	co-binder, thickener	0.5–1.5	co-binder, thickener
55–68%	solids content	65–70%	solids content

Table 7.12 White-lined chipboard (WLC-mainly recycled fibers) – triple coated.

Precoat Metering bar Amount (parts)	Component	Middlecoat Air knife Amount (parts)	Component	Topcoat Bent-blade Amount (parts)	Component
80–100	GCC (60–75% < 2 µm)	60–80	GCC (60–90% < 2 µm)	80	GCC (90–99% < 2 µm)
0–20	kaolin	10–20	titanium dioxide	20	high glossing kaolin
12–14	synthetic binder	10–20	calcined kaolin	12–14	synthetic binder
0.5–1	co-binder, thickener	14–18	synthetic binder	0.5–1.0	co-binder, thickener
		0.5–2.0	co-binder (low viscosity)		
50–60%	solids content	45–60%	solids content	66–70%	solids content

7.7
Coating Color Preparation [1, 3, 4, 8]

7.7.1
General Aspects of Coating Kitchen Set-up

The objective of a coating color preparation plant is to prepare the desired amount of coating color in the required quality using a combination of mixing, pumping, storing, conveying, metering, and screening processes. Such a plant consists of storage tanks, pipelines, pumps, valves, mixer, screens and dosing equipment. Figure 7.12 shows the key processes starting from unloading chemicals to the coating color application.

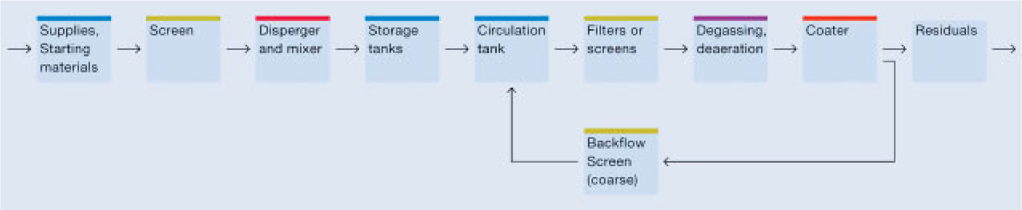


Fig. 7.12 Schematic flow of coating color preparation (source: Omya).

In the coating kitchen all raw materials needed for coating are combined in the requisite form and sequence. In the past, work in the coating kitchen was largely manual. Today, the same tasks are usually handled by a process controlled system, without much human intervention except for monitoring. The mill operators can track every detail of preparation and coating operations. All the process data are stored for instant recall. This is to support uniform high quality by selection of the appropriate raw materials, their separate or joint preparation with strict adherence to timed dosing sequences, and clean working practices.

Coating kitchens operate either batchwise or continuously. In view of problems such as dusting of powdery products and for operational reasons, many paper mills have switched from dry to liquid storage of their starting materials. This also brings the advantage that individual components can be precisely dosed. In every case a special handling and make-up process for the individual products is necessary.

7.7.2
Dispersing of Pigments

These days, most of the pigments are delivered as slurries or dispersions with 60–78 % solids. These pigments are very well dispersed by the suppliers. Pigments supplied in the dry form have to be carefully dispersed in the paper mill before being temporarily stored and converted in liquid form. Poor dispersing leads to problems such as blade scratches, excess rejects at screens, rheological fluctuations, and runnability disturbances at the coaters.

The first step in dispersing is wetting the particles, eliminating the air layers on the pigment surfaces. Water is absorbed into the agglomerate pores by capillary action. Chemical deflocculation will proceed slowly by diffusion. The resulting dispersion will not be homogenous and will contain agglomerates, which require physical stress to break them down. For good pigment dispersion at high dry solids content, a disperser is used to create the physical shear and mixing forces. Two examples of batch dispersers are shown in Fig. 7.13 and Fig. 7.14. To achieve the required high solids content of the coating colors some chemicals, namely dispersing agent and caustic soda, must be added to the suspension to improve and stabilize the dispersion (see section 3.6.9.3.2).

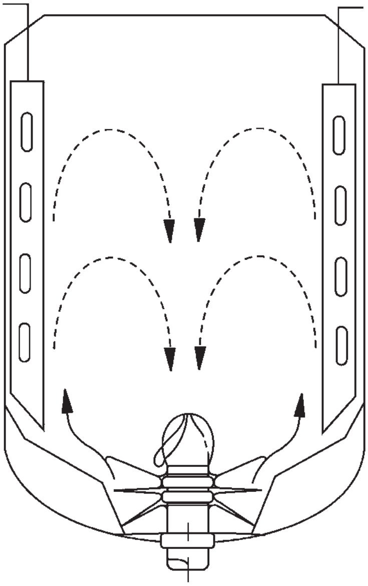


Fig. 7.13 Deliteur disperser (source: Metso).

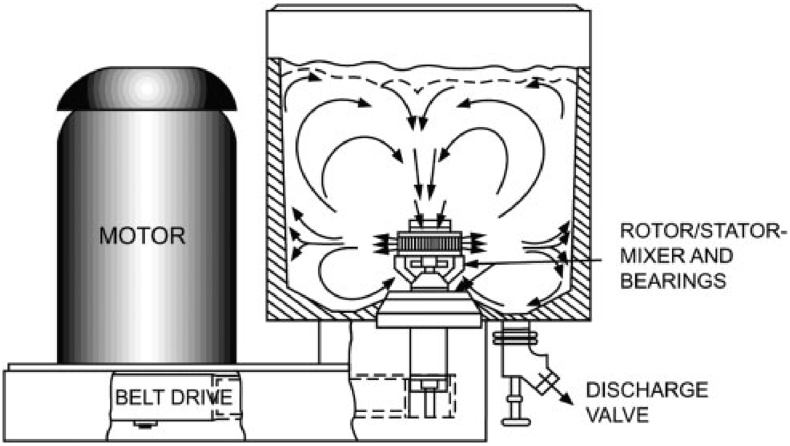


Fig. 7.14 Kady mill disperser (source: Metso).

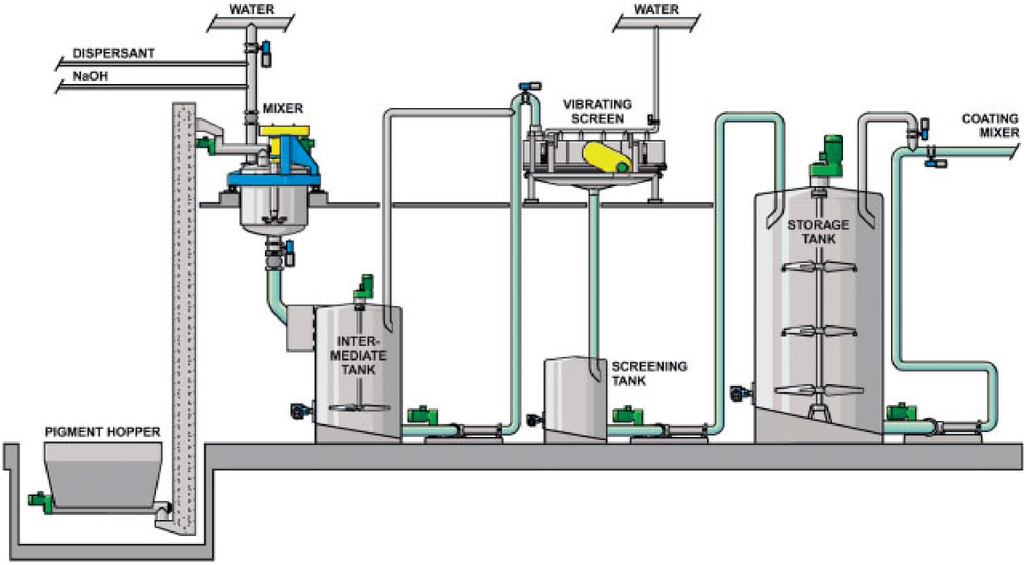


Fig. 7.15 Pigment makedown process (source: Metso).

A complete pigment makedown batch process is shown in Fig. 7.15. Railway cars or truckloads are emptied into a hopper. The pigment is conveyed and dosed into a disperser by measuring the weight of pigment with load cells. The same is done with the feed water and dispersing agent plus pH-control chemical. After dispersion the content of the disperser is emptied into an intermediate tank. Screening is a continuous process to ensure maximum capacity and screening efficiency. From the screens, the slurries go to a screening tank. The slurry will then be pumped to a large storage tank where it waits for pumping and dosing into the coating color mixer.

7.7.3
Processing of Binders

7.7.3.1 Latexes

Latexes are delivered by the manufacturers as a water-containing dispersion of polymerized synthetic chemicals at dry solids levels of approximately 50 %. Latexes contain certain surface-active chemicals, and the main task in coating color preparation is not to disturb or break their balance. This means that the whole handling must be clean and without any harmful chemicals. For delivery and storage of the different latexes a truck or railway car is emptied, using either its own pumps or a pump from the mill. The storage capacities of latexes are optimized according to their consumption. Normally these storage tanks are made of stainless steel and not equipped with any agitators. From these storage tanks, latexes are pumped and screened into the coating color mixer.

7.7.3.2 Starch

Starch has been one of the most popular binders for decades, because it is a cheap product, especially when utilizing low-cost unmodified starches. These grades are normally sold at lower costs than pulp. Starch is also a very flexible material and a paper or board coating mill can convert it to their specific coating requirements. The starch producing companies can also modify starch by introducing esters or ethers of starch. A special feature of starch acetates for the paper industry is that these ester groups are efficient in preventing amylose retrogradation (see below). They have extremely good viscosity stability. An ether starch, e. g., is appropriate for its good film-forming property or holdout of organic solvents.

Native or unmodified starch dispersed in cold water, settles out rapidly due to lack of solubility. A dispersion of starch in water has no adhesive power. To become an adhesive, the starch has to be heated in water above the gelatinization temperature of the starch, which differs depending on its plant origin (Table 7.13). When a starch suspension is heated beyond the gelatinization temperature, the individual starch granules begin to swell and, after a time, a colloidal sol or starch paste is obtained with adhesive and binding properties. The hot gelatinized starch paste is a non-Newtonian fluid. A starch paste derived from unmodified starch has relatively high viscosity at very low solids concentration. In practice, it is nearly impossible to prepare a manageable starch paste exceeding 7 % unmodified starch. With time and temperature decrease, an increase in viscosity or thickening can be observed. This thickening is due to a well-known phenomenon for all unmodified starches called setback. It occurs because during thermal decomposition, e. g., gelatinization, the original crystalline arrangement of the starch molecules is lost. When cooling the starch paste, the molecules cling together again, thus forming insoluble aggregates. As a result of this crystallization process, the paste solution gradually turns turbid, while the viscosity increases. Finally, the viscous paste turns into an opaque mass or gel. In very dilute solutions, there is not enough material

Table 7.13 Basic characteristics of starch.

	Potato	**Barley**	**Wheat**	**Corn**	**Waxy maize**	**Tapioca**
Source	Tuber	Grain	Grain	Grain	Grain	Tuber
Particle size (m)	10–100	10–35	3–35	5–25	4–30	3–30
Gelatinization temperature (°C)	60–65	80–85	80–85	75–80	65–70	65–70
Moisture at 65 % RH (%)	19	13	13	13	13	13
Protein (%)	0.05–0.1	0.3–0.5	0.3–0.5	0.3–0.5	0.2–0.4	0.05–0.1
Fat (%)	0.05	0.4	0.8	0.7	0.2	0.1
Ash (%)	0.3–0.4	0.1–0.2	0.2–0.4	0.1–0.2	0.1–0.2	0.2–0.3
Phosphorus (%)	0.08	0.02	0.06	0.02	0.01	0.01

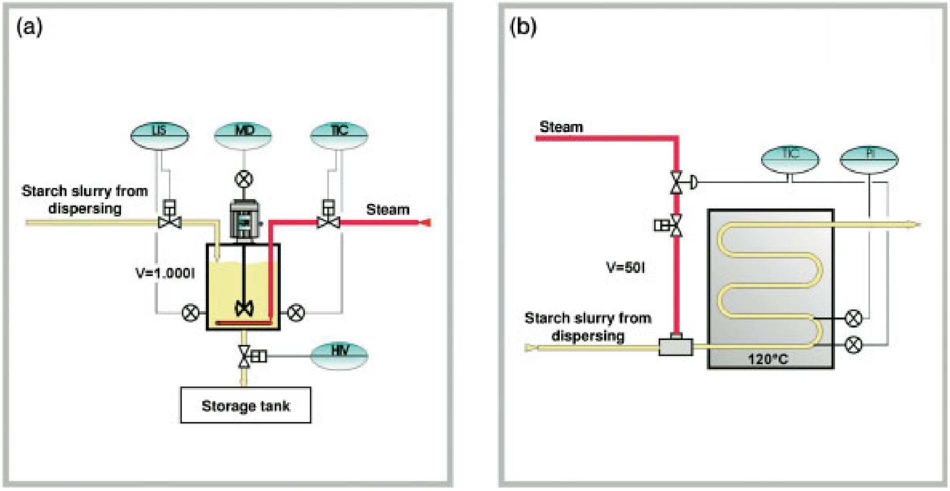


Fig. 7.16 Starch cooking processes: (a) discontinuous, (b) continuous (source: BVG).

to gel the entire solution so insoluble starch particles sink to the bottom. It is mainly the linear amylose molecules which exert this usually undesirable tendency, called amylose retrogradation or simply retrogradation, which is an irreversible process. To prevent retrogradation effectively, modification of the starch is necessary. Methods to reduce and stabilize the viscosity of starch by gelatinization and depolymerization are discontinuous or continuous cooking processes. All starch cooking applications involve an initial dispersion of starch in water to give a slurry. According to the intended application of the starch, the slurry concentration will vary between 5% and 40% dry substance.

The batchwise cooking of modified starch takes place unpressurized at temperatures around 95 °C for approximately 30 min under good stirring conditions (Fig. 7.16(a)). Continuous starch cooking is done in the so-called jet cooker at a steam temperature of approximately 120–130 °C. The steam immediately interacts with the starch in a Venturi tube and the gelatinization is completed within a few seconds (Fig. 7.16 (b)). Another common possibility is the enzyme conversion of native starch, again done either discontinuously or continuously. With the aid of highly active protein molecules from bacteria, so-called alpha-amylase, the starch molecules are broken up at 70–85 °C and the enzyme must be inactivated after approximately 10–20 min, in order to stop further break up. The inactivation can take place through the addition of acids and holding at 95 °C for 10–15 min or by swift heating up to 130 °C. A continuous starch cooking and converting system is shown in Fig. 7.17.

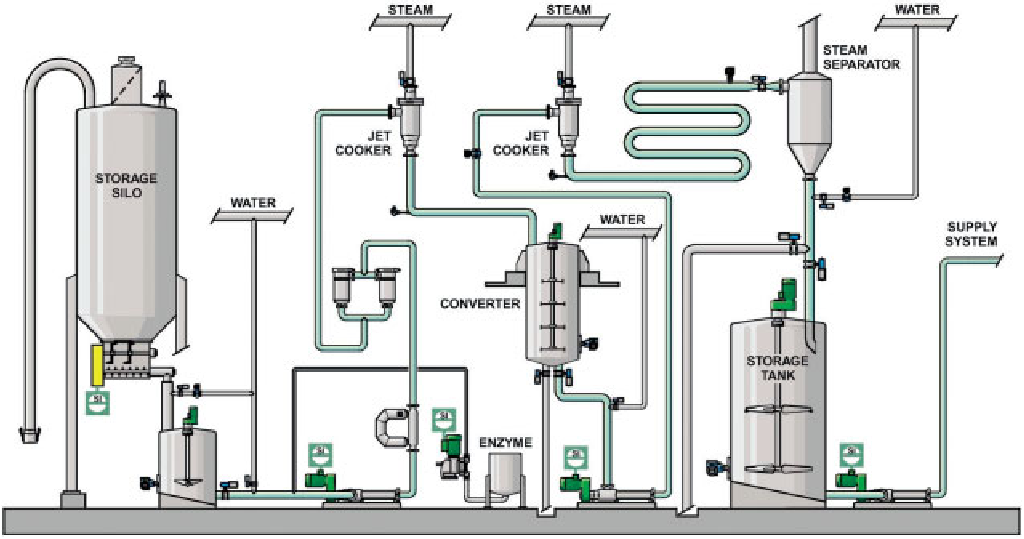


Fig. 7.17 Continuous starch cooking and converting process (source: Metso).

7.7.3.3 Other Binders

Polyvinyl alcohol (*PVA*) and *proteins* are delivered to the paper or board mills as dry powder. in sacks or big bags. The handling system for these products has the same features, cooking with steam, as starches. The key equipment here for the batch process is a heavy-duty mixer with steam inlet tubes for even distribution of steam bubbles. The product slurries are heated to 90–100 °C with direct steam heating and then held at this temperature for 20–30 min until there is a clear solution of the product in the batch cooker. For example, the PVA solution has a viscosity maximum at temperatures of 65–75 °C. The major difference between PVA and starch cooking is that in a PVA cooking system the molecular structure or polymer chain length is not altered. The hot PVA solution is also held warm in its storage vessels in order to avoid viscosity changes due to decrease in temperature.

The key control parameter of a protein solution is the solids content, therefore the metering of water and protein powder must be accurate. Some pH-controlling chemicals must be added to have the right caustic process conditions. Typical protein processing parameters are 10–25% solids content, alkali amount (one-third of sodium hydroxide and two-thirds of ammonium water) around 7% of the protein, heating to 60 °C and holding at this temperature for between 15 and 30 min. The protein will be cooked until the binder is a lump-free solution.

7.7.3.4 Additives

Additives are, for example, carboxy methyl cellulose (CMC), flow modifiers, pH-controlling chemicals, preservatives (biocides), defoamers, deaeraters, dyes and optical brighteners. All products except CMC are delivered as solutions, emulsions, or dispersions. Their concentration can be suitable for direct metering into the coating color preparation, or they may be diluted to a lower concentration in order to improve the metering accuracy or to avoid shocks caused by too strong chemicals. Therefore proper investments in handling and metering systems of these additives have to be made.

7.7.4
Tanks

The mixing, storage and circulation tanks for coating colors are made of stainless steel, since the pH range of raw materials and coating colors tends to corrode standard steels. Most vessels are equipped with an agitator, and some also have a shell/jacket that may be heated or cooled. Agitators are mostly indispensable because, in low-viscosity colors especially, solid color components are prone to sedimentation unless the suspension is stirred continuously.

7.7.5
Screens and Filters

Impurities of any kind in coating colors may lead to serious problems in coating machines so these contaminants have to be removed by means of either open vibrating screens (Fig. 7.18) or closed filters (Fig. 7.19). Open screens are frequently preferred, because the retained dirt is visible and defective screens can be quickly replaced. However, there is a risk of air becoming entrained with the coating color. Also, color splashes and blocked screens can heavily contaminate the immediate environment. Closed filters are clean by comparison. In parallel arrangement, they incorporate pressure controls and automatic backwashing functions. In everyday practice, color losses inevitably occur during backwashing. Also, retained dirt particles can only be identified after filter cartridges are removed.

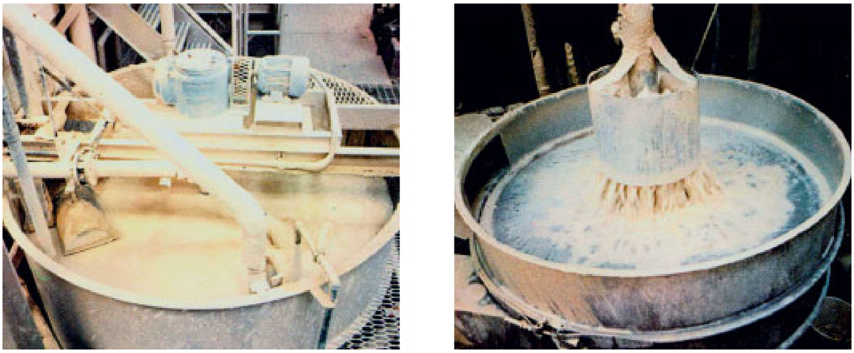


Fig. 7.18 Open Screen for filtration of pigment slurry/coating color (source: Omya).

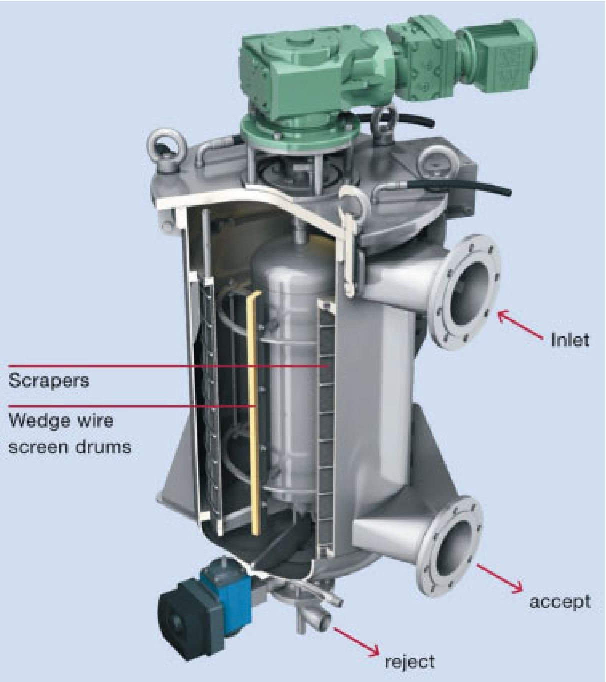


Fig. 7.19 Closed filter system (source: Metso).

Whichever system is chosen, the mesh of screens or filters has to be small enough to retain all particles > 50 µm.

In modern coating kitchens the various starting materials are usually prescreened over mesh widths around 50–60 µm before the finished coating color is passed through 100–150 µm screens or filters in the circulation system. Smaller mesh sizes are inadvisable, because they would largely restrict the passage of the highly viscous color. Coarser screens are frequently installed in the coater recirculation system to retain scraps of paper that may have been introduced into the coating circuit after web breaks.

7.7.6
Degassing of Coating Colors

Coating colors contain air and gas bubbles of various sizes that originate from the raw materials and turbulence during color preparation. Gas content can vary greatly: 10–15% by volume is typical, although it may exceed 35% in extreme cases. Gas levels in coatings have become a major quality issue since the introduction of new jet applicators because every air or gas bubble leaves a crater in the coating surface. This compelled papermakers to install online degassing equipment in coaters with jet applicators. Most of the degassing systems are based on

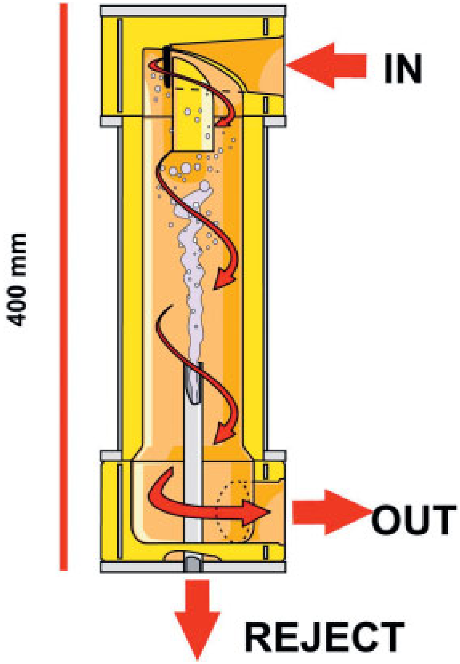


Fig. 7.20 Degassing cyclone.

the density differences in a centrifugal field of a cyclone (Fig. 7.20). Modern systems are capable of reducing gas levels to 4%. The effiency of such physical degassing apparatuses will be further improved by the additional use of chemical deaerators (see 3.6.9.3.4.5).

7.7.7
Batch Preparation of Coating Colors (Fig. 7.21)

All components of the coating color formula are pumped from their storage tanks into a mixer and hereby screened once again. A recirculation pipe installed between the component storage tank and the mixer is used for those chemicals that have a settling tendency, like pigment slurries, or to keep certain products homogeneous in their temperatures and concentrations, like starch, CMC, or proteins. The mixer is placed on load cells to measure accurately the batch sizes and weights of the major components. Other precise ways to dose the additives are mass flowmeters and metering pumps. In batch processes, these metering devices can be optimally calibrated and dimensioned because the flow rates are normally kept constant and the dosing time is varied depending on the amount of each additive used in a coating color formula. Batch processes are also very flexible for a wide dosing range of each component. The difference between the maximum and minimum rates does not negatively influence their accuracy or the flexibility. One set of metering instruments and valves can easily be used to serve two mixers optimizing

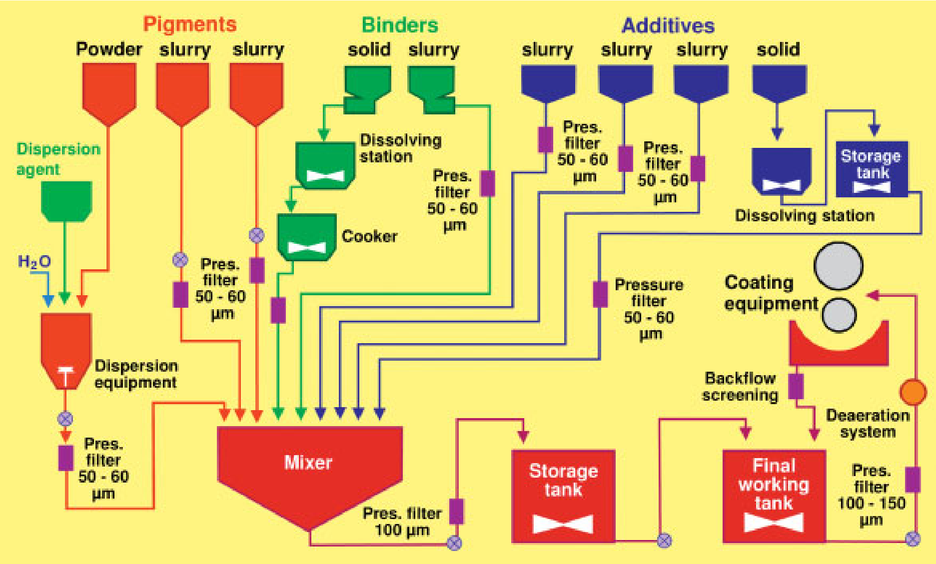


Fig. 7.21 Batch preparation of coating colors (source: Metso).

investment costs and space in the coating color kitchen. The flexibility of a batch process is obvious in cases where the rheological or other properties of coating colors have to be changed by altering the order of addition of the same chemicals. The mixing time and mixing energy can also be easily changed.

7.7.8
Continuous Coating Color Preparation (Fig. 7.22)

The major advantage of a continuous process is the smaller size and thus lower cost of pumps, valves, flow meters and pipings. So-called “calibration systems” for each line ensure the metering accuracy and are fully automated. These continuous systems are most effective in high-capacity coating with large volumes of coating colors with the same color quality, such as in a one-grade paper mill. Here the number of different coating colors is low and, if there is a grade change, different coatings are usually allowed to be mixed with each other. This continuous system differs from a batch process in many aspects: The components of coating colors are continuously pumped, screened, and metered into a continuous mixer. Besides the size difference of the piping equipment the mixers are completely different because mixing must be completed during the short time when the components are passing through the mixer. It is equipped with high-shear, high-energy mixing zones, usually two, or two separate mixers in series are operated. Dosing of all additives is crucial for constant coating color quality, they are metered with mass flow meters, magnetic flow meters, or metering pumps. The mixer feeds its ready-made coating color directly to the coater supply tanks which results in a low stor-

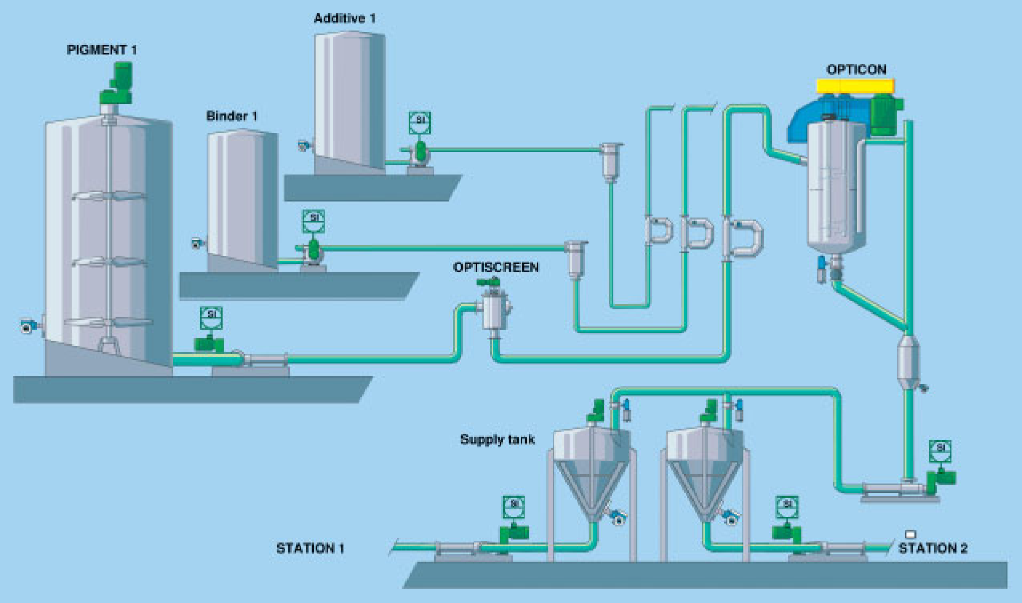


Fig. 7.22 Continuous preparation of coating colors (source: Metso).

age volume of processed coating color. The advantages are fast control measurements of the coating color properties and the possibility of quick changes in the color composition. On the other hand the range of volumetric capacity of each chemical line is strongly limited for a given installation.

7.7.9
Coating Color Supply Systems for Coaters

The basic function of the coater supply system is to supply coating color to the coating heads to be evenly spread on the paper or board web. In most cases only about 10% of the pumped coating color will be applied onto the running fiber web. About 90% of the coating color flows back to the supply tank. This high internal coating color recirculation is required to ensure homogenous and constant color properties for trouble-free coater operation. The feed of the fresh color into the supply tank is controlled by its level. From the supply tank, the coating color will be pumped first to the screens, which eliminate all impurities larger than 50 µm, depending on the geometry of the screening elements. The second key process is degassing of the coating color. Depending on the design of the coating heads, the coating color flow is led to the ponds or chambers through one or two inlet pipes (Fig. 7.23) controlled by a throttling valve for accurate flow. The overflow goes back freely to the supply tank. The contents of solids and gas as well as temperature and pH and their variations are monitored continuously.

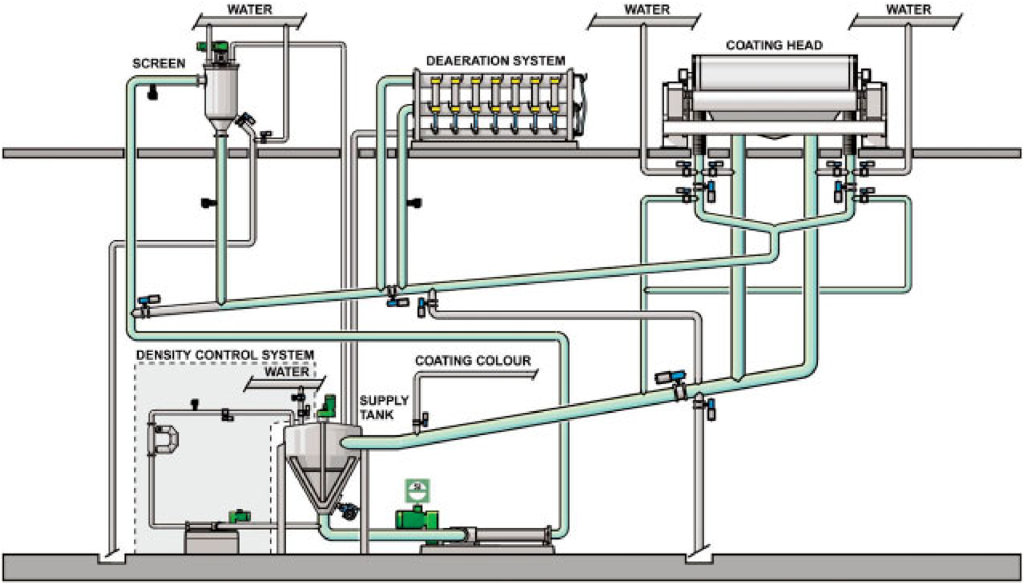


Fig. 7.23 Coating color supply system (source: Metso).

7.8
Measurements of Coating Colors [3–4, 8]

The shear-viscosity and viscoelastic properties of paper coatings and their time-dependent behavior are important attributes that need to be measured for better understanding and optimization of the process.

7.8.1
Viscosity

Viscosity is measured with rheometers or viscometers. The methods used include rotational deformation, squeezing deformation, extrusion (capillary) flows, and free surface stretching. For rotational instruments, there are two modes of operation: controlled strain and controlled stress. Rotational measurements can be further subdivided into different measuring methods (flow, oscillatory, stress relaxation, and creep) and different measurement devices (spindle, cone-and-plate, parallel plate, concentric cylinder). As for a capillary rheometer, there are two modes of operation: controlled flow (strain) and controlled pressure (stress).

7.8.2
Viscoelasticity

Viscoelasticity refers to rheological behavior that is a combination of viscous (liquid-like) and elastic (solid-like) behavior. Ideal elastic behavior is called Hookean, where the stress is directly proportional to the strain. A Hookean solid deforms as long as stress is applied. Once stress is removed, it fully recovers its original shape. This behavior can be modeled by a spring that stores energy under deformation and then releases it. Ideal viscous behavior is called "Newtonian", where the stress is directly proportional to the rate of strain.

A Newtonian fluid flows as long as a stress is applied and retains its final shape once the stress is removed. This behavior is modeled by a dashpot that consists of a piston moving in a viscous liquid.

Paper coatings can be generally considered as viscoelastic fluids. The viscoelasticity of a material is most often measured by applying oscillatory shear instead of steady shear. There are two common types of oscillatory tests. A strain sweep test is carried out at a fixed frequency while the amplitude of the oscillation is varied. As the amplitude is increased, more energy (or shear) is applied to the sample. This energy may begin to break down the internal structure of the material. This is analogous to stretching a spring too far. The strain at which the coating structure begins to break down is called the critical strain, which gives some information on the nature of the internal structure of the material. For example, flocculated dispersions have critical strains of about 1%, polymer solutions have critical strains of about 10%, and polymer melts have critical strains of about 100%. Most paper coatings have critical strains of about 0.5–5%, indicating that their elastic behavior is a result of a weak network structure between pigment particles and/or thickener. The second common type of oscillatory test is a frequency sweep where the amplitude of oscillation is fixed while the frequency of oscillation is varied. The amplitude for the frequency sweep is chosen to be within the linear viscoelastic region, as determined by the amplitude sweep measurement.

An alternative way to measure the viscoelastic properties of a material is to apply a step change in stress or strain and then measure the response of the material over time. This is the basis for stress relaxation and creep testing of materials. In a stress-relaxation test a constant strain (or shear) is applied for a period of time and then removed. Upon removal of the strain, the stress begins to relax. Typically, one measures the relaxation time needed for the stress to relax to half of its equilibrium value at long times. Closely related to stress relaxation is a stress-growth test. Here a sudden increase in strain is applied to the sample, and the growth in stress is monitored over time. Both stress-relaxation and stress-growth measurements are used to characterize paper coatings. A correlation between the stress-relaxation time and the healing of coating defects can be observed in practice: Coatings with a shorter relaxation time (more fluid-like) show narrower residual widths of an induced blade streak. Stress-relaxation properties of a coating also correlate with improved leveling of orange peel patterns for high-speed metered film coatings.

7.8.3
Water Retention

During coating consolidation the liquid coating color on the base paper transforms into an immobilized (stiff) coating layer. The runnability of a coating color in coating is determined by the properties of the liquid color, i. e., wet coating structure, whereas the final quality of the coated paper depends on the dry coating structure. The transfer from wet to dry coating structure is a result of the aqueous phase penetrating from the coating color into the base paper and, later, due to evaporation on drying. A prerequisite for liquid transport in porous material is the presence of a driving force. Some common examples for water transport in paper are capillary pressure, external pressure, vapor pressure, concentration gradient, and temperature gradient. Several driving forces may be present at the same time, which makes the transport mechanism complex.

The various water retention measurement techniques can be divided into static (direct and indirect) as well as dynamic methods. The first provides a quantification of the amount of aqueous phase leaving the coating color and penetrating into the base paper. The measurement principle is based on filtration of coating color under the influence of external pressure. The indirect methods measure other parameters reflecting the penetration of aqueous phase into the base paper, such as electric conductivity, ultrasonic transmittance surface gloss, and coating viscosity. The dynamic techniques are usually based on measurement of solids increase in the coating pan or various scrape-off experiments during laboratory and pilot coater trials.

7.8.4
Solids Content

The right solids content of pigments is important as pigments are the biggest portion in the coating color recipe. The solids content of the coating color being too high or too low, directly affects the coat weight, the runnability of the coating unit and the necessary drying energy. The solids content is measured by drying a sample in an oven and calculating the amount of dry components as a percentage. Because the traditional oven method takes several hours to measure solid content, quicker methods have been developed for “just-in-time quality control”. In these quick methods, infrared and microwave drying are used.

7.8.5
pH

In practice it is easy and quick to ascertain pH from aqueous suspensions and chemicals. However pH is sensitive to temperature variations; therefore pH measurements should be performed under constant conditions and the calibration rules of each individual pH gauge have to be followed carefully. The normal coating color pH is between 8 and 8.5, but higher levels are needed when using some synthetic thickeners or pH-dependent latexes. The ISO 787–9 method should be followed for pH value measurements.

7.8.6
Screening Residue

This is defined as the percentage of coarse particles in the measured material after screening through a given Mesh-number screen (e. g. for pigment slurries and finished coating colors a Mesh number of 300 is used, and for latex Mesh numbers 150 and 80 are used). If blade stripes or other similar coating problems occur, it is worth measuring the screening residue and determining whether any larger particles are mixed in the coating color.

7.8.7
Bacteria Level

A high bacteria level of coating color chemicals may influence the machine runnability. Furthermore, for coated paper that comes into contact with food the bacteria level has to be low. The bacteria level of a material can be counted by the so-called Easicult Combi test. This method of control is easier than doing a plate cultivation (see also section 3.7.4).

7.9
Measurements of Coated Surface (see also Chapter 12), **[4, 5, 10, 11]**

Different printing methods have their own requirements for coated paper and paperboard. The coating amount has a big influence on the physical and optical surface properties. Physical properties are smoothness, gloss, surface strength, ink absorption, dusting/linting, piling and visual defects. Optical properties are brightness, whiteness, color shade, opacity, mottling and print unevenness. Taste and odor are important properties, especially for paper and paperboard grades used for food packages.

7.9.1
Coat Weight

Coat weight measurement in the laboratory is based on the ash content (925 °C) of base paper and the ash content of coated paper. Several different technologies have been used to measure on-line coat weight. The Beta or dry weight technique measures dry weight before and after the coating operation and the coat weight is calculated by difference. Weight and moisture sensors are required at both locations. The ash or X-ray absorption method is similar except that ash sensors are used instead of basis weight measurement. IR absorption is the newest technique to be used, as with X-ray fluorescence, latex and/or carbonate in the coating color are measured. The methods are used in differential mode, i. e., two scanners are applied.

7.9.2
Smoothness

The same basic smoothness measurements are applicable for coated paper as for base paper. As rotogravure printing is the most demanding printing method for paper surface, a special test method is used only for that purpose. The so-called "Helio-test" is performed with an IGT-tester (see Section 7.9.5). In this simulated printing test, the number of missing dots, counted visually, provides information on the printability.

7.9.3
Gloss

Gloss describes the mirror-like property of a coated surface and is defined as the percentage of the light that is reflected from the surface at an angle equal to the angle of incidence, in comparison with a standard surface.

7.9.4
Ink Absorption

This is the ability of a (coated) paper surface to absorb ink during printing. If ink absorption is too slow, there may be a risk of set-off. Generally used tests are the K&N test (TAPPI Method 553), the Lorilleux Porometrique test, the Microcontour test, or the Croda test, depending on the test ink used. All the above-mentioned tests follow similar test procedures: The ink used is applied to a paper surface in a thickness of 0.1 mm; after 2 min nonabsorbed ink is wiped off. The brightness of the colored area is measured and subtracted from the original brightness of the paper to give the ink absorption value as a percentage. The test area can also be used for visual evaluation of the evenness of absorption. If the area is mottled, there is a risk of mottle during printing.

7.9.5
Surface Strength

This is the internal and surface bond strengths of paper which are necessary to prevent fibers, fines, filler, or coating from being removed in printing or converting operations that involve ink and/or aqueous liquids such as in offset printing. Generally, for coated paper, the picking test and rub resistance are used. The picking test is done either by using a wax pick test (Dennison Wax/TAPPI Method UM 463) or a simulated printing by using a device from the Institute for Graphische Technik (IGT tester/TAPPI UM 591). Rub resistance describes the ability of printed paper to withstand marking, scuffing, or smudging during handling coated material. Laboratory rub testing of dry print can be carried out with an optional number of rubs and pressure. The results are assessed visually against set standards. The rub resistance method follows TAPPI 592.

7.9.6
Dusting or Linting

This is an accumulation of cutter or slitter dust on the blanket around edges of the web and an accumulation of fibrous materials or/and pigment on the blanket of the print press. These phenomena influence both print quality and production efficiency. Dusting and linting are tested on a full-scale heatset press at a printing speed of 50 000 sheets h^{-1} (6.2 m s^{-1}) under normal press conditions. Usually 30 000 copies of each paper have to be printed. The accumulated lint on the printing blanket from 50% halftone and the nonprinting area is collected with a tape and weighed. The lint can be analysed with a microscope to determine the origin of the lint (small shives, fibers, ray cells fines, etc.).

7.9.7
Piling

This results in the accumulation of coating particles and ink on the tail-edge of the solid printing area or/and the halftone area on the blanket. The accumulation is tacky material of the same color as the ink. Piling is also tested on a full-scale heatset press at a speed of 60000 sheets h^{-1} (7.4 m s^{-1}), with a special tacky ink on the first and second units, a high water feed on the first unit to lower the surface strength and a low water feed on the fourth unit (adjusted with graphometronic; the goal is between the normal water feed and the toning level). Further print conditions are a special layout, papers are printed to a constant density and 30 000 to 40000 copies of each paper are printed. The degree of piling will be classified as "extreme piling" (printed amount less than 20000 copies at good printing quality, danger of web break), "major piling" (printing amount 20000–40000 good copies, danger of web break), "minor piling" (printing amount up to 40000 good copies) and "no piling" (printing amount significantly above 40000 good copies).

7.9.8
Visual Defects

As the primary objective in pigment coating is to improve the printability and appearance of the material, no visual defects should appear. Typical defects are holes, spots, blade scratches and streaks and creases. Visual defects are controlled using on-line detectors and visual checking. Visual checking is done in two places: The machine crew take a cross sample from the web at the top of each machine reel and examine it under strong light sources with different light angles to mark the defects. In laboratories, sheets are checked visually under a light source, and defects are counted and recorded. The on-line devices measure faults like slime holes, wrinkles, creases, edge nicks, turnovers, blade stripes, etc. Detection and counting of dirt specks are done online today. With low-viscosity colors, upstanding fibers in the surface cause pimples because the color climbs up these lumps of coating. Faults such as whiskers on the surface, loose fibers, coarse fibers, dust, lint, and fuzz, are usually only determined by inspection.

7.9.9
Brightness and Whiteness

Brightness and whiteness are highly dependent on the coating composition, pigment type, coating amount and the use of optical brightening agents (see section 3.6.9.3.5.4). Fiber type and basis weight also influence optical properties. Brightness measurements are taken over a range of wavelengths by using instruments conforming to ISO 2469/2470. Such instruments commonly found in use are the Elrepho 3000 (Datacolour/Zeiss) and the MacBeth White-Eye. The American paper industry uses a standard brightness instrument that has 45° illumination and 0° viewing (TAPPI Test Method T 452).

Whiteness is a comprehensive term used to express the visual impact of near-white surfaces by means of a single value. Numerous equations have been developed to this end, and CIE (Commission Internationale de l'Eclairage) whiteness is the most common in practical use. Whiteness is also used to denote a more comprehensive expression of color and color shade by use of the CIE color coordinates L^*, a^*, and b^* (or CIELAB). Three reflectance figures L^*, a^*, and b^* are calculated from measurements using a standard D65 light source. Here the UV content of the D65 illuminant must be accurately controlled to ensure reliable assessment of surfaces containing optical brightening agents. The coordinates a^* and b^* measure color. Positive figures for a^* express redness, negative figures greenness, and positive figures for b^* indicate yellowness, negative figures blueness. L^* is a percentage which measures luminance on a scale where black is zero and pure white is 100%. One can measure color coordinates as well as brightness with the same instrument, e.g., with a Hunterlab colorimeter or any other equipment. The calculations are complex and require the aid of computerized systems. Color coordinates are currently also measured and controlled by fixed-point or moving on-line equipment in paper machines.

7.9.10
Opacity

This is a measure of the amount of light transmitted through paper. When no light is transmitted, the opacity is 100%. The measuring principle is based on comparison of reflectance for a single paper sheet over a black background compared to an opaque stack of paper samples. As opacity increases with increased absorption and scattering of light, the following parameters are of prime importance for opacity: basis weight, filler content in base paper, degree of calendering, type and treatment of pulp, as well as coat weight and coating color components, especially the type of pigment used (fine pigments increase scattering). Opacity is measured in accordance with ISO 2471 and TAPPI Test Method T 425.

7.9.11
Mottling

There are several types of mottling: first color mottling, wet repellance mottling and back-trap mottling. First color mottling results from unevenness of the physical surface structure of the coated sheet (roughness, pore structure) and from the unevenness of optical surface properties (brightness, gloss). Wet repellance mottling occurs when the fountain solution layer between coating and ink interferes with ink transfer. Back-trap mottling leads to uneven ink setting in the coating layer. Mottling can be tested during normal print conditions either in a print house or research environment. For its investigation large areas (5×5 cm^2) of solid and halftone are needed. For checking first color mottling, packing is removed from the first, third and fourth unit: no water under the cyan ink and no back-trapping after ink transfer means no water or back-trap mottling. To test wet repellance mottling, packing is removed from the first unit: if there is no water under the cyan ink then no water mottling is given. For back-trap mottling packing is removed from the third and fourth units: when no back-trapping after ink transfer occurs then no back-trap mottling is given.

7.9.12
Print Unevenness

This means unwanted variation in density, color or gloss in print. The size and intensity of the variations are measured. Print density variations (graininess 0.5–2 mm; mottle 2–8 mm) are measured from an even black and/or cyan tone of at least 40% and as an average of eight images with a size of 51×51 mm^2.

7.9.13
Taste and Odor

When paper is used for packaging purposes, no off-taste or off-odor from the package must contaminate the product itself. Odor and taste from paper can arise from a number of sources such as wood resins in mechanical pulp or residual chemicals in pulp making, or the paper may have internal biological activity, which can also produce odorous substances. The most sensitive instrument available to measure the odor and taste of a substance is a human being. Members of trained panels assign numerical ratings and record their impression of tainting flavors or volatile odors experienced. The test methods available are the triangle test (the test states if differences between specimens are found, DIN 10 951), the pair test (a test describing the differences between specimens, DIN 10 954) and the Robinson test (a taste test identifying how much taint a paper has given to a taste medium; chocolate very commonly being used, DIN 10 955). Beside the trained panel, gas chromatography (GC) and mass spectrometry (MS) are used to identify the originating chemical compound. The so-called "electronic nose", an original invention from the military world, has also been utilized to detect off-odors.

7.10
Coating Machines
Martin Tietz

7.10.1
Overview

Coating machines are separate machines in which a previously produced dry base paper is unwound, coated, dried, and then reeled again (Fig. 7.24). In contrast to coating applicators placed on-line in a paper machine (Section 6.8), they are usually called "off-line coaters" or "OMC" (off-machine coaters).

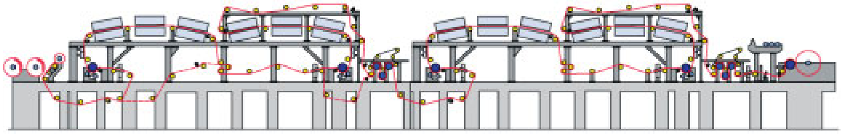


Fig. 7.24 Off-line coater (source: Voith).

In a paper mill, one off-line coater is usually associated with one paper machine. Sometimes, however, one OMC receives paper from different paper machines. In most cases, the off-line coater has the same width as the corresponding paper machine (except for the edge trim). Some coaters with half width are in operation, where the jumbo reels from the paper machine are split, and the two halves are coated separately.

Off-line coating has the advantage that the paper machine can continue production during machine stops on the off-line coater. These stops can be for instance due to coating color changes, which is especially important for machines with a very broad product range. Since off-line coaters operate faster than the paper machine to which they belong, the time efficiency of the entire line is higher than for on-line concepts.

7.10.2
Applicators

The actual coating process usually comprises two steps: (i) the application of the coating medium onto the paper or board and (ii) the metering of the coating medium to the desired quantity (or coat weight). If the metering is done directly on the paper after the application, the process is called direct coating or blade coating. If, however, metering is done before the transfer of the coating medium to the paper or board, the process is called indirect coating or film coating.

7.10.2.1 Direct Coating

In direct coating, the web is supported by a backing roll and the coating medium is fed in excess onto the web. After a certain distance, defining the "dwell time", the coat layer is metered down to the final thickness, being the desired coat weight.

In the "roll applicator" or "LDTA" (long dwell time applicator), feeding is done with a roll, which draws the coating medium from a pan onto the web (Fig. 7.25). The applicator roll and the backing roll form a nip. The nip pressure and, consequently, the nip gap are adjustable, determining the amount of coating medium fed to the web. The nip load also yields an external penetration pressure which, together with the capillary pressure, causes penetration of some coating medium or components thereof into the paper or board web. This is to a certain extent desirable, because it anchors the coating to the base paper and gives surface strength. Excessive penetration, however, would reduce the gain in surface properties, such as smoothness or gloss.

Penetration of the coating into the base paper can be controlled with the "water retention" of the coating medium. At elevated machine speeds, e. g. above approximately 1500 m min^{-1}, the splitting of the coating color between applicator roll and paper at the nip exit shows irregularities, which negatively influence the homogeneity of the coat layer. Also, the relatively short nip and the considerable penetration caused by the nip load cause runnability and quality problems. To overcome these limitations, the application of the coat medium to the paper can be performed with a free jet. In a "free jet applicator" (Fig. 7.26), the jet usually has a thickness of less than one millimeter and a length of a few centimeters. The resulting coat layer (still before final metering) is much more homogeneous than that of a roll applicator, and, since the external pressure at the impingement point is considerably less than in the roll nip, the penetration of the coating medium into the base paper is reduced. This improves the so-called "coating holdout", which results in a better surface quality of the coated paper.

The final metering of the applied coating is often performed with a blade. With this blade, most of the coating medium is removed and returns to the working tank. The coat layer remaining on the paper or board is evenly distributed. The blade pressure ensures that the surface voids of the web are filled with coating. Due to the blade geometry, the coated web has a good smoothness. The blade usually has a thickness of less than one millimeter, typically approximately 0.4 mm. The stick-out length (or unsupported length) is usually a few centimeters.

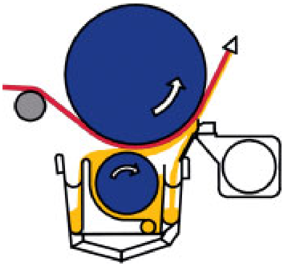


Fig. 7.25 Roll applicator (source: Voith).

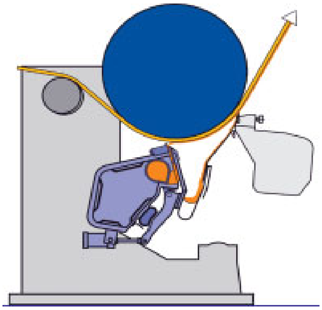


Fig. 7.26 Jet applicator (source: Voith).

The operating angle between blade and paper web is usually 20–35°. Under these conditions, the blade is considered a "stiff blade", because its bending is negligible with respect to the operating principle. If, however, a blade geometry is chosen where the bending of the blade results in an operating angle close to 0°, the mode is called "bent blade". The bent blade gives – in comparison to the stiff blade – an even smoother surface but it is more prone to surface defects, such as blade scratches, and is more difficult to operate. Since the web has a considerably reduced roughness after coating, the coat layer itself must be nonuniform in caliper to even out the base paper roughness. On certain grades, especially board, this nonuniform layer thickness can be seen as inhomogeneous coverage or mottling. If coverage is desired rather than smoothness, metering can be done with a rod rather than with a blade. Rod metering is typical for the pre-coat of board and for specialty papers where the base web has to be evenly covered with a specialty coat.

In most cases, the metering blade (or rod) is placed against the same backing roll as the coat applicator. The angle between point of application and point of metering is then approximately 60°. This results in a dwell length of 400–600 mm, depending on the backing roll diameter. The resulting "dwell time" depends strongly on the machine speed. It is in the range of 10–200 ms.

A "short dwell time applicator" (or SDTA) was tried in order to reduce the dwell time to much shorter values. This SDTA consists of a closed chamber which incorporates the coating feed and the metering blade. However, vortices in the chamber caused a streaky appearance of the coat layer at elevated machine speeds. Therefore, the SDTA has not received much attention outside North America.

7.10.2.2 **Indirect Coating**

As an alternative to direct coating, a film press can be used for the application of coating media. The film press was derived from the size press, which is used for the application of starch or size solutions. Today, a wide variety of coating media are applied, including pigment dispersions with high solids content. In a film press, a film of the coating medium is formed and metered on a large diameter roll. This roll forms a nip with another roll. The paper or board web passes this nip and picks up a certain portion of the film. Application can be – but does not have to be – simultaneous on both sides. A schematic drawing of a film press is shown in Section 6.7.

Metering is performed using metering rods. These can be either smooth or profiled. Profiled rods provide a certain volume of coating medium due to the open cross section in the profile. A deeper or coarser profile gives a higher coat weight than a fine profile. The application weight is mainly adjusted by choosing an adequate profile. Fine tuning of the application weight can be done by modifying the rod pressure. Profiled metering rods are mainly used for low viscosities (i.e. low solids contents of the coating medium) and low machine speeds. With increasing viscosity and speed, the rod loses contact with the roll due to the hydrodynamic forces of the coating medium, comparable to aquaplaning. Then, the application weight depends less on the profile and more and more on the hydrodynamic conditions, such as rod pressure, rod diameter, viscosity and speed. Consequently, a smooth metering rod is used. Typical rod diameters are 14–38 mm for smooth rods. Larger diameters yield higher application weights. Higher viscosities and machine speeds require smaller rod diameters for the same application weight than lower ones. The coating medium is not transferred completely to the web. A certain amount remains on the roll and returns to the application unit where it is mixed with fresh coating medium. The transfer ratio depends on the acceptance behavior of the web, on the properties of the coating medium and – to a limited degree – on the surface properties of the roll. For starch, where the absorptivity of the web is high, the transfer ratio can be more than 90 %. For pigment coats, it can be as low as 50 %.

The pre-metered films usually have thicknesses of 7–20 μm (or ml m^{-2}). Lower values would require very high rod pressures and also coverage of the web would be insufficient. Higher values are not meaningful since the web has a limitation with respect to coating acceptance. If the amount of pre-metered coating medium is too high, the surface of the coated web appears uneven, with an "orange peel" character. At elevated machine speeds, the film split at the nip exit can create a fine mist of coating medium. This mist deposits on machine parts or even on the paper or board web. Since this misting increases with film thickness, it is the major limitation for the application weight at high speed. For typical applications, misting becomes a limitation above 1500 m min^{-1}. At 1800 m min^{-1}, for example, coat weights above 7 g m^{-2} are difficult to achieve without disturbing misting.

7.10.2.3 **Curtain Coating**

Besides film and blade coating, curtain coating is used for the application of coating media onto paper surfaces. Although curtain coating is a very old application technique, going back to the end of the 19th century, it has only been used for coating of paper since the 1990s. Curtain coating is mainly used for specialty papers. Specialty coats are usually very expensive. Therefore, the application amount must be kept to an absolute minimum. On the other hand, a certain amount is required to achieve the desired function of the coat. In a curtain coater,

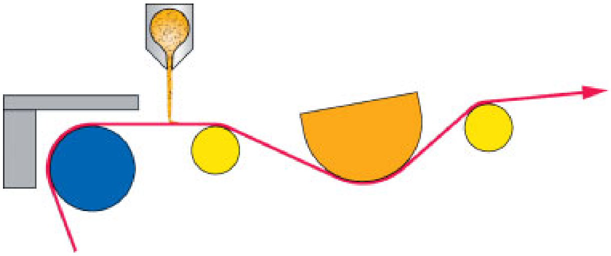


Fig. 7.27 Principle of curtain coating (source: Voith).

a thin film of coating medium is formed which falls by gravity onto the paper surface. The only metering device for the coating color is the nozzle slice. The slot opening is about 20 to 50 times larger than the actual coating color thickness. Thickness is reduced by gravity forces while the jet is moving towards the web and by the shear forces exerted by the high speed difference between the jet and the running web (Fig. 7.27). Due to the homogeneity of the film, the coverage of the paper by the coating medium is very uniform.

Unlike film and blade coaters, the application is contact-free. This considerably reduces the risk of web breaks and, therefore, improves runnability. It is expected that the significance of curtain coating will increase.

7.10.3
Application Concepts

Typical coat weights for graphic papers are given in Fig. 7.28, plotted against the basis weight of the base paper. The coat weight is typically 25–40% of the final basis weight of the paper.

Wood-containing papers are mainly single-coated (LWC). Coat weights are usually between 6 and 10 g m^{-2} per side. Traditionally, the coat is applied with a blade coater. More modern installations use a film press for the single coat.

At higher basis weights (MWC), two coat layers may be applied per paper side. Here, the top coat is usually a blade coat. The pre-coat may be either a film or a blade coat.

Woodfree papers cover a very wide basis weight range. Depending on the basis weight, the application can be single coat, double coat or triple coat. The coat weight per layer can vary in a wide range between approximately 8 and 20 g m^{-2}.

For board grades, the coat weight depends on the requirements of the final product and on the quality of the base board. Coverage, brightness and smoothness are the main properties that are improved by the coating. Depending on the required coat weight, two or three coat layers are applied.

Due to their functions, different formulations are used for the individual coat layers. For instance, pigments with high opacity are used in the first layers, whereas very fine pigments with good smoothness potential are used for the top coat.

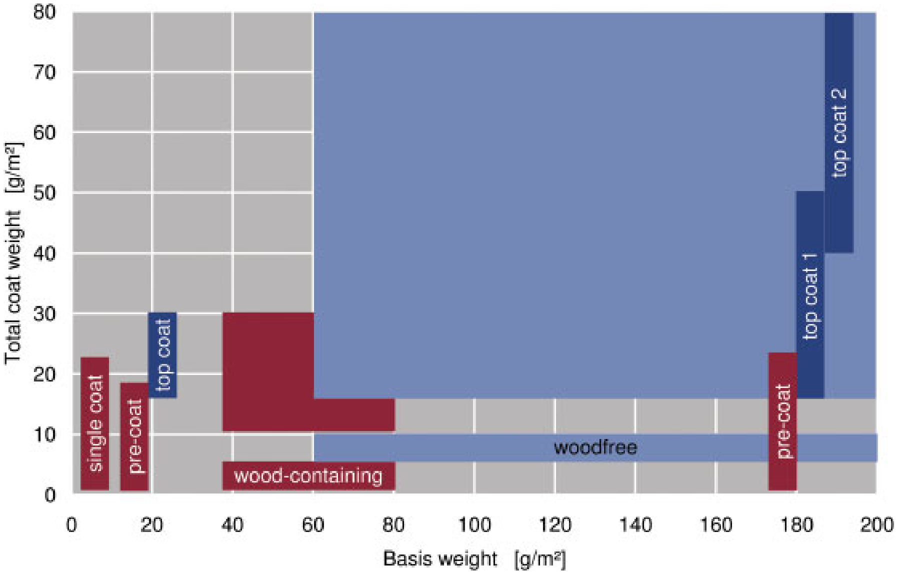


Fig. 7.28 Typical coat weights for graphic papers. Basis weight includes base paper + coat weight (source: Voith).

7.10.4
Drying

After its application, the wet coat must be dried. Three different drying principles are used: radiation (infrared), convection (hot air), and contact (cylinders).

Infrared drying yields a very good energy transport, whereas mass transfer is inferior. Therefore, infrared is especially suitable for heating the paper or board web to temperatures where considerable drying occurs. Heating of the infrared radiators can be by electricity or gas. Gas-heated infrared dryers reach higher temperatures and are usually cheaper. Electrical infrared dryers are easier to control and are, therefore, often used for moisture profiling in the cross machine direction. It depends very much on the local conditions at the mill site, such as availability and prices, which heating principle is used for infrared drying.

Air flotation dryers are widely used for the drying of coat. In an air-flotation dryer, hot air is blown onto the paper surface. Air temperature can be as high as 350 °C, sometimes even higher. The impingement velocities of the air can exceed 40 m s^{-1}. The impingement effect gives a very effective heat and mass transfer between air and paper surface. The blowing nozzle sections in the dryer are alternately placed on one side of the paper and on the other side. This gives a sinusoidal web run through the dryer with a web-stabilizing and wrinkle-avoiding effect.

Cylinder drying of coat is possible, as soon as the freshly coated surface is dry enough that the coating color does not stick on the cylinder surface. Therefore, drying cylinders are only found after a certain amount of contact-free drying, i. e.

towards the end of the dryer section after a coater station. In modern coating machines, cylinder drying contributes only a small amount to the total drying capacity, sometimes less than 20%. Contact drying has usually the lowest specific costs. Furthermore, the cylinder group is an excellent fix point for the web run. When no cylinders are used, a separate fix point between the coater stations has to be included, such as an S-wrap or a pull stack.

In some machines, the last cylinders are used to cool down the web rather than for drying. After drying, the web can reach temperatures well above 70 °C and does not cool sufficiently before the next coater station. Too high a web temperature causes excessive penetration of the coating color into the web so cooling provides a higher product quality.

7.11

Coated Paper and Board Grades (for more details see Chapter 11) **[4, 7]**

Werner Auhorn

Table 7.14 gives an overview of coated paper and board grades as related to the main components of base paper, basis weight, coat weight, brightness, and their main usage.

Figure 7.29 illustrates the relative positions of coated, mechanical pulp dominating papers in basis weight and brightness. Figures 7.30 and 7.31 present typical end uses for coated mechanical papers and for coated fine papers worldwide.

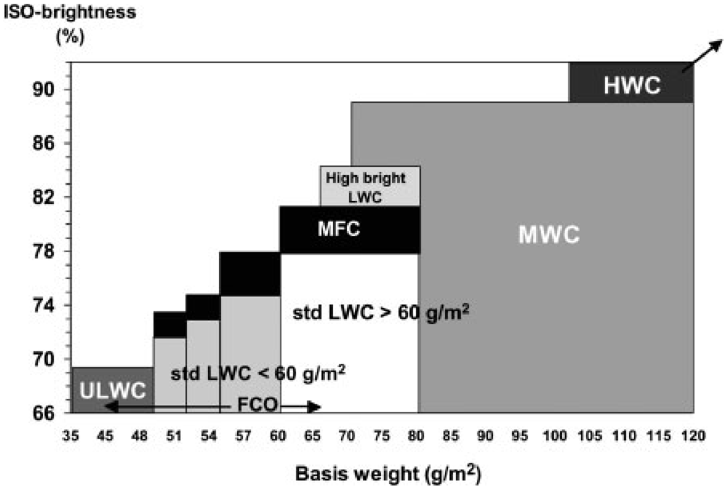


Fig. 7.29 Classes of wood-containing coated printing papers and their positioning according to basis weight (base paper + coating layers) and brightness (source: H. Paulapuro, Dep. of Forest Products Technology, Helsinki Univerity of Technology).

Table 7.14 Overview of coated paper and board grades and their most import characteristics.

Paper/board grades	Base Paper main fiber furnish	Basis weight base paper ($g\ m^{-2}$)	Coat weight per side ($g\ m^{-2}$)	No. of Coating Layers	ISO brightness (%)	Main usages of paper/board grades
Printing Papers (both sides coated):						
ULWC (ultra light weight coated)	MP, CP, DIP	25–35	5–7	single	69–72	catalogs, magazines
LWC (light weight coated)	MP, CP, DIP	35–45	6–12	single	72–78 (84)	magazines, inserts
MFC (machine finished coated)	MP, CP, DIP	35–60	5–15	single, double	72–78	magazines, catalogs
FCO (film coated offset)	MP, DIP	30–45	4–10	single	72–78	inserts, flyers, advertising
MWC (medium weight coated)	MP, CP, CP	45–65	12–25	double	80–88	special magazines, advertising
HWC (high weight coated)	MP, CP, CP	65–100	25–35	double, triple	82–90	magazine covers, advertising
WFC (woodfree coated fine papers)	CP	60–120	25–35	single, double, triple	88–98	magazines, image brochures, labels
Art Paper	CP	60–150	20–40	double, triple	94–98	illustrated books, calendars, image br.
Board Grades (mainly top side only coated):						
FBB (folding box board)	DIP, RP, MP, CP	135–425	12–35	single, double, triple	72–86	packaging of food, book covers
WLC (white lined chipboard)	DIP, RP, MP, CP	170–425	10–30	single, double	76–92	shoe and wine boxes, protection packaging
SBS (solid bleached sulfate)	BHSP, BSSP	120–250	15–25	double	84–98	packaging of chocolate, cigarettes, cosmetics
LPB (liquid packaging board)	BSSP, UBSSP	280–330	10–15	single	76–86	milk and juice packaging

Abbreviations: MP = mechanical pulp; DIP = deinked pulp; CP = chemical pulp; RP = recovered paper; BHSP = bleached hardwood sulfate pulp; BSSP = bleached softwood sulfate pulp; UBSSP = unbleached softwood sulfate pulp

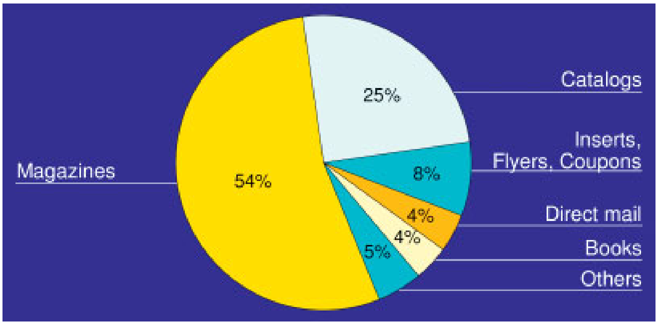


Fig. 7.30 Worldwide usage of all coated mechanical paper grades for printing.

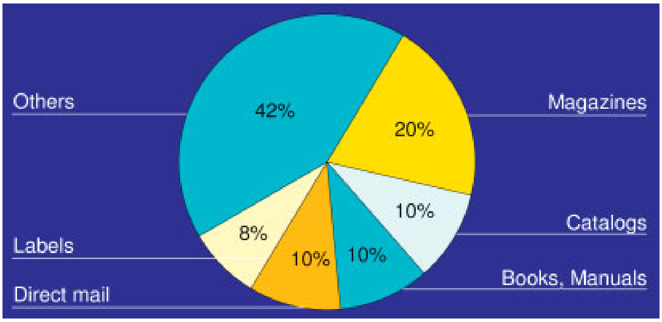


Fig. 7.31 Worldwide usage of coated fine paper grades for printing.

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8
Finishing

Herbert Holik

In a paper mill the process steps after the paper machine, i. e. reel slitting and roll packaging, format cutting and packaging of the formatted sheets, in a wider sense also offline calendering, and sometimes offline coating, can be summarized under the term finishing. Reel-slitting converts the large parent reels from the paper machine into suitable size rolls, to be delivered to the (external) customer after being adequately packed, or for further in-house processes such as sheet cutting. The input into the sheet cutter is pre-cut reels of up to 2.5 m. The sheet cutter cuts the web into individual sheets, i. e. cuts the web first in MD and then in CD. The individual sheets are piled automatically and packed. Reel slitting as well as roll wrapping and handling will be described in the next two sections.

8.1
Reel-Slitting

Rüdiger Feldmann

8.1.1
Objective and General Description of Reel-slitting

The objective of reel-slitting is to convert the large parent reels (machine reels, jumbo reels) from the paper machine into suitable size rolls which can be either sent directly to the end-user, e. g. a printer, or receive further mill-internal treatment such as sheeting.

The machine on which reel slitting is done is commonly called a winder. Basically, winders consist of equipment for parent roll change, an unwind station for the parent rolls, a slitting station and a rewind station.

The rolls have to be free from defects (Fig. 8.1) such as:

- soft centers
- bursts
- corrugations/rope marks
- crepe wrinkles
- dishing

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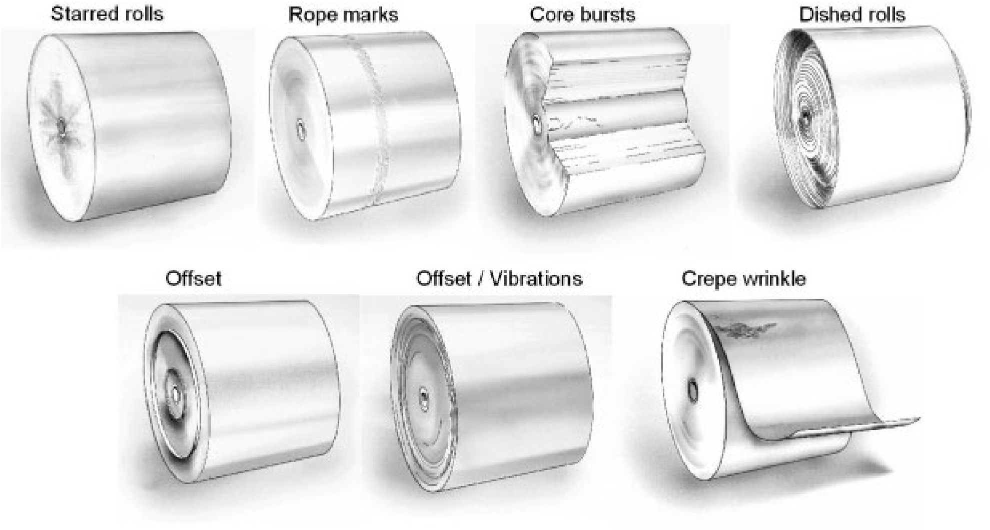

Fig. 8.1 Various roll defects (source: Voith).

- dust
- concave or convex faces.

These kinds of defects may disturb the subsequent working steps in or outside the mill and may reduce the quality e.g. in printing or the productivity. The roll quality ultimately determines the mill's reputation with its customers and so the winding process is very important.

Winders have a series of basic operations in common, e.g. unwinding, slitting, reel and set change etc. These operations will be reviewed in the following. Later, special attention will be paid to the various winder types and their suitability for obtaining optimum winding results for the main paper grades.

Though various slitting techniques are available, e.g. water jet slitting and laser slitting, most of the winders make use of the tangential shear slitting technique. With this method, the web is cut between two edge-contacting circular knives, the top slitter blade and the bottom slitter blade. In order to achieve optimum slitting results, the cut point should be located at the beginning of the wrap, i.e. the area where the web contacts the bottom band. The depth with which the blade should incise into the web depends on the paper grade and ranges between 0.5 and 2.5 mm with 1.5 mm being a normal depth. The overlap of the top blade and the bottom blade should be between 0.5 and 2.5 mm, the exact amount depending again on the grade of the paper to be slit. Furthermore it is recommended that the top blade exerts a light side load in the range of 20 to 45 N on the bottom blade. Since the bottom bands wear, counter measures have to be taken in order to avoid the cutting nip opening up, resulting in band wobble, so called slitter run out. The speed with which the bottom blade is driven is yet another decisive factor. As a

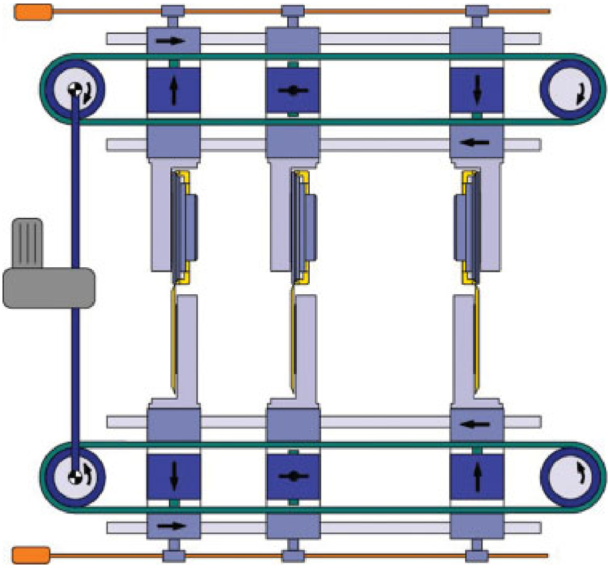

Fig. 8.2 Positioning system for slitters (source: Voith).

rule, this blade is driven at a speed that is somewhat higher (2 to 3%) than the running speed of the web.

With an improper setting of the blades, the slitter often generates dust but even under optimum conditions, slitter dust cannot always be avoided and hence suction devices are installed to remove the dust.

The pair of knives must be accurately positioned so as to obtain precisely the desired format for the sheets. Various solutions exist in this respect. Figure 8.2 shows one example: The apparatus for positioning has slides displaceable along guides and a belt with oppositely moving stretches as the belt is moved in a single direction. A coupling between the belt stretches and the slide can be actuated to press against one or the other stretch or pass of the belt to couple it with the slide. The coupling also has a cylinder-and-piston to lock the slide by clamping it against its guide when the proper position is reached. Positioning can be carried out manually, semi-automatically or in a fully automated manner.

After slitting, the partial webs have to be separated. Any overlap is unacceptable. The extent of separation is 0.2 to 0.5 mm. In order to achieve proper separation, winders are featured with a spreader device consisting, as a rule, of two spreader rolls arranged parallel to each other (Fig. 8.3).

The following provides an overview of the main technical data of current winders:

- parent rolls:

– max. width	11.000 mm
– max. diameter	4.500 mm
– max. weight	135 t

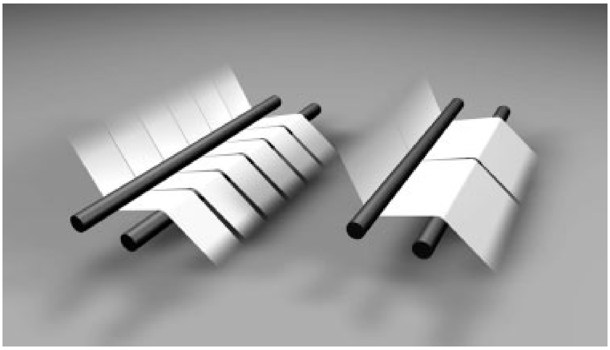

Fig. 8.3 Web separation device (source: Voith).

• finished rolls:	
– min. width	150 mm
– max. width	5.000 mm
– max. diameter	1.800 mm, paper grades 2.500 mm, board grades
– max. weight	10 t
• max. working speed	3.000 m min^{-1}
• max. availability	99%

8.1.2
The Different Winder Types and Their Suitability for the Various Paper Grades

8.1.2.1 Classical Two-drum Winders

The rewind station of a classical two-drum winder consists of a first and a second steel drum forming a winding bed wherein the set of rolls is wound side-by-side, and a rider roll. The two-drum winder uses tension, nip load and torque as winding parameters.

The first parameter "tension" is necessary to get the single web-sheets spread and to give them a basic strain at the front drum. The amount of tension needs to be in the range of the elasticity of the web. A programmable tension curve is one basic instrument to influence the roll quality.

The second parameter, "torque", is another tool for controlling the "wound-in-tension" or the density of the rolls. Increasing torque tightens the rolls. The torque is introduced by the second drum which is not wrapped by the paper. Therefore the second drum is torque controlled.

The first drum (wrapped drum) is a speed controlled drum.

The third parameter, "nip load in the winding bed", results from the weight of the roll set and the rider roll load. At the beginning of the winding process, the weight of the rolls is not sufficient to produce the required line load for introducing additional torque by the second drum. Hence it is the rider roll placed on top of

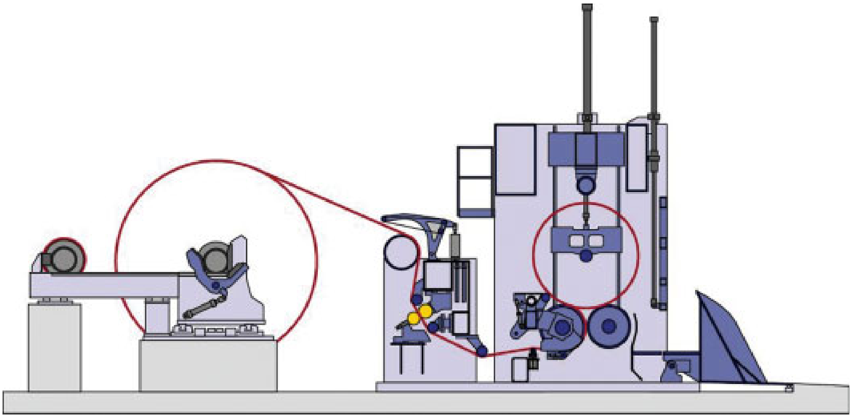

Fig. 8.4 Two-drum winder with steel drums (source: Voith).

the roll set which provides the required nip load. As the diameter of the rolls grows, the pressure exerted by the rider roll is decreased. Finally, the rider roll serves only as means of keeping the set in the winding bed, for instance in the case of vibrations (Fig. 8.4).

All of these parameters influence each other and have to be carefully adapted to the different paper grades.

Classical two-drum winders are used for winding

- cigarette paper
- corrugated medium
- decor paper
- filter paper
- kraftliner
- test liner
- uncoated board.

8.1.2.2 **Modified Two-drum Winders**

The two-drum winder is often called the "work-horse" among the winders on account of its easy set-up combined with high productivity and efficiency and its initial investment cost being lower than with the single-drum winder. The classical two-drum winder is an economic solution but its technological limitation is the uncontrollable nip loads that necessarily occur when the roll diameters get above nip-load critical limits, with the consequent risk of roll defects. To overcome this drawback and to achieve low-intensity controlled nip pressures various modifications have been developed.

Modified two-drum winders are in use for the following grades:

- coated board
- directory paper
- envelope paper

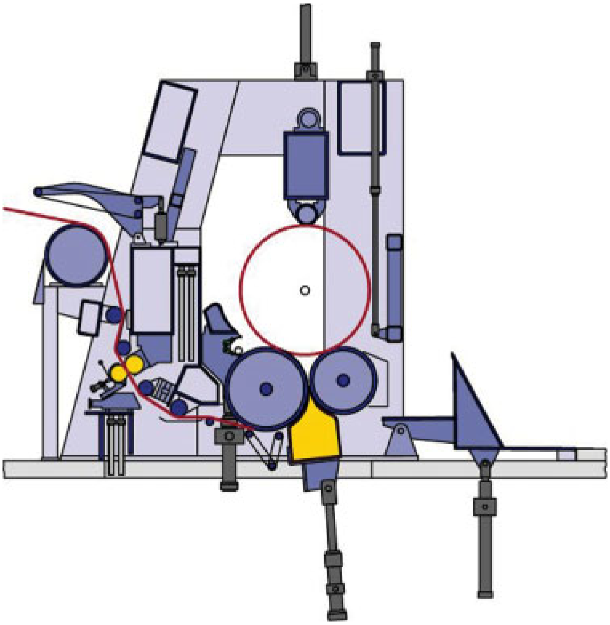

Fig. 8.5 Two-drum winder with air relief (source: Voith).

- LWC paper
- newsprint paper (standard and improved grades)
- SC offset paper
- silicone base paper
- woodfree coated and uncoated paper.

8.1.2.2.1 **Two-drum Winders with Air Relief**

The two-drum winder with air relief is equipped with a pressure box arranged underneath the winding bed and extending over its entire length. Compressed air fed through this box defines a compressed air cushion in the roller bed and counteracts the weight of the rolls. Since the supporting area increases with increasing roll diameters (the supported roll surface gets bigger with growing roll diameter), a rather low pressure (< 10 kPa) is sufficient to effectively relieve the set of rolls (Fig. 8.5).

8.1.2.2.2 **Two-drum Winders with Belt Support**

This variant of the two-drum winder family consists of a drum and a belt bed to support the roll set. As the roll diameter exceeds a certain diameter, the weight of the roll set is partially transferred to the belt bed whereby the specific pressure in the nip is reduced (Fig. 8.6).

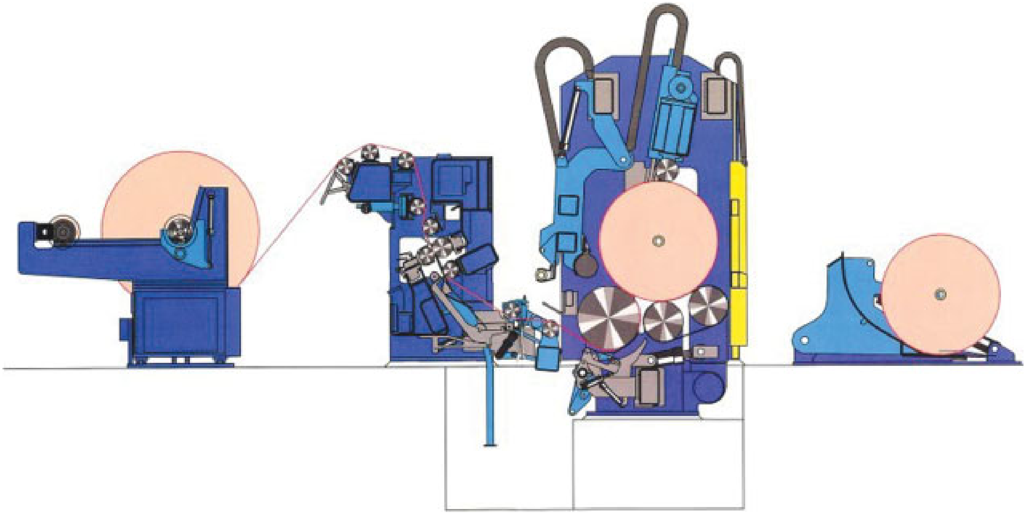

Fig. 8.6 Two-drum winder with belt support (source: Metso).

8.1.2.2.3 Two-drum Winders with Soft Covered Drums

The purpose of covering the drums with a soft material is to make the nips wider, thus reducing the radial stress between the rolls and the drums to a level where even with heavy rolls no nip load-induced defects can occur.

The deformation of the covers in the nip especially at the first, i.e. “wrapped drum”, avoids roll defects such as corrugations and rope marks and allows winding of defect-free rolls with a larger diameter (Fig. 8.7).

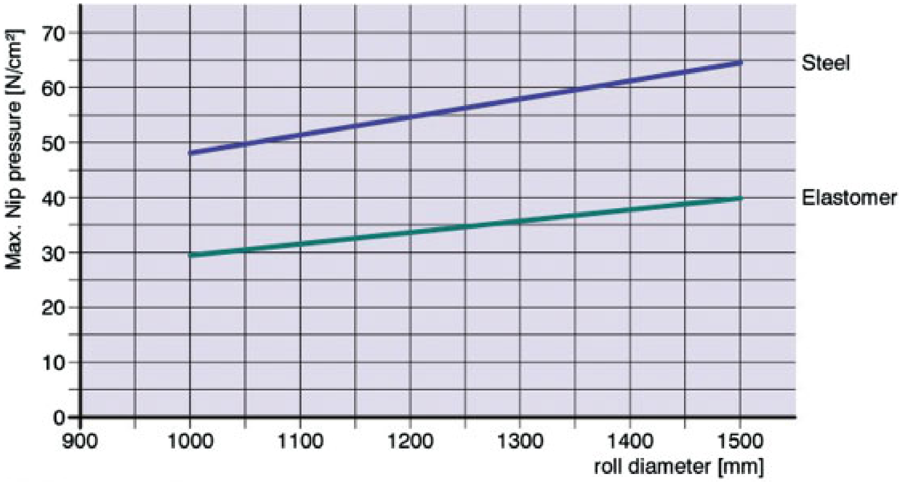

Fig. 8.7 Comparison of a two-drum winder with soft covered drums with a two-drum winder with steel drums (source: Voith).

8.1.2.3 Single-drum Winders

The characteristic of single-drum winders – also called multi-station winders – is that each paper roll is supported on a common center drum, yet is wound in a separate station. Since the rolls are held by core chucks on both sides, they have to be arranged alternately on either side of the single-drum at approximately 11 and 1 o'clock positions (Fig. 8.8). As a consequence, the weight of the rolls is partly supported by the center drum and partly by the core chucks – the proportion can be freely selected. The 11 and 1 o'clock arrangement is used for winding wide rolls (normally of width 4.320 mm) of high density paper with a need for a very tight core winding to get the roll stiff enough for the further production process, e.g. printing. A tight core winding is achieved by connecting the core chucks to an electrical motor which leads its torque via core-chucks directly to the core of the wound roll.

In special cases, 9 and 3 o'clock positions are also used (Fig. 8.9). This arrangement is used for paper grades with surfaces that are very sensitive to high nip loads. Due to the position of the rolls during the winding process the nip load can, theoretically, be reduced to zero. The necessary torque for tight core-winding is created by the center torque motor.

Modern single-drum winders are core-, periphery- and rider-roll supported winders. The main parameters influencing winding are web tension, nip load (by rider roll load or core-chuck carriage load) and torque. At the beginning of the winding process, rider rolls are placed against the cores so as to produce the required nip load or to avoid bending of wide cores due to web tension. When the diameter of the rolls has reached a certain value, the rider rolls are no longer necessary. The desired nip load is then obtained by the roll weight alone or by the relief pressure of the core-chuck carriages. Therefore, the rider rolls are disabled or pivoted downwards in order to support the wound rolls from below.

The grades to be wound on single-drum winders are:

- carbon copy paper – winder as in Fig. 8.9
- cast coated paper – winder as in Fig. 8.9
- LWC paper – winder as in Fig. 8.8
- SC rotogravure paper – winder as in Fig. 8.8

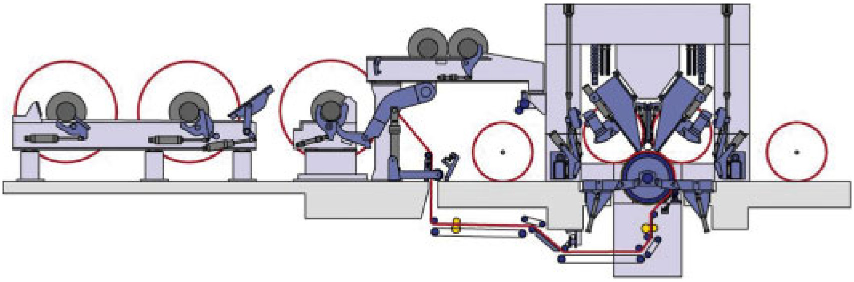

Fig. 8.8 Single-drum winder – finished rolls at 11 and 1 o'clock positions (source: Voith).

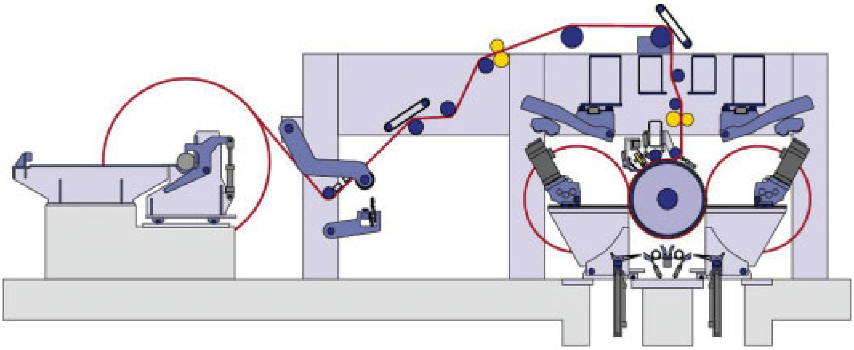

Fig. 8.9 Single-drum winder – finished rolls at 9 and 3 o'clock positions (source: Voith).

- silicone treated paper – winder as in Fig. 8.9
- thermal paper – winder as in Fig. 8.9.

8.1.3
Automatic Functions

The productivity of a winder is a function of its speed, its acceleration rate and its necessary stop times for set-change or reel-spool change. The stop times can be reduced by using automatic functions. To that end, equipment and controls have been developed which abridge the following functions:
- reel changing
- reel splicing
- web threading
- slitter positioning
- core inserting
- core gluing
- automatic set-change
- web cutting
- tail gluing
- roll ejecting
- automatic stop at wind-up and unwind-diameter.

Furthermore, diagnostic functions are available that help the operator to quickly detect the cause of problems on the winder and in the paper:
- automatic stop at detected paper faults (holes, edge-cracks etc.)
- extended help messages if winding process discontinues
- run-time messages for preventive maintenance.

8.1.4
Automation/Operation

Modern winders are equipped with PC/PLC technologies. This allows high flexibility in adjusting the winding parameters, such as tension, torque, nip load, to the special requirements of the different paper grades. Furthermore, these technologies permit collection of all data of the winding process for advanced analysis of the production process.

8.2
Roll Handling

8.2.1
Objective and General Description of Roll Handling

The objective of roll handling is to prepare the finished paper rolls for shipment in such a way that they arrive at the end user in the best possible condition. The mill can contribute to this aim by two means, i. e. by very gentle internal transportation and by thoroughly wrapping the customer rolls so as to protect them from dangers to which they are exposed during external transportation on account of frequent loading and unloading actions, varying temperatures and humidity changes.

8.2.2
Roll Wrapping

8.2.2.1 Wrapping Material

There are two different kinds of wrapping material, stretch film and packaging paper. Shrink film is hardly ever used for wrapping paper rolls, since the creases formed on the faces of the wrapped rolls do not allow one to store the rolls in a vertical position. Shrink wrap is only found in special applications, e. g. for holding finished paper rolls on pallets.

Stretch wraps offer the advantages of uncomplicated wrapping machinery and low-cost material. The drawbacks are high UV sensitivity, slackening of the stretch wrap and vulnerability to dirt. Furthermore, smooth plastic wrapped rolls are more likely to fall off the forklift trucks, particularly at low temperatures and due to stretching, even slight tears caused by forklift handling can rapidly turn into serious damage. Some of the drawbacks can be avoided by wrapping plastic covered rolls with paper as well. The simplest way to do this is with crepe-like packaging paper, using the same wrapping equipment as for stretch film.

Packaging paper is the classical and most commonly used wrapping material for paper rolls. It offers optimum protection for long transport distances and storage times. Packaging paper mainly comprises kraft or test liner sandwich papers with a PE lining.

Fig. 8.10 Conventional roll wrapping machine (source: Voith).

8.2.2.2 The Different Types of Wrapping Machines

8.2.2.2.1 Conventional Wrapping Machines using Paper as Packaging Material

These machines basically consist of a two-drum winding cradle wherein the roll to be wrapped is rotated, a crimping device, a header press and a number of unwind stations for packaging paper rolls (Fig. 8.10). The wrapping method employed is the so-called "wide" method, i.e. the width of the packaging paper is selected according to the width of the roll to be wrapped plus a crimp overhang. Depending on the width spectrum of the rolls to be wrapped, a series of unwind stations with packaging rolls having a different width is necessary.

The wrapping process is as follows: Before the packaging paper is applied, the roll is furnished with inner board header disks to protect the roll faces from possible glue and damage resulting from edge crimping. However, these inner header disks do also contribute to a face protection during later transportation. Then the packaging paper, having a width which corresponds to the width of the paper roll (see above), is wrapped one to four times around the body of the roll. The wrapping can be further strengthened by gluing the outer layers of the packaging paper together, either with cold or hot glue. Thereafter the overlap is crimped. Finally PE-coated test liner outer header disks are pressed on top of the inner header disks and the crimped overlaps. These outer header disks are normally fixed without any additional glue, just by pressing them against the inner header disks once the PE-coating has been plasticized.

Conventional wrapping machines produce excellent wrapping. The only disadvantages of these traditional machines are that they require a lot of space for the multitude of unwind stations and that the mill has to store a lot of packaging paper rolls of different widths. These disadvantages are eliminated with the wrapping machines described below.

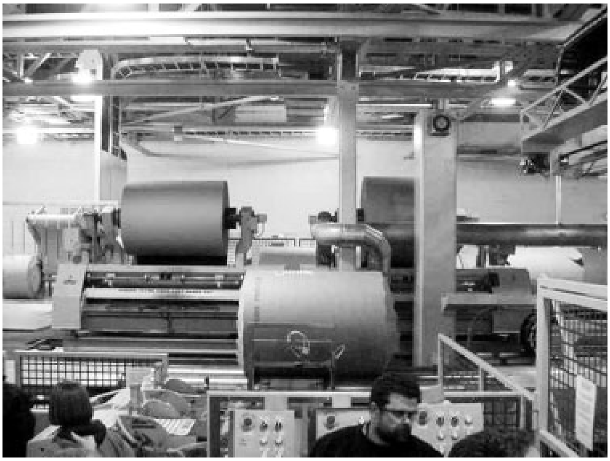

Fig. 8.11 Overlap wrapping machine (source: Metso).

8.2.2.2.2 Offset Wrapping Machines using Paper as Packaging Material

Theses machines are similar to the above described conventional machines in so far as the packaging paper is fed to the roll to be wrapped in a straightforward way. The main difference is that two or more packaging paper webs are combined into one broad sheet (Fig. 8.11). Thus, rolls whose width exceeds the width of the available packaging rolls can be wrapped effectively with a reduced number of unwind stations.

8.2.2.2.3 Spiral Wrapping Machines using Paper as Packaging Material

The spiral wrapping machines employ a narrow standard width packaging paper strip (e. g. 500 mm) for wrapping. This strip is wound at a sharp angle around the roll body. The desired number of layers is automatically obtained by correctly selecting the angle or degree of strip overlap. The roll edges are additionally wrapped at right angles with a constant overlap of approx. 150 mm (Fig. 8.12). Spiral wrapping is suitable for all paper roll sizes and provides a wrapping that is even stronger than classical wrapping, since the glued spiral layers closely encircle the roll body and since the edge strips offer additional protection for the vulnerable edges of the paper roll. Spiral wrapping is not limited to any particular roll length. A comparison of Figs. 8.13 and 8.14 shows that the space required by a spiral wrapping machine is much lower (27 m^2 vs. 70 m^2, i. e. approx 40%) than the space needed for a traditional wrapping machine.

Fig. 8.12 Spiral wrapping machine (source: Voith).

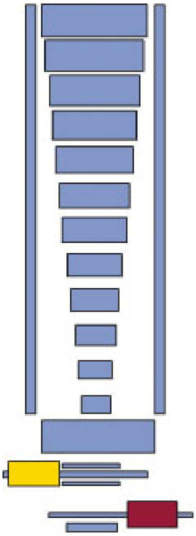

Fig. 8.13 Top view of a conventional roll wrapping machine (source: Voith).

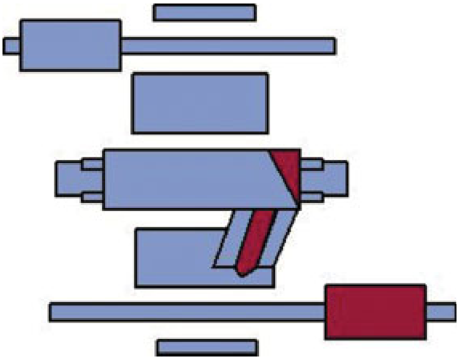

Fig. 8.14 Top view of a spiral wrapping machine (source: Voith).

8.2.2.2.4 **Wrapping Machines using Stretch Film as Packaging Material**

These machines consist of a stretch film dispenser and a two-drum cradle wherein the roll to be wrapped is rotated. The winding cradle can additionally be mounted on a turntable. Accordingly, there are two different wrapping methods: exclusively radial wrapping (Fig. 8.15) or a combination of radial and axial wrapping (Fig. 8.16).

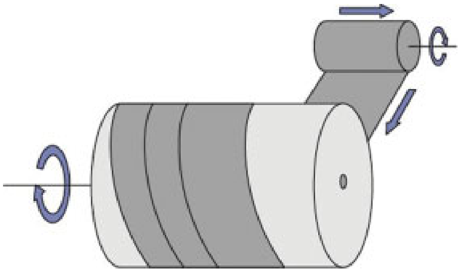

Fig. 8.15 Radial stretch wrapping (source: Voith).

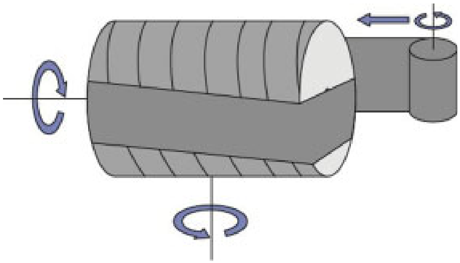

Fig. 8.16 Radial and axial stretch wrapping (source: Voith).

For radial wrapping of the rolls, the stretch film is guided into the nip between the rotating roll and the first carrying drum and is subsequently wrapped in a helical manner around the roll. If the two-drum cradle is mounted on a turntable, the roll can also be wrapped axially by rotating the turntable.

Rolls wrapped exclusively radially must be protected by header disks made of boxboard or corrugated board. These headers must be of exactly the same diameter as the paper roll, since they are only held on by about 100 mm of stretch overlap around the roll edges. Such end covers enable trouble-free vertical stacking of the wrapped rolls.

In contrast to exclusively radial wrapping, axial wrapping delivers hermetically sealed rolls, however, since the face covers are rather irregular, axially wrapped rolls are inconvenient for upright storage.

8.2.3
Roll Conveying

Roll-conveying systems move the paper rolls from the winder discharge area via the wrapping machine to the roll up-ending device in the mill's warehouse. Naturally, layouts of the roll-conveying systems differ from mill to mill but the basic components are always the same. These are:

- Segmented cushion stop lines (Fig. 8.17).
- Belt conveyors (Fig. 8.18). Belt conveyors have been somewhat superseded by slat conveyors, since they have a tendency to damage the paper roll because of micro-motions within the belt

Fig. 8.17 Segmented cushion stop lines (source: Voith).

Fig. 8.18 Belt conveyor (source: Voith).

- Slat conveyors (Fig. 8.19).
- Carousel conveyors (Fig. 8.20).
- Turntables (Fig. 8.21).
- Lifts (Fig. 8.22).
- Sorting decks (Fig. 8.23).
- Up-enders (Fig. 8.24).

Fig. 8.19 Slat conveyor (source: Voith).

Fig. 8.20 Carousel conveyor (source: Raumaster).

Fig. 8.21 Turntable (source: Voith).

Fig. 8.22 Lift (source: Voith).

Fig. 8.23 Sorting deck.

Fig. 8.24 Up-ender (source: Voith).

8.2.4
Automation

The wrapping and conveying processes including roll identification, marking, weighing and labeling as well as roll tracking are managed by automated systems based on computers and electronic devices. The majority of the functions are carried out automatically so that the operators only have to supervise the processes.

9
Control Systems for Paper Machines

Rudolf Münch

9.1
Objective and General Terms of PM Control Systems

9.1.1
Objective

A typical paper machine has a few thousands remote or automatically controlled functions like positioning systems, drives, valves and more than a thousand additional measurement devices to monitor the process and the condition of the machine. It is impossible for an operator to oversee all these devices without the help of modern automation systems. For example, he is guided through the process of starting the machine, and many control sequences happen automatically after a "start" button is pressed and he gets detailed diagnostics if something fails. Computers are also used to maintain the quality standards, however the operator is still needed to handle the exceptions and to decide how to proceed when something fails.

9.1.2
Explanation of Terms

Control systems for paper machines can be categorized in different ways. The following terms are those most commonly used :

- MCS, machine control system:
  Discrete logic, safety interlocks, sequential controls.
  The MCS ensures that the machine attendant can safely operate the machine using control desks with pushbuttons, switches, status lamps, etc. Many of these functions are usually also available on screen displays. Examples of MCS functions are movements of rolls, blades or other machine parts with involvement of limit switches or other safety interlocks.
  MCS functions usually require fast reaction by the MCS. For example: If a machine part reaches a limit switch during a controlled movement, it usually has to

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be stopped by the MCS in less than 20 ms. The cycle time of a MCS is therefore in the 5 to 20 ms range.

- DCS, distributed control system:
  - Analog process controls

  Analog process controls are mainly simple standard controllers. Examples are level controllers in chests, pressure controllers in pipes, etc. Most process controllers act much more slowly than the MCS controls. Actions happen in seconds to minutes. The cycle time of typical DCS functions is therefore in the 1 to 4 s range.

  - Wet end controls

  Some controls in the process are more complex than just PID control loops. One example is the wet end control which ensures uniform process conditions in the approach flow of the paper machine and in the forming section by maintaining constant consistencies, gas content, charge and other parameters. It involves e.g. special software tools (soft sensors) using wet end data instead of direct measurements to predict basis weight during start up of the machine, when the paper has not yet reached the reel or the quality measurements. Such, wet end controls not only reduce the start up time of the process, but also minimize the consumption of chemicals, i.e. only as much retention aid is used as is really needed to reach a required retention level in the forming section.

- QCS, quality control system:
  - Paper quality measurement

  The QCS has on-line sensors for basis weight, ash content, moisture content, gloss and other paper quality parameters. The sensors are mounted on measurement frames, which allow the sensors to move (scan) within 20 to 40 s across the paper width. These sensors measure the paper quality parameters in cross machine direction (CD) and machine direction (MD). Each scan typically gives about 1000 measurement values (databoxes), equally spaced across the web width. An array of CD measurement values is also called a CD quality profile or CD profile.

  The average measurement of each scan gives one MD quality value. A time series of MD measurement values is also called an MD quality profile or MD profile.

  MD measurement values and CD profile measurements are available only every 20 to 30 s.

  - Paper quality control in the machine direction

  The first target of quality control in MD is to keep the main quality parameters of the produced paper within the limits defined for the current production. As an example, basis weight control is achieved by continuously adjusting the stock valve, which feeds the blended stock to the machine.

  The second target is to ensure fast grade changes, i.e. to ensure a fast change of basis weight, moisture and ash content to meet the specification of the next produced grade with a short transition time.

  The third target is to allow the operator to change machine settings without too large an impact on paper quality. The most important example is the coordinated speed change control. This is a tool to allow machine speed changes without disturbing paper quality during the transition period. The effect of a speed change is compensated by coordinated adjustments of stock valve, ash valve and drying energy, based on a dynamic process model.

MD controls are slow but complex control loops. Only two to three measurements are available per minute. Using interpolation techniques or Kalman filters, control steps can be performed every 5 to 10 s. MD controls are complex because of the considerably large transport dead time between actuators (i.e. stock valve) and measurement (i.e. scanner at the reel), which is typically larger than 1 min.

Additionally the quality parameters have some influence on each other. Opening the ash valve increases not only the ash content but also the basis weight and moisture. Increasing the basis weight leads to higher moisture content at the reel, if the drying energy is not increased simultaneously. Thus, a decoupling controller with dead time compensation is required.

– Paper quality control in cross machine direction

Many paper properties can be controlled in small control zones across the machine, to ensure uniform quality in CD. Such actuators are located e.g. in the headbox to control basis weight, in the press and in the dryer section to control moisture content, and in the calender section to control caliper across the paper width.

CD controls act even more slowly than MD controls: The measurement noise on zonal measurements is much higher than the noise on MD measurements. The measurement time of one zonal measurement (databox) is around 20 ms, whereas MD measurements are averages of typically 1000 databoxes (1 scan).

The special complexity of CD controls is the coupling of adjacent control zones. Each control zone affects the quality of some neighboring control zones. The controller needs to know exactly the spatial response of actuator movements in the CD. On the other hand the exact location of the response of a CD actuator in the paper may change over time e.g. due to changing shrinkage of the paper in the drying section, or by web wander to the left or right.

– Paper quality reports

The QCS not only controls quality, but also documents the achieved quality, which is required according to ISO 9000 and other quality regulations.

The quality reports also serve internally within the paper mill as a means of supervising the efficiency of the production process, by reporting per week, per day or per shift how much paper of which quality has been produced.

- MCC, motor control center:

  – From these cabinets hundreds of motors on the machine are controlled. These are motors for pumps, movements of machine parts or others. The MCC is additionally used to control a few other consumers of electrical power, for example heating devices for oil in calenders.

  – The MCC is not responsible for the roll drives in the paper machine. The drive system is usually an independent package, which is delivered by the machine drive supplier, and which receives its setpoints from the DCS.

- Monitoring systems:
  - Bearing and vibration monitoring

    Acceleration sensors are attached to bearings and close to roll shafts, to detect bearings at risk of failing and roll roundness abnormalities before they have a negative impact on the process. Thus bearing and roll changes can be done during the next planned shutdown of the machine, and do not cause extra downtime.
  - Monitoring of periodic paper quality variations

    Typically 30 to 100 process data are measured in parallel. The measured signals include important quality data, taken from the QCS sensors. The target is to detect the occurrence and the reasons for periodic paper quality variations.
  - Web break monitoring

    Web break monitoring is a camera-based tool to find the reason for paper breaks, and as a consequence to improve efficiency of the production process.
  - Web inspection system

    Web inspection systems are also camera based. Cameras are mounted in the CD direction across the web, and check the complete production for defects like holes, dark spots, white spots.
  - Information system:

    An information system mainly fulfils three tasks:

    1. It collects on-line data of MCS, DCS, QCS and monitoring systems into a central data storage.
    2. It provides a user interface to view the historical data of these systems, allowing one to compare and correlate the data from the various origins. The most convenient user interface is based on web browser technology, similar to the Internet. Some of the data are presented to the user as time trends, others as statistical reports over a defined production period.
    3. It provides tools for data analysis. This usually includes the capability of showing the fourier transform or the cross correlation of selected data. More sophisticated information systems contain expert systems or data mining tools, to automatically detect relationships between data.
- Automation system:

  All the systems above together form the complete automation system of a paper machine (Fig. 9.1). The automation systems are grouped around a fiber optical data network, which has a ring topology for redundancy reasons. The connected systems are operating stations, engineering stations for configuration or maintenance work, DCS cabinets, server computers and dedicated control computers for various monitoring and control purposes. The dashed lines indicate the different locations with automation equipment, such as control rooms for operators, electrical control rooms (rack rooms) with DCS or QCS computers, or the paper machine.

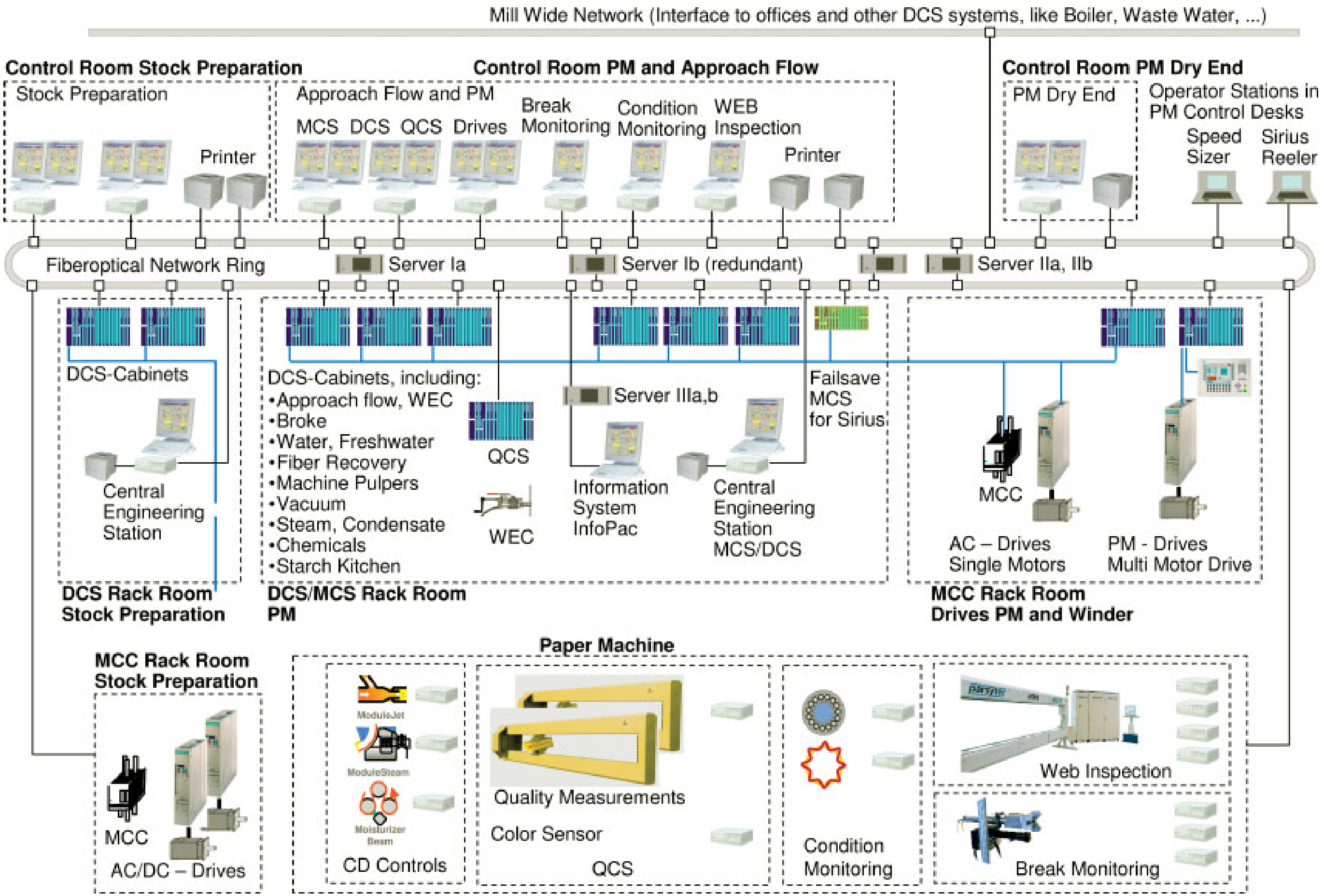


Fig. 9.1 Example of an automation system – overview (source: Voith).

To summarize, nowadays systems can be divided into the following categories

- DCS/MCS
  - Control systems for analog and digital controls
  - Capable of implementation of advanced model based controls which are needed for e.g. soft sensor or QCS applications
- QCS
  - Quality measurements for paper properties (direct measurements)
  - Measurements for felt and wire condition
  - Indirect measurements of paper properties, also called soft sensors
  - Quality controls (sometimes integrated into DCS systems)
- Monitoring systems
  - Bearing and vibration monitoring
  - Monitoring of periodic paper quality variations
  - Web break monitoring
- Information system
  - Process history database
  - User interface
  - Diagnostic tools
- Automation system
  - Includes all of the above systems

In the following chapters some elements of a paper machine automation system are discussed in more detail. The focus is on QCS and information systems, as they are mainly responsible for the ability of the mill to maximize quality tons on the reel.

9.2
Quality Control System (QCS)

9.2.1
Quality Measurements

9.2.1.1 Scanning Measurement

Most paper quality measurements in the paper machine are scanning measurements. In various locations so called "scanners" with usually one upper and one lower measurement head are found (Fig. 9.2). Both measurement heads move synchronously across the paper width. One scan takes about 20 to 30 s. The paper moves much faster than the scanning measurement. While the paper is moving e.g. 500 m the scanner moves across the web only 7 to 10 m. Thus, the scanning sensors can be seen as a system which measures paper quality in MD and which is moved slowly across the web.

During each scan hundreds of measurement values are collected. The resolution in CD is typically 10 mm. Each scan contains information of MD and CD variation of the measured paper quality. MD and CD information are used for different purposes and have to be separated from each other.

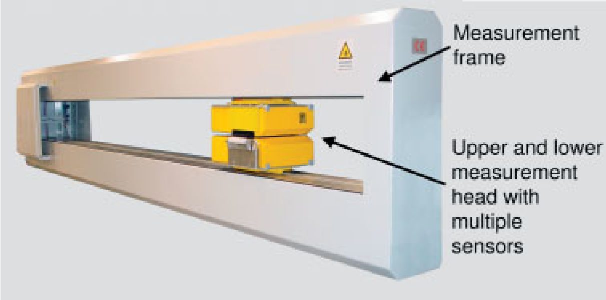


Fig. 9.2 Quality measurement – scanner (source: Voith).

- The stable CD profile is given by a weighted average of multiple scans. Typically the displayed CD profiles on an operator screen correspond to an average of 9 scans. Averaging is needed to suppress the MD variation and the residual variation of the process. Thus a CD profile contains the average of the last 3 to 5 min.
- The MD profile is the time series of average values of the individual scans. Advanced methods use e.g. Kalman filters to generate a best estimate of the current MD value every 5 s, by assuming, that the CD profile has less dynamics than the MD profile.

9.2.1.2 **Fixed Point Measurement**

Besides scanning measurements there are also a few fixed point measurements for paper properties which are assumed to be constant across the web width. For example color measurements are sometimes fixed point measurements as color should not vary across the web width.

9.2.1.3 **Basis Weight**

Basis weight is measured in g m^{-2} and it is the total mass of 1 m^2 of paper, including all components, like fibers, fillers and water. The sensors consist of a radioactive source and a radiation detector on the opposite side of the paper. The absorption of radioactive radiation is a measure of the total mass of the paper. Radioactive sources are usually promethium, krypton or strontium. Promethium provides the signal with the highest sensitivity and can be used for basis weights up to 250 g m^{-2}. Strontium is used only in very heavy board applications.

Nowadays detectors are either ion chambers or solid state detectors. Ion chambers are gas filled tubes and require a high voltage to detect electrons. Solid state detectors use the photovoltaic effect to detect electrons.

There are also other possible ways to measure basis weight, such as X-ray tubes to generate radiation, or spectroscopic methods, but currently they cannot compete with the sensors based on radioactive radiation.

The accuracy of a basis weight measurement is typically $0.1\ \mathrm{g\,m^{-2}}$. To get a better understanding what this figure really means, it is good to know that the surface of the detector is smaller than $10\ \mathrm{cm}^2$. Thus, if a sample is fixed between the sensor heads with a size of $10\ \mathrm{cm}^2$, the weight of this sample is measured with a precision of 0.0001 g.

9.2.1.4 **Moisture**

Moisture is measured in per cent of basis weight. The measurement is usually performed by analysing absorption of infrared light at three to four different wavelengths. Two of the wavelengths match the absorption peaks of water and fiber. The other wavelengths are taken for reference purposes. Modern moisture measurements have internally four detectors to make sure that all wavelengths are measured simultaneously, whereas older measurements used only one detector and a spinning filter wheel.

For high weights above $300\ \mathrm{g\,m^{-2}}$ infrared radiation can no longer pass the sheet. Therefore in this case microwave radiation is used instead. The measured physical effect is that moisture slows down the speed of microwaves, which can be detected by e. g. evaluating the phase shift of the signal.

The best achievable accuracy of moisture sensors in a PM today is 0.25 % relative moisture content.

9.2.1.5 **Fillers**

Fillers or “ash” mean the amount of inorganic material within the paper. The measurement output is either $\mathrm{g\,m^{-2}}$ or % of basis weight. Typical inorganic components are:

- clay
- calcium carbonate ($CaCO_3$)
- titanium dioxide (TiO_2)

Filler content is measured by absorption of radioactive radiation or by absorption of X-ray radiation. Thus the principle of filler measurement is similar to basis weight.

Radioactive radiation is monochromatic and stable. The radiation has one exactly defined wavelength. Clay, $CaCO_3$ and TiO_2 have different absorption coefficients for radiation of the given wavelength. Thus,

- for measurement with radioactive radiation, the percentage of each filler component has to be known beforehand. With deinked pulp (DIP) an additional measurement of the ratio of the different components is required. This can be carried out by using XRF (X-ray fluorescence)
- for X-ray radiation the spectrum of the radiation source has to be tuned by filters to compensate for the different absorption characteristics of the different fillers.

The accuracy of ash measurement today is typically 0.1 g m^{-2}, similar to basis weight.

9.2.1.6 **Caliper**

Caliper is measured in micrometers. There are three main ways to measure caliper:

1. Contacting caliper measurement: Two measurement fingers contact the paper from both sides. The distance between the fingers is measured using electromagnetic fields. This method is used when accuracy demands are high. For high speed paper machines the contacting measurement has many disadvantages:

- At the contacting point the paper becomes polished. A small glossy stripe may be visible on the paper surface.
- If the stock is not of best quality and if for example a small hard or sticky piece happens to be at the paper surface, the contacting sensor will tear it out. This may result in a hole in the paper or even in a web break.
- The fingers are subject to wear as minerals in the paper grind the measurement fingers when passing by at high speed.

The accuracy of this method depends on the application and is between 1 and 0.5 microns. The relative accuracy, which is needed to measure the shape of a cross profile, can be better than 0.25 microns.

2. Air bearing caliper measurement: The sensors are mounted onto flat measurement plates with a diameter of roughly 60 mm. Those plates are drilled, with pressurized air coming out of the tiny holes. The plates are pressed towards the paper from both sides. The distance of the plates from the paper is controlled by the air flow. The distance between the plates is measured using an electromagnetic field.

The thickness of the paper is calculated by subtracting the thickness of the air bearings from the distance of the sensor plates. As the thickness of the air bearings is not known precisely, this method is mainly used as a relative measurement to detect MD and CD profile variations of very sensitive papers, where a contacting measurement is not applicable. But also the relative accuracy is much less than the accuracy of the contacting sensor.

3. Optical caliper measurement: Due to the deficiencies of the air bearing sensor and the need for a precise noncontacting caliper measurement, most sensor manufacturers currently push the development of optical noncontacting measurement methods. They consist of three sensors:

- An electromagnetic distance measurement which measures the distance between the two sensor plates on opposite sides of the paper.
- Two optical distance measurements which measure the distance between each sensor plate and the paper.

The difficulty here is, that the paper surface is optically not well defined. The outer layer of the paper is less dense or may even be transparent. Thus optical measurements "see" the paper surface as being about 5 microns beneath the real physical surface. Therefore, the accuracy of the existing optical measurements is for most applications still not sufficient.

9.2.1.7 **Coat Weight**

Coat weight measurement usually requires two measurements, one before and one after the coater, which are subtracted from each other. These measurements can be basis weight measurements or ash measurements. Coat weight is measured in g m^{-2}.

Nowadays in some cases single sided infrared coat weight measurements are used, as both sides of the paper are coated simultaneously, and the paper maker wants to know the amount of coat on each side. Such infrared coat weight measurements are hard to calibrate, as the infrared beam penetrates through the coating color into the paper, and the paper also contains minerals and pigments. Thus the accuracy of this kind of coat weight measurement varies a lot, depending on the application.

9.2.1.8 **Color**

Color measurement is a collection of optical measurements. The basic measurement is color itself and is presented to the user in a color coordinate system. A common color coordinate system is for example CIELAB, where the parameters a^* and b^* define the color space and L^* defines the brightness.

Paper color is usually defined as the reflection of the surface of a pile of paper in defined light conditions, where all paper sheets in the pile have the same color. Thus the following difficulties arise in an on-line measurement:

- In a paper machine there is a running web, i.e. one single layer of paper. The background of the paper is visible. Thus, the on-line measurement has to compensate for the opacity of the paper. This is performed by two measurements in sequence, one with a white background, one with a black background.
- Fluorescence transforms UV light into visible light. Thus the fluorescence effect changes the appearance of the paper e.g. in daylight. Fluorescence has to be measured separately when optical brighteners are added to the paper.

This explains why brightness and opacity measurements are usually part of a color measurement.

9.2.1.9 **Gloss**

Gloss is a measure of the reflectance of the paper at a given angle. The measurement is calibrated:

- The appearance of black velvet corresponds to the measurement value, i.e. a gloss value of zero.
- The appearance of black glass corresponds to the gloss measurement value of 100%.

9.2.1.10 Others

Other available sensors include the measurement of formation, roughness, and porosity.

Further sensors are still in the process of development and cannot be treated as standard sensors. These include sensors for fiber orientation, strength properties, etc.

However, there still remain many important paper properties which are not yet measurable on-line, and where on-line measurements will probably not be available in the near future. Most important to note in this category is printability. A printability sensor, e. g., would be able to predict "missing dots" in a real printing test.

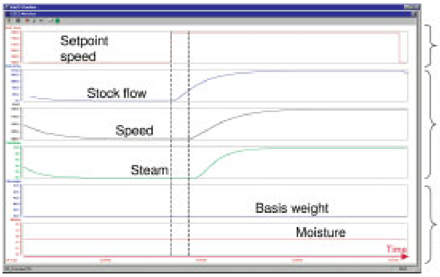
Some of those properties will be measurable using so called "soft sensors". For example a soft sensor for porosity would "measure" porosity based on a calibration of about 100 process data against corresponding laboratory measurements of porosity.

9.2.2
Quality Control

9.2.2.1 Machine Direction Control

Machine direction control uses MD measurement values to control the downstream quality of the paper. Advanced MD controls are based on physical process models of the papermaking process. This means, mathematical models describe the physical process and are able to predict the effect of control actions on the process and on paper quality. Such model-based controls are especially essential to achieve

- Start up control: to control the paper quality as fast as possible during start up of the machine. This is a topic for machines which restart quite often during the day, as for example off-machine coaters.
- Coordinated speed change control: to keep quality constant even during speed changes. This requires a coordinated change of at least stock, ash, drying capacity and speed. For example: If the stock valve is turned it takes a while until the consistency change arrives at the headbox. This is due to the transport delay time between the stock valve and the headbox, and also to the mixing time in the chests. The increase in machine speed should start when the consistency at the headbox changes (Fig. 9.3). Control of ash content and the settings of the dryer section have to be done in a similar way.
- Production maximization control: to increase the machine speed when the process is not at the limit, for instance when drying capacity is still left, and machine speed is below a user defined maximum speed. In fact this involves a series of coordinated speed changes.
- Grade change control: to keep the time for a grade change as short as possible.



User input of new speed setpoint

Coordinated change of stock flow, speed and steam

Paper quality: basis weight and moisture remain constant

Fig. 9.3 Coordinated machine speed change control (source: Voith).

9.2.2.1.1 Basis Weight MD Control

Basis weight controllers adjust the stock valve, and adjust the amount of blended stock to achieve a constant basis weight at the reel. Basis weight is the total weight per square meter. Thus it includes not only fibers but also water and fillers. To avoid too much coupling with other controls means mostly “basis weight oven dry”, which consists only of fiber and fillers, is controlled. Advanced basis weight controls are in fact “dry fiber weight controls”, which leave fillers and moisture to other control loops which run almost independently.

9.2.2.1.2 Moisture MD Control

Moisture controllers usually adjust a heating device, such as

- steam pressure in drying cylinders
- infrared radiation devices
- valves to control the air flow in contactless air impingement drying hoods.

In some cases moisture at the reel is controlled by adjusting rewetting devices having a series of spray nozzles across the web.

9.2.2.1.3 Filler MD Control

The filler control adjusts an ash valve, to meter i.e. to add fillers within the approach flow of the paper machine. Filler control is needed because of filler variations in the blended stock, especially if DIP is used.

9.2.2.1.4 Wet End Control

Wet end control is not a classical MD control but it belongs nowadays to the category of MD quality controls as it stabilizes the process in the MD direction.

In the past quality was mainly assured by quality tests after the manufacturing process. i.e. quality controls looked only at the outcoming paper at the end of the machine.

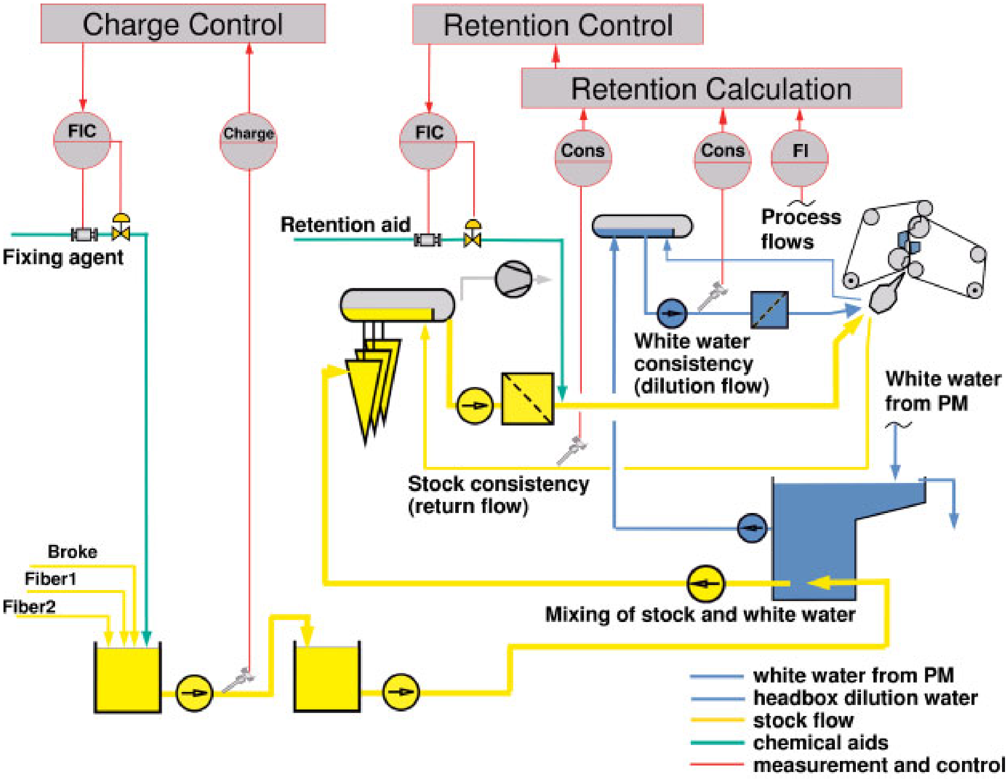


Fig. 9.4 Retention and charge control (source: Voith).

Nowadays the process itself is the target of improvement, assuming that a good and stable process ensures good quality production by itself. So intermediate controllers ensure process stability and the traditional quality controllers achieve their target more easily.

Wet end control comprises the following parts:

- Retention control: In reality this is a white water consistency control. The amount of retention aid is controlled to ensure that the white water consistency stays constant. This means that the percentage of fibers, fines and fillers remaining on the wire after the filtration process in the former stays constant. Retention control is linked to filler control, as adding fillers means that more retention aid is needed to keep retention in the forming process constant.
- Charge control: Fixatives are added to the stock to keep the charge constant. This is important because charged particles influence the effectiveness of retention aids. Therefore retention control and charge control are frequently used simultaneously (Fig. 9.4).
- Gas control: Defoamers are added to keep the air content in the stock constant at a low level. Using gas control reduces the amount of defoamer needed. Air in

the stock has many side effects, e. g. it alters the calibration of consistency meters.

- Consistency sensor calibration: Measurement of fiber or filler consistency is one of the most demanding process measurements. Accuracy has to be very high for control purpose but consistency meters are sensitive to a lot of process parameters like gas content, flow rates, etc. Therefore wet end control comprises a means to improve the calibration of consistency meters, by taking other process parameters into account. Thus the advanced consistency sensor calibration uses a soft sensor calibration technique.
- Basis weight prediction: When a paper machine starts up, it takes a while until the paper is fed through the machine and finally passes the scanning measurement device. After starting the scanner it takes another 20 to 30 s to get the first measurements. To shorten the time until on-grade production is reached, basic controls like basis weight have to start earlier. Therefore basis weight is predicted based on wet end measurements. MD control can adjust basis weight even before the scanner starts measuring. This prediction is again realized using soft sensor technology.

9.2.2.2 **Cross Direction Control**

Cross directional control uses measured CD profiles to adjust actuators which are spaced across the machine width. The goal of CD controls is to ensure even quality in the CD. The challenges of CD control are:

- The effect of an actuator adjustment can also be seen in adjacent zones. From a control point of view the zones are coupled with their neighboring zones. A spatial decoupling controller is required for good CD control.
- Sometimes more than one actuator controls the same quality profile. For example both a steam box and a moisturizer control the CD moisture profile at the reel. The two actuators have to be coordinated in their actions.
- Sometimes one actuator has an effect on more than one paper quality. For example a headbox actuator has effect on the basis weight profile and, as a side effect, also on the moisture profile.

9.2.2.2.1 **CD Basis Weight Control**

Actuators at the headbox are used to control the CD basis weight profile. Two principles are widely used:

- Slice lip actuators: Linear displacement actuators with a spacing of between 75 mm and 150 mm deflect the slice lip of the headbox nozzle.
- Dilution actuators: Motorized valves feed dilution water into the stock distributor, which is located upstream of the headbox nozzle. Typical spacing between actuators is 35 to 100 mm.

The advantage of dilution actuators is, that the headbox nozzle is not changed mechanically. Local changes in the headbox nozzle result in a nonuniform jet velocity and jet direction. This leads to CD components in the jet flow, which widens up the response of an actuator movement and reduces the capability to control narrow streaks.

The uneven jet velocity also has negative side effects on other paper properties like the fiber orientation profile.

9.2.2.2.2 **CD Moisture Control**

For CD moisture control different actuators can be used:

- Steam box actuators: A steambox in the press section is used to increase the temperature of the web and hence decrease the viscosity of the water in the web. Thus zonal heating results in a zonal effect of improved press dewatering.
  The dryness of the sheet entering the drying section should be as uniform as possible or the profile should have a certain shape. Deviations in CD dryness profiles before the dryer section result e. g. in uneven shrinkage, curl, overdried edges, edge cracks, paper web breaks or poor moisture profile at the reel.
  To ensure uniform dryness after the press, moisture profile measurement after the press is required to control the steam box CD actuator settings. For good CD profile control capability steamboxes can have an actuator spacing down to 75 mm and quite small overlapping responses of neighboring actuators in the paper.
  However, as steam boxes are often used to increase production, the mean value of all CD actuators should be as high as possible. The remaining potential to change the actuators is sometimes no longer sufficient for good high resolution CD control performance. In these cases the steam box may control only long wave profile deviations, whereas the correction of short wave deviations is left to the moisturizers. Thus, for steamboxes an actuator spacing of 150 mm or larger is in many cases completely sufficient, especially if moisturizers are also available in the machine.
- Moisturizers: Moisturizers with spray nozzles are used to rewet the paper to adjust the moisture CD profile. The spray nozzles can be controlled individually by a CD control computer. Rewetting for profiling purposes is usually kept as low as possible. Rewetting is in fact a waste of drying energy, if it is not needed for other reasons, like curl control. Moisturizers usually have an actuator spacing of about 100 mm. A typical design is where each actuator consists of four pairs of valves and nozzles. Thus the amount of water added to a CD location is defined by which valves are opened. Thus, for the amount of water added in a given control zone, $2^4 = 64$ different combinations can be chosen.
  To avoid streaks, the nozzles have a defined spray angle and a defined distance to the sheet. Spray angle and distance are chosen to ensure an overlapping spray pattern. Thus, each nozzle sprays 50% of the water into neighboring control zones. This avoids moisture streaks in the rewetting process.
- Air water moisturizers: Air water moisturizers are used to control droplet size and droplet speed over a wide operating range. Droplets are much finer and faster than with pure hydraulic moisturizers. This allows one to apply more water.

Air water moisturizers usually have only one nozzle per CD control zone, which is controlled continuously. This avoids the limitation to the 64 control steps of the moisturizer and gives better controllability. Additionally the CD spacing of the nozzles is much less. In some applications more than 300 nozzles are controlled individually, having a CD distance of 25 mm.

Air water moisturizers are used

- in sensitive applications, where too large droplets have a negative impact on paper quality, e. g. on printability.
- in applications, where paper is for quality reasons overdryed in the drying section, and then rewetted e. g.
  - to control curl
  - to reduce mottling
  - to reduce two-sidedness of roughness and gloss
  - to achieve the best possible moisture CD profiles, down to a 2б deviation of 0.1 % relative moisture.
- Infrared heating: Zonal infrared heating corrects moisture profile deviations within the drying section and has the additional advantage of improving the drying capacity of the machine, instead of reducing it as do moisturizers. Infrared heaters use either gas or electric energy. Both are more expensive than drying by steam which limits the number of applications in industry. The zone width of the infrared heating system is usually around 150 mm, but half this size is possible.

9.2.2.2.3 **CD Caliper Control**

For CD caliper control in on-line calenders, off-line calenders or supercalenders their nip pressure is zonal controlled by local change of the roll shell diameter or shape.

- Zone-controlled calender rolls: The roll shell is internally supported by an oil cushion or a series of oil hydraulic pistons which can be controlled individually. The number of CD control zones per roll varies, usually between 8 and 60, depending on the construction. Limiting factors are for example the number of pipes inside the roll, which are needed to allow individual oil pressures in the various zones. Additionally counter zones are frequently used. They are on the opposite side of the nip. The purpose is to get more degrees of freedom in the zonal nip adjustment.

  The mechanics of roll shell together with nip pressure zones and counter zones are quite complex. For example, if only an edge zone is loaded, the whole shell is affected. Therefore the control is done in two steps:

  1. The CD control algorithm calculates the required line load profile in the nip.
  2. A simulation model of the roll is used to calculate the required zonal pressures to achieve the line load profile. This model of the roll is generated by the machine builder and also takes safety limits into account, to avoid roll damage by profile control actions.

- Zonal heating of rolls using eddy current: The principle is similar to eddy current breaks. A magnetic field generates current in the moving metal roll. The current heats the roll. With increased temperature the roll diameter increases as well. The advantages of using eddy current are:
  - high energy efficiency
  - heating may have a positive side effect, if higher gloss is required at that position
  - zone spacing can be smaller than with calender rolls and is typically around 100 to 120 mm.

  The downsides are:
  - A zone cannot actively decrease the roll diameter. This limits the ability to react on small streaks in the profile.
  - The heat flow in the roll does not allow short wave profile corrections. For example, if every second zone is heated, heat also flows to the nonheated zone in between from both sides. In narrow spaced applications its temperature tends to be like that of its neighbours.
- Zonal heating/cooling of rolls using hot/cold air: This kind of equipment is usually applied at heated rolls, to control the surface temperature profile of the roll. The advantages are:
  - Less energy consumption and less investment than eddy current actuators.
  - Compared to the eddy current solution, short wave profile corrections are much easier to achieve, as between two heated zones the middle zone can be actively cooled. Only cold air can actively decrease roll diameter i.e. between two heated zones.
  - Smaller zone spacing can be achieved due to the active cooling principle. Usual applications have 75 mm zonal spacing, 38 mm spacing is possible if the demands on caliper profile are very high.
  - If the actuator is used together with a zone controlled calender roll, it is beneficial if the smallest possible zone width is used. In this case CD control activities are split: Long wave corrections are done with the calender roll, whereas the hot/cold air device takes care of the short wave deviations, which cannot be handled by the calender roll itself.

9.2.2.2.4 **CD Gloss Control**

CD gloss control uses actuators in on-line calenders, off-line calenders or supercalenders. Gloss is affected by heat, line load and surface moisture in the nip. As the CD line load and CD roll temperature also affect caliper, CD gloss control usually uses zone controllable steam boxes to change surface moisture. As steam affects the paper very locally, controllability of gloss profiles is very good. Zone spacing is not less than 150 mm, due to space restrictions in the calender, and each zone in the steambox requires its own steam chamber with a steam valve.

9.3
Information Systems

9.3.1
Importance of Information Systems

Information systems in the paper mill exist mainly at two different levels:

1. Enterprise level: To collect all information concerning the material flow in the paper mill, including e.g. quality parameters of the produced paper. The information is usually collected in a very rough time scale, i.e. reel based. The purpose is to derive figures which are required for commercial control of the mill.
2. Process level: To collect quality and process data in quite high time resolution to be able to analyse and track process problems, to find the technical reasons for poor/excellent production, or to summarize the data in reports as needed by the enterprise level systems.

Whereas enterprise level systems deal mainly with production quantities (amount of good/bad production) process level systems include tools to analyse reasons for good/bad production.

Comprehensive collection of process data is more and more widely used but in many older mills is still not available. This is due to

- lack of communication standards in automation systems
- strict border between QCS and DCS/PLC type of systems when those mills were built.

The earliest information systems were:

- QCS quality reports: summarizing production and quality over reel, shift, day or grade
- DCS process trending: trend of important process variables.

Until recently there was no simple means to show in a flexible way on one screen e.g. how press settings (DCS data) affect moisture profile quality (QCS data). One obvious reason is, that DCS systems are (still) not built to handle “array based” information like CD profiles. They can deal only with single values like a steam pressure. On the other hand QCS systems are not built to handle thousands of process values, which requires totally different engineering and configuration tools.

Modern information systems bridge the gap, by using history data bases which can deal with tens of thousands of tags (variables), with single values and with profile data as well. Additionally they provide simple access to the data via a web browser and also from the operating screens on the production floor.

Besides QCS and DCS there exist more systems at a paper mill, which have the main task to collect information for diagnostic purposes:

- Machine condition monitoring system: These systems collect information via vibration sensors, to analyse bearings, and drive components. Advanced systems include an expert system for quite detailed analysis of the drive component. A machine condition monitoring system can e. g. detect whether the outer ring or the inner ring of a bearing is damaged and is likely to fail within the next weeks. Based on this information the mill personnel can arrange countermeasures and exchange the bearing during the next planned shutdown.

Typically a few 100 vibration sensors are connected to such a system. They are scanned one by one. Scanning occurs about every hour. The signal analysis uses known geometrical bearing and roll data and relates them to the actual measured signals to diagnose the condition of the bearings. The measurements have to be taken with a sampling rate of about 10 kHz to be able to diagnose bearings in detail and to give a prediction of the remaining lifetime of the bearing.

- Process condition monitoring system (sometimes also called technological monitoring system): These systems collect information from QCS sensors, vibration sensors, pressure sensors, triggers at rolls and fabrics, etc. to analyse the reasons for periodic quality disturbances. All collected signals are taken simultaneously with sample rates from 100 Hz to 4 kHz, depending on sensor type and application. The required measurement frequency is given by the revolution time of the machine elements which can cause quality variations, like felts, rolls, pumps, etc.

  The correlation results are calculated using time synchronous averaging. A process condition monitoring system can e. g. detect whether an applicator roll is responsible for periodic coat weight deviations, or whether a moisture variation is correlated with the revolution time of a press felt.
- Barring monitoring system: This system identifies calender rolls which cause barring. Technically it works similarly to a process condition monitoring system.
- Web inspection system: A series of cameras arranged in the CD inspect 100 % of the produced paper. Image analysis technologies are used to automatically classify the paper defects into different categories, like bright spot, dark spot, wrinkle, hole, etc. The web inspection systems generate reports, independently from QCS. Based on the camera based measurement and the image analysis, areas with serious defects can be marked on-line. A special winder control can stop the winder precisely at these positions, to cut off the low quality production.
- Web break monitoring: A couple of cameras are installed at the front side and drive side of the machine to supervise positions where the web is not guided by wires or felts, and where the paper risks to break. Optical light barriers detect paper breaks. In the case of a paper break, the last minute of the camera readings are stored to a hard disk for later analysis by the production personnel. Based on the camera recordings it can be analysed at which position of the machine e. g. an edge crack started to be seen, and how it evolved to a paper break, or it can be seen whether paper clipped to a roll and caused a web break. This allows the mill personnel to analyse the reasons for breaks and to optimize the runnability of the machine.

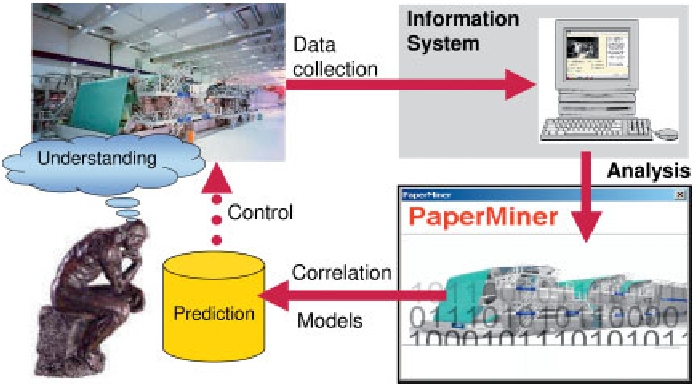


Fig. 9.5 Data mining in the paper manufacturing process (source: Voith).

9.3.2
Process Analysis using Information Systems

Current development of information systems aims to automatically derive knowledge from historical data (Fig. 9.5). When analysing difficult technological problems such systems still need off-line analysis by technological experts to interpret the results. In a typical application 6 to 12 months of recorded quality and process data are analysed with respect to given technological questions, like: “Most of the production in the last 6 months showed average printability but sometimes printability was excellent. Why? Which are the machine settings to achieve best quality?”

Such questions are difficult to answer, as several hundred machine settings and raw material parameters have to be taken into account as potential influencing factors. Data mining technologies based on neuronal networks, expert systems or algebraic methods are used to find the requested answers. Algebraic methods are in many cases not sufficient, as these can deal only with numbers (process values) but not with cardinal data like felt supplier, ash supplier, etc. which are also of high importance.

Simpler, but still difficult applications can run online and give information of a produced paper quality which is not measurable online. Those applications are called soft sensors. The paper quality property is estimated based on historical data. For example: Basis weight can be predicted quite well based on some process parameters in the wet end section. Historical data can be used to “learn” the relation between the measured process parameters and the produced basis weight. The learning takes place iteratively to adapt to slowly changing production conditions. Such a prediction is useful during start up of the machine, while the paper is still not through the drying section and still not measured by a quality scanner. Having a basis weight predictor the user can still adjust basis weight and therefore achieve good quality, even before the quality measurement starts scanning.

The challenge of soft sensors is to automatically reject data which are not adequate in order to learn relationships between the quality parameter concerned and the process data, e. g. because a sensor was wrong, the machine settings were just in the process of being changed, the press felt was worn out and just before replacement. This is especially challenging in applications where a hundred or more process data are required to really predict a given paper quality. An example is the prediction of strength parameters. Influences on strength are e. g. the furnish composition, the jet/wire ratio, retention, dryness after press section, tension in the draws, and calendering conditions.

10
Environmental Aspects

Udo Hamm

10.1
Wastewater

The paper industry has a high fresh water demand. At the beginning of the 20th century, about 500 to 1000 m^3 of water was required for the production of one ton of paper. Today the specific fresh water demand is much lower. The German paper industry, for instance, has succeeded in reducing the specific fresh water consumption to 13 m^3 (t paper)$^{-1}$ which corresponds to a wastewater volume of about 11 m^3 (t paper)$^{-1}$. In an international comparison, the performance in sustainable use of water resources of the German paper mills is very good. In the following mainly data from the German pulp and paper industry is presented, because of the high technical standard of wastewater treatment in this country.

10.1.1
Characterization of Untreated Wastewater

The pollution in the wastewater of a paper mill depends on the type of raw material, the type and amount of fillers and chemical additives applied, and on the degree of circuit closure. Effluents from mills that largely or exclusively process chemical pulps have a lower degree of pollution than those from mills in which mechanical pulp or recovered paper is employed. The use of starch or other organic additives results in a marked increase in oxidizable effluent compounds, measured as BOD_5 (biological oxygen demand) or COD (chemical oxygen demand).

Dyes and fillers can lead to discoloration and/or turbidity of effluents. Effluents from paper mills have a low content of nitrogen and phosphorus compounds. For this reason, these elements must be added as nutrient salts (e.g. urea and phosphoric acid) to feed micro-organisms during treatment in biological purification plants. The closure of the water circuit within the mill results in an increase in the concentration of the effluent components. On the other hand, the inorganic and

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organic load is reduced owing to its partial elimination via the paper produced. For this reason, the specific load in kg per t of paper (specific load = concentration × specific amount of effluent) is a more suitable parameter for quantifying the effluent pollution. Information on the specific COD and BOD_5 loads, classified according to product groups, is given in [1].

10.1.2
Wastewater Treatment

Most of the wastewater from German pulp and paper mills is treated biologically, either in municipal treatment plants (18% of production volume) or in in-mill plants (74% of production volume). 4% of the annual paper volume is produced in mills with a totally closed water circuit which means that these mills are absolutely effluent free [2].

10.1.2.1 Suspended Solids Removal

Effluents from paper mills contain solids and dissolved substances. Solids (fibers, fillers) are mostly removed from the effluent in a chemo-mechanical clarification process by the use of flocculants. The degradation of dissolved organic substances is performed in aerobic and anaerobic biological treatment plants.

Chemo-mechanical clarification of effluents is carried out almost exclusively in sedimentation plants (round and rectangular basin with bottom sludge removal) as shown in Fig. 10.1. Only in a few cases it is necessary to neutralize the effluents. Rakes for the separation of coarse material and sand traps are seldom used. The clarifying efficiency of sedimentation plants is increased considerably by the use of flocculants. Undissolved substances are removed with an efficiency exceeding 90%.

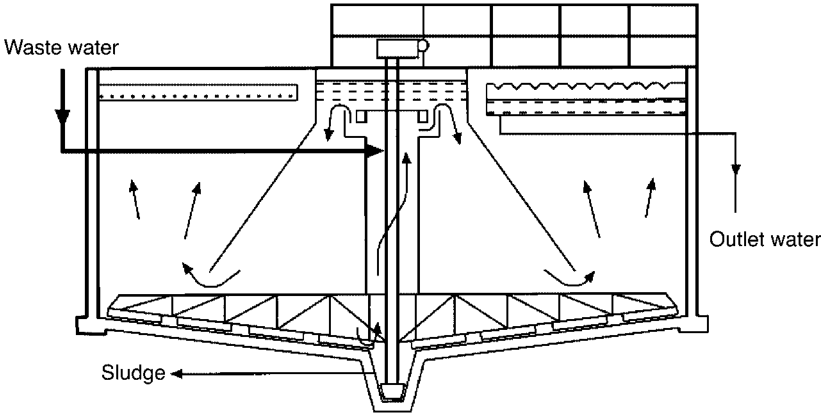

Fig. 10.1 Scheme of a sedimentation clarifier.

10.1.2.2 Biological Treatment

Primarily, activated sludge processes and, less often, trickling filter processes are employed for aerobic biological treatment. In North America and Northern Europe, effluent purification is frequently carried out in aerated oxidation ponds. Recently, anaerobic treatment has become established, especially in paper mills processing recovered paper.

10.1.2.2.1 Aerobic Treatment

The activated sludge processes applied are single-stage processes, systems with recycled sludge aeration, cascade systems, and two-stage processes. Atmospheric oxygen transfer is employed, using surface aerators (roll aerator, gyratory aerator) or pressure aerators. Pure oxygen processes with pressure aeration are also used occasionally. It is possible to improve the purification efficiency of activated sludge plants by using pulverized brown coal or foamed plastic carriers in the activated sludge tank. Biological treatment with a two-stage activated sludge process is shown schematically in Fig. 10.2. The trickling filter system usually operates in combination with an activated sludge process. The trickling filter can be either the first stage (in high-load operation) or the second stage (in low-load operation). Combination processes also include activated sludge processes with fixed-bed internals and submerged disk filters. Activated sludge plants and trickling filter plants are almost exclusively fed with mechanically pre-clarified wastewater. The addition of nitrogen and phosphorus compounds is required. The BOD_5 efficiency attainable with activated sludge processes is usually in the range of 90–98%, and the COD efficiency between 80 and 95%. For final clarification after the aeration tank, horizontal (rectangular and round basin) or vertical-flow (hopper basin) sedimentation basins are preferred. Biofilters are occasionally employed as a further purification stage. Third-stage purification processes for the elimination of nitrogen and phosphorus compounds are not usually required.

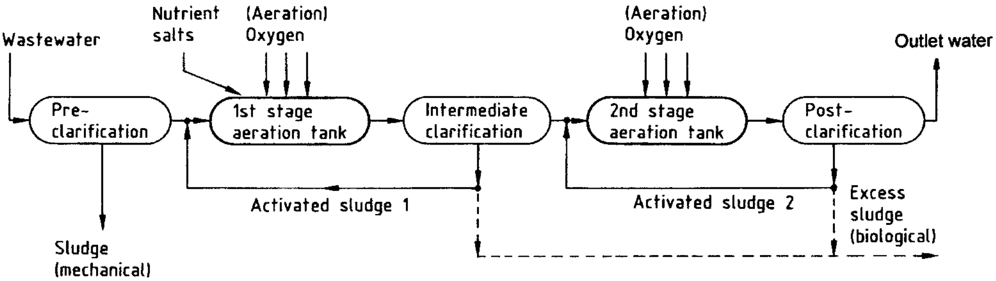

Fig. 10.2 Scheme of biological effluent treatment with a two-stage activated process.

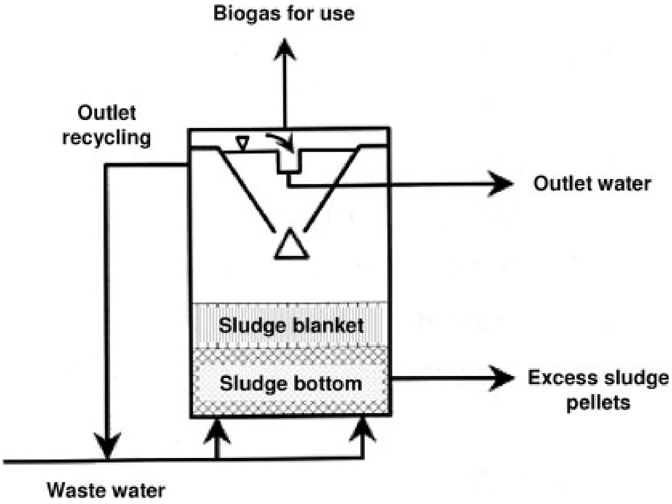

Fig. 10.3 Upflow anaerobic sludge blanket (UASB) reactor [11].

10.1.2.2.2 **Anaerobic Treatment**

Anaerobic processes have been employed recently for the treatment of more highly polluted effluents (COD > 2000 mg L^{-1}). Effluents from paper mills processing recovered paper are most commonly treated in anaerobic contact systems with sludge recycling and in UASB (upflow anaerobic sludge blanket) reactors. Figure 10.3 shows schematically an UASB-reactor which is used in the German paper industry for treatment of highly polluted effluents. Information on plants installed up to now and on operational experience is given in [3]. Fixed-bed reactors, fluidized-bed reactors, and other anaerobic reactor concepts are of minor importance. Anaerobic effluent purification is almost exclusively operated as a preliminary step to the aerobic treatment.

The sludges generated in effluent treatment must be dewatered and disposed of if they cannot be returned to the papermaking process. Screen belt presses, chamber presses, vacuum filters, or centrifuges are used for dewatering. The dewatering behavior can be improved by the addition of chemicals (polymers, trivalent metal salts, lime). Machines and plants for sludge treatment and their dewatering efficiencies are described in [11].

Most dewatered sludges (solid content 20–60%) are disposed of in landfills. Thermal utilization (combustion) is becoming increasingly important. The sludges can also be composted together with bark, applied to agricultural land, and used as a porousing agent in the production of bricks, as additives for fiberboard, and in making cat litter.

10.1.3
Characterization of Treated Wastewater

Biological processes can eliminate nearly 100 % of biologically degradable organic substances in the wastewater of paper mills. Considering the amount of organic substances determined as COD, the level of elimination is 80 to 95 %. A distinction must be made between a genuine biological degradation and a physico-chemical elimination, e. g. adsorption to anaerobic biosludge or activated sludge. COD and BOD concentrations and loads in biologically treated wastewater of paper mills producing different paper grades are given in [1].

Treated wastewater of paper mills is not normally toxic to water-borne organisms, as evidenced by the results of fish and other biological tests. Due to the low nitrogen and phosphorus concentration in the treated effluents only a small risk of extensive growth of water plants in surface waters exists. The wastewater has very low heavy metal content.

The additives used in paper production generally contribute only slightly to the load of the treated wastewater. For example, some starches, soaps or surfactants are easily biologically degradable. Others, and especially higher molecular weight additives such as retention agents, wet strength agents or coating binders, adsorb strongly to the biosludge. Detailed research on the subject is described in [4] and [5].

10.1.4
Closed Water Circuit

A closed water circuit is achieved when no wastewater leaves the paper mill. The process water is then almost 100 % utilized. Only evaporation and vaporization losses and the water content in the paper and in the residual matters must be replaced by fresh water (1–2 L (kg paper)$^{-1}$). A closed water circuit is shown schematically in Fig. 10.4. The essential requirement for reusing circulating water in the tertiary circuit is adequate save-all clarification. The quality of the clarified water must be suitable for the operation of sensitive systems (e. g. showers, trim showers). There must be enough storage capacity to compensate for variations in quality caused by disturbances and interruptions in production. Until now, closed circuits have been realized only in paper mills processing recovered paper. In Germany about ten recovered paper processing mills have closed the process water circuit totally. Most are small paper mills producing corrugating medium and testliner [6]. In the middle of the 1990s a German paper mill applied a biological in-line treatment plant to control the demanding conditions of the effluent-free process water loop. The biological treatment uses two UASB reactors as anaerobic stages followed by two activated sludge basins, a sedimentation basin and a sand filter. The process water volume treated in this plant corresponds to about 4 m^3 t^{-1} of paper produced. Before installation of the process water treatment plant, the COD concentration of the process water amounted to 35 000 mg L^{-1}. After the start-up of the treatment plant the COD decreased to 8000 mg L^{-1} [7].

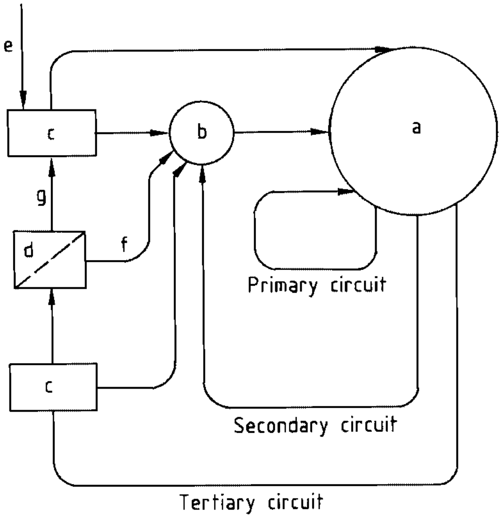

Fig. 10.4 Scheme of a closed water circuit [6]. (a) Paper machine, (b) stock preparation plant, (c) storage, (d) save-all, (e) fresh water, (f) high density stock, (g) clarified water.

In a new development the aerobic activated sludge plant was replaced by a compact aeration reactor, in order to reduce the odor of the anaerobic treated process water and to eliminate $CaCO_3$, which might cause problems when the biologically treated water is led back into the papermaking process [8, 9].

10.2
Solid Waste

The different processes within the pulp and paper industry result in the formation of different solid and sludge-like residues. In terms of volume, the largest are those from the deinking of recovered paper and from the treatment of effluents. Wood residues are also produced in large quantities, mainly in the pulp production. Other wastes arising at pulp mills are green liquor, lime sludge and ashes from energy generation and flue gas treatment.

Table 10.1 shows the solid wastes encountered in paper mills. Besides material removed from the pulper or ejected from a drum pulper, solids separated by screening and cleaning are all rejects. Among the sludges encountered there are deinking sludges, solids removed during the mechanical clarification of fresh water, process water and wastewater, and sludges from biological effluent treatment plants. Classified as incineration residues are ashes and slags from internal power plants and waste incineration plants including fly ashes. In the category of other waste are chemical residues, used oil, wire and felts and hazardous waste, such as

Table 10.1 Solid wastes of paper mills.

Wood residues	Stock preparation rejects	Sludges	Incineration waste	Other waste
Bark	Ragger tails	Deinking sludges	Ashes	Chemicals
Sawdust etc.	Drum rejects	Clarifier sludges	Cinders (slags)	Used oils
	Screening rejects	Biological sludges	Flue ashes	Wires
	Rejects of cleaner		Gypsum etc.	Felts
				Hazardous waste etc.

certain laboratory chemicals, batteries or transformer fluids. Wood residues such as bark and sawdust occur where mechanical pulp is also produced at the paper mills concerned.

In Germany the most recent survey on residues from pulp and paper mills dates back to 2001 [10]. According to the data gathered by the German Paper Industry Association a total of 3.6 million tons of residues was produced. This volume refers to the residues in their original state. The calculated mean dry content of all residues was 57%. Figure 10.5 shows that deinking sludges and sludges from process water and effluent treatment account for the largest proportion of residues with 30% each. Rejects from recovered paper processing contribute 15%, followed by incineration residues (11%) and bark (10%). Rejects from primary fiber proc-

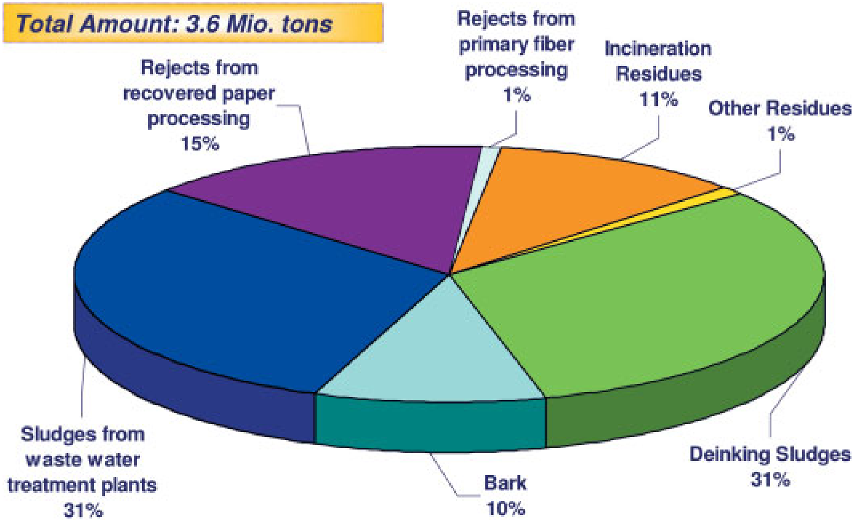

Fig. 10.5 Wastes of the German pulp and paper industry in 2001.

essing and other residues e.g. chemical waste, used wires and felts, and used oil account for only a small share.

10.2.1
Solid Waste Composition and Characteristics

As shown in Fig. 10.5 most of the German paper industry's waste is generated in recovered paper processing. To produce recycled fiber pulp suitable for use in the manufacture of different paper and board grades all substances likely to disturb the processing of recovered paper or the quality of the final product must be removed as far as possible from the disintegrated recycled stock. Depending on the contamination of the recovered paper with non-paper components and the paper grade produced, larger or smaller volumes of waste result. The volume also depends on the amount of effort invested in separation at the different process stages. Table 10.2 shows the percentages of waste amounts related to the recovered paper used and dependent on the paper and board grades produced.

Table 10.3 shows the composition of waste that occurs at different stages of recovered paper processing [11]. The waste from disintegration, cleaning and screening is reject material or rejects. The wastes that occur during flotation deinking and the cleaning of process water from wash deinking are sludges. Because

Table 10.2 Amount of rejects and sludges dependent on the recovered paper grade and the paper produced [11].

Produced paper	**Recovered paper**	**Amount of waste [% by dry weight]**				
		Total	**Rejects**		**Sludges**	
		Rejects and sludges	**Heavy-weight and coarse**	**Light-weight and fine**	**Flotation deinking**	**White water clarification**
graphic paper	news, magazines	15–20	1–2	3–5	8–13	2–5
	high grades	10–25	< 1	≤ 3	7–16	1–5
hygienic paper	files, office paper, ordinary, medium grades	28–40	1–2	3–5	8–13	15–25
market DIP	office paper	32–40	< 1	4–5	12–15	15–25
liner, fluting	sorted mixed recovered paper, supermarket corrugated paper and board	4–9	1–2	3–6	–	0-(1)
board	sorted mixed recovered paper, supermarket corrugated paper and board	4–9	1–2	3–6	–	0-(1)

Table 10.3 Solid waste from different stages in recovered paper processing.

Source of waste	Composition of waste
pulper, drum pulper	larger objects such as plastic bags, bookbinding backs, textiles, bottles, shoes, strings, tools, wires, wood pieces, wet strength paper…
high-density cleaning	glass, nails, paper clips, textiles, pins, staples
pre-screening	long, thin and wide contaminants
flotation deinking	fillers, fibers, fines, printing ink, stickies
low-density cleaning	small compact particles with high density such as sand, shives, hard particles from UV-colours, coating colours, varnish…
fine screening	plastic fragments, light-weight contaminants, hot melts, stickies
process water clarification	colloidal material, fillers, fibers, fines, ink particles

today's processing methods are selective only to a limited degree, both rejects and deinking sludges continue to contain a certain proportion of fiber and fiber fines.

Sludges also result from process water clarification and biological treatment of wastewater. The sludge from wastewater treatment plants can be divided into primary sludge from mechanical treatment and bio-sludge from biological treatment. It is technically possible to return these sludges to the production process in manufacturing paper grades as corrugating medium or testliner. Because the in-mill reuse may affect product quality and process runnability the use as raw material in production processes must always be considered on a mill-by-mill basis.

The amount and characteristics of ash resulting from energy generation and flue gas cleaning depend on the fuel and the combustion technology used. In the German paper industry the total amount of ashes in 2001 was 400 000 tons. Like all other wastes from pulp and paper processing, the ashes are non-hazardous and were mainly used in the construction material industry.

10.2.1.1 **Rejects**

The amount of rejects produced during recovered paper processing and their composition depends largely on the recovered paper grades. Figure 10.6 shows the composition of a reject sample as a mixture of rejects from six paper mills producing newsprint. Pulper and drum pulper are used for slushing of the recovered paper (old newspapers and old magazines). The proportion of the reject fractions as dry solids was 4 to 6 % related to air-dried recovered paper.

Due to the high proportion of plastic materials the heating value of rejects is more than 20 GJ t^{-1} of dry substance. The use of rejects as an energy source such as secondary fuels for cement production can be limited by a rather high chlorine

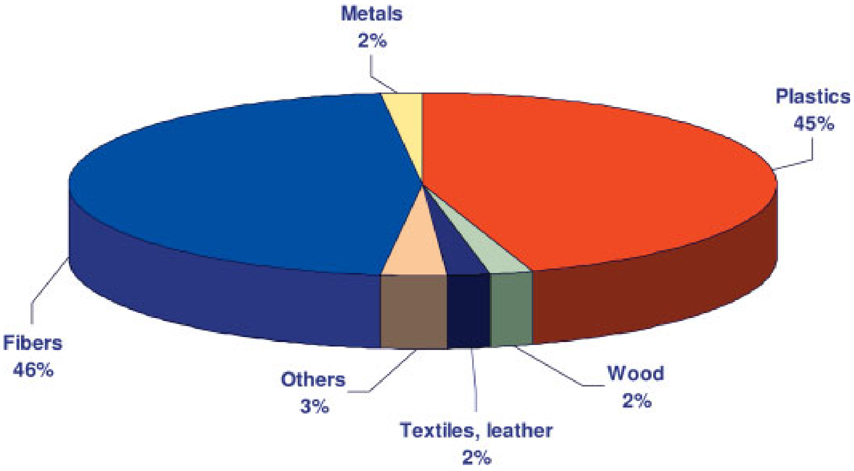

Fig. 10.6 Composition of a mixture of reject samples from the production of newsprint based on recycled fibers related to dry substances (Germany) [12].

content. It can amount to 3 % by weight of rejects on a dry basis. Polyvinylchloride (PVC)-containing materials such as self-adhesive tapes, foil laminates, carrier handles and PVC products thrown in error into recovered paper containers are the main sources of this chlorine content.

10.2.1.2 **Deinking Sludges**

Deinking sludges consist of fillers and coating pigments, fibers, fiber fines, printing inks (black and colored pigments), and adhesive components. Figure 10.7 shows that more than 55 % of the solids removed by flotation are inorganic compounds. They are primarily fillers and coating pigments such as clay and calcium carbonate. The proportion of fiber material at 7 % is low. Materials extractable with methylene chloride have an average proportion of 8 %. They contain wood components from the fibers such as resins, fats and resin acids as well as extractable printing ink and adhesive components and flotation deinking chemicals. The remaining 29 % comprises fibers fines, nonextractable ink components (mainly carbon black and colored pigments) and nonextractable adhesive components.

Table 10.4 provides a summary of ash contents, heating values, elemental contents and levels of different contaminants of deinking sludges. It shows minimum, maximum and average values for sludges from different German paper mills. A characteristic for deinking sludges is their high ash content, 70 %. The heating value depends on the ash content and is 4.7–8.6 GJ t^{-1} of dry substance. The sulfur, fluorine, chlorine, bromine, and iodine contents are low. For this reason, no costly flue gas purification systems are necessary when incinerating deinking sludge. Compared with sludges from biological effluent treatment plants, the nitrogen and phosphorus contents are very low. This is something that requires

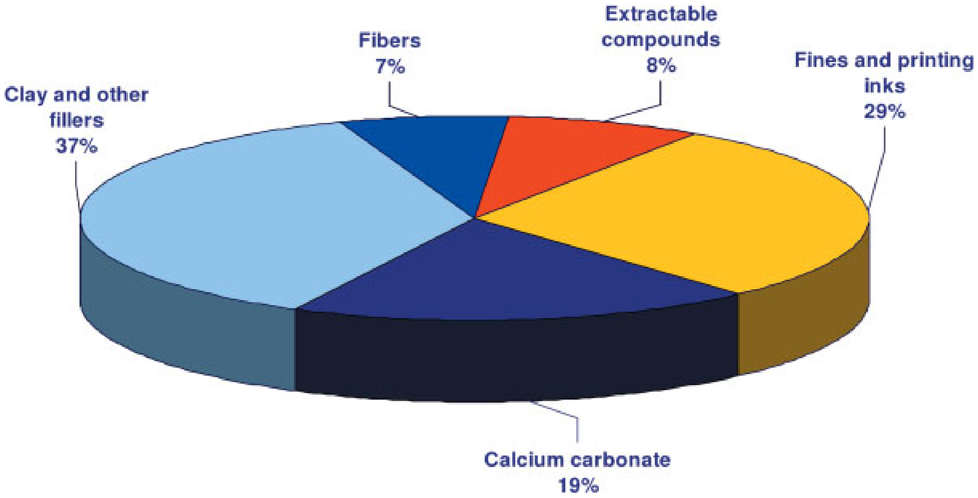

Fig. 10.7 Composition of deinking sludges from the production of wood-containing graphic papers related to dry substances (Germany) [11].

consideration when using deinking sludges for composting and agricultural and land application purposes.

The level of heavy metals in sludges of recovered paper processing is generally low. Figure 10.8 compares the concentrations of heavy metals in deinking sludge with the contents of heavy metals in biological sludge of wastewater treatment plants of paper mills and in municipal sewage sludge. This data shows that sludges of deinking plants have less contamination than those of municipal wastewater treatment. The concentration of cadmium and mercury is especially insignificant and sometimes even below the detection limit of the test method applied (atomic absorption spectrometry). Only the concentration of copper has the same order of magnitude as that of municipal sewage sludge. The copper content of deinking sludge is primarily due to blue pigments of printing inks which contain phthalocyano compounds.

Traces of halogenated organic compounds such as polychlorinated biphenyls (PCB), polychlorinated dibenzodioxins (PCDD), and polychlorinated dibenzofurans (PCDF) also require consideration. PCB compounds were used in the manufacture of carbonless paper until the early 1970s. The PCB level of deinking sludge has decreased significantly since then. Recent data obtained from several deinking plants confirm that the PCB concentration is below 0.3 mg kg^{-1} dry solids (0.3 ppm) using the most relevant seven congeners.

PCDD/PCDF concentrations of deinking sludges show a similar pattern of decline. Due to the continuing change from elemental chlorine bleaching of chemical pulp to chlorine dioxide and oxygen bleaching, the PCDD/PCDF contents of deinking sludges of German paper mills have been decreasing significantly. Today, PCDD/PCDF concentrations of deinking sludge are 25–60 ng I-TE kg^{-1} dry solids

Table 10.4 Chemical characteristics of deinking sludges with data related to dry substance [11].

Parameter	Unit	*n*	Minimum	Maximum	Average
dry content	wt%	11	38.1	62.1	51.2
ash content	wt%	14	36.4	67.3	54.8
heating value	$\mathrm{kJ\ kg^{-1}}$ (wet)	12	1240	4320	2310
heating value	$\mathrm{kJ\ kg^{-1}}$ (dry)	13	4750	8600	6940
pH		13	6.8	8.3	7.5
sulfur	wt%	3	0.06	0.12	0.08
fluorine	wt%	14	n/a	< 0.1	n/a
chlorine	wt%	14	0.01	0.1	0.05
carbon	wt%	14	19.1	35.8	26.0
hydrogen	wt%	14	2.6	4.2	3.3
nitrogen	wt%	14	0.20	0.50	0.35
phosphorus	$\mathrm{mg\ kg^{-1}}$	14	300	560	464
potassium	wt%	14	0.08	0.30	0.19
calcium	wt%	14	1.5	14.9	9.3
magnesium	wt%	14	0.16	0.79	0.37
aluminum	wt%	6	2.8	6.5	4.6
iron	wt%	6	< 0.1	0.5	0.2
silicon	wt%	6	3.3	7.6	5.8
lead	$\mathrm{mg\ kg^{-1}}$	14	9.5	79.4	44.6
cadmium	$\mathrm{mg\ kg^{-1}}$	14	0.02	1.54	0.34
chromium	$\mathrm{mg\ kg^{-1}}$	14	4.8	96.6	39.1
copper	$\mathrm{mg\ kg^{-1}}$	14	64.2	345.0	186.2
mercury	$\mathrm{mg\ kg^{-1}}$	14	0.10	0.89	0.26
nickel	$\mathrm{mg\ kg^{-1}}$	14	< 31.3	31.3	11.4
zinc	$\mathrm{mg\ kg^{-1}}$	14	34.2	1320	269
PCB	$\mathrm{mg\ kg^{-1}}$	5	n/a	< 0.3	n/a
AOX	$\mathrm{mg\ kg^{-1}}$	14	160	1200	516
dioxins/furans	$\mathrm{ng\ I\text{-}TE\ kg^{-1}}$	3	26.5	58.3	37.9

n = quantity of analyzed deinking sludge samples. n/a = not available.
I-TE = International Toxicity Equivalent according to NATO/CMS.

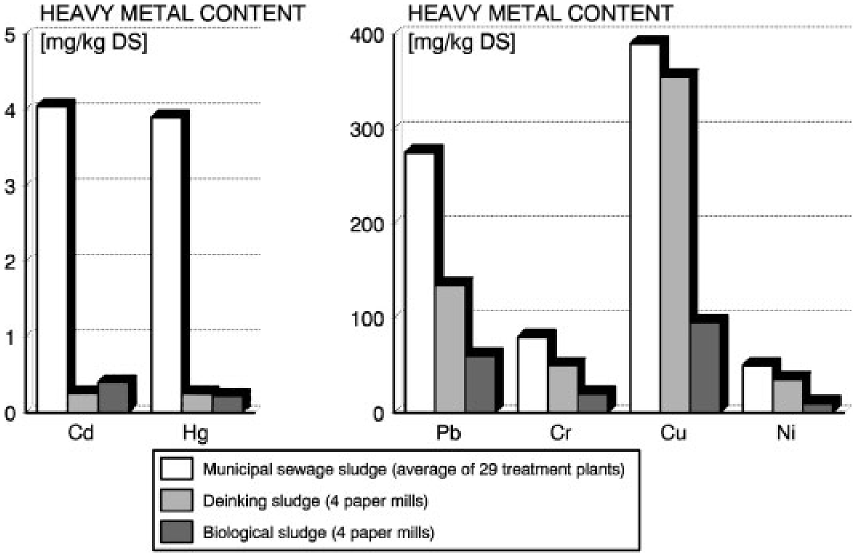

Fig. 10.8 Heavy metal contents of deinking sludge, biological sludge and municipal sewage sludge (Germany) [13].

(I-TE = International toxicity equivalent). These figures are not significantly higher than the average contents of PCDD/PCDF in municipal sewage sludge. As a result of modifications of the bleaching sequences in chemical pulping, dioxin formation does not occur in most pulp producing countries. Consequently, dioxin discharges from recovered paper processing mills are already low and will decrease further.

The parameter AOX (adsorbable organic halogen-containing compounds) plays an essential role in environmental regulations. In Germany for example, the direct application of sewage sludge on agricultural soil is regulated for heavy metal concentration, PCB and dioxin concentrations, and AOX level. In many cases, the AOX of deinking sludge is often above the acceptable limit of 500 mg kg^{-1} dry solids. Investigations have shown that up to 80 % of AOX in deinking sludge is due to chlorinated yellow pigments that are components of printing inks. These pigments are water insoluble and nonbiodegradable.

10.2.2
In-mill Waste Handling

The aim of in-mill waste handling is usually to achieve as high a dry solids content as possible, because all commonly used methods for material and energy recovery benefit from a high solids content.

In a sludge suspension, water exists in the following forms:

- Free water
- Capillary water
- Bound and intercellular water.

Free water can be removed simply by gravity settling. Much of the water is removed by allowing the sludge to stand, when solids sink to the bottom and water forms a supernatant. Capillary water can be removed mechanically by filtration or centrifugation. Bound and intercellular water can be removed by drying.

10.2.2.1 **Dewatering**

For sludge dewatering two-stage processes are often used. An initial step for dewatering using gravity tables or drums and disk thickeners occurs before a high-consistency dewatering with belt filter presses or screw presses. Batch-agitated chamber filter presses are of only minor importance due to their costly sludge conditioning with inorganic precipitation agents (metallic salts and chalk) or organic polymers, and their high maintenance costs. Centrifuges are universally applicable and generally managed without steps before the dewatering. With pure biological sludges, systems using these devices can achieve the highest dry contents.

Figure 10.9 shows the basic function of a belt filter press. The sludge is transported between two wire belts where it is subjected to a gradually increasing pressure. Direct pressure forces and shearing forces squeeze water from the sludge. Conditioning with polyelectrolytes is necessary for most types of sludge. Figure 10.10 shows the basic function of a screw press. The sludge is transported by a slowly rotating screw working against discharge restriction. The water squeezed out is released through openings in the cylindrical housing surrounding the screw. Some screw presses have the optional possibility of heating the sludge by injecting

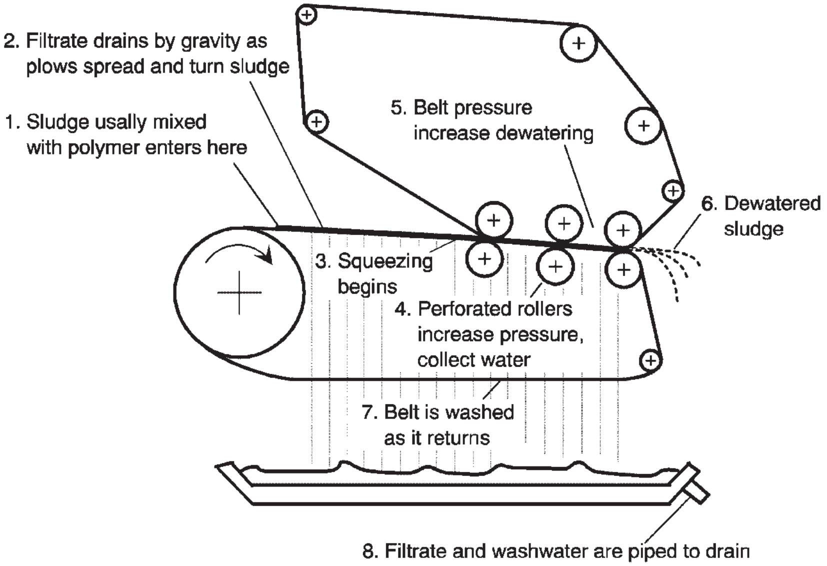

Fig. 10.9 Basic functions of a belt filter press [11].

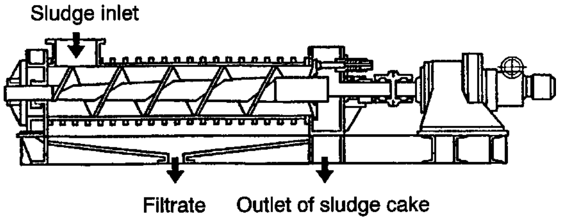

Fig. 10.10 Basic function of a screw press.

steam through the screw shaft. Conditioning of the sludge with polyelectrolytes is common.

Today, the ragger and the rejects from the pulper disposal system are usually not subjected to any special dewatering. Due to their material composition, "draining off" gives dry contents of 60–80%. Screen spiral conveyors, vibrating screens, and screw and rake classifiers are useful for dewatering heavy and coarse rejects. Dewatering of light and fine rejects with screens, endless wires or vibrating screens is usually followed by additional dewatering using a reject screw press.

Table 10.5 summarizes the most common dewatering systems for different types of waste. The achievable dry solids contents are also indicated. The differences in the dry solids contents are due to different pressure levels and times. For example, screw presses operate with pressures up to 8 bar for times up to 10 min. Belt filter presses work with pressures only up to 0.5 bar and short pressing times of only 1–2 min. With increasing proportions of biological sludges from wastewater treatment plants, the dry solids contents decrease for all techniques. Independent of the technique applied, dry contents of only 15–40% are possible with purely biological sludges.

Table 10.5 Composition and dewatering of rejects and deinking sludges.

	Heavy-weight and coarse rejects	**Light-weight and fine rejects**	**Deinking sludges**
composition	glass, nails, sand, stones, paper clips, pins	sand, textiles, fibers, coating colors, plastic fragments, hot melts, stickies	fillers, pigments, fibers, printing ink, stickies
dewatering facilities	screens vibrating screens screw classifiers rake classifiers	screens disk thickeners dewatering drums gravity tables screw presses	dewatering drums gravity tables belt filter presses screw presses chamber filter presses centrifuges
achievable dry solids contents	60–80%	50–65%	one-stage operation: < 15% two-stage operation: < 65%

10.2.2.2 **Drying**

Thermal drying processes are used for more comprehensive removal of water from mechanically dewatered sludges. Sludge dryers find use primarily when available or potential disposal processes are impossible or uneconomical, e. g. high landfill costs per ton of moist sludge due to insufficient dryness. Besides giving mass reduction, drying of the sludge has other advantages that broaden the waste management options:

- Sludges at about 95% dry substance are odorless. The bacteria-free conditions mean that sludges can be stored in the open or in simple silos.
- Dried sludges can be transported without any problem in the same way as bulk goods in regular transport systems.
- Dosing and mixing with other waste and combustibles is simpler.
- Combustion is easier and produces more heat per unit of mass of dry material.

Direct and indirect drying systems are in operation. Direct systems are convection dryers, and indirect systems are contact dryers. With convection dryers, heat transfer occurs by direct contact between hot air and the sludge. The hot air also provides pneumatic transport through the dryer. Convection dryers can be heated directly or indirectly. Compared with the contact dryers, the contamination of the resulting condensed exhaust air is low, but the volume of exhaust air is considerably higher.

Among the contact drying processes in the paper industry are steam heated centrifugal dryers and disk dryers. The types of convection dryers used are drum dryers, belt dryers or rack dryers.

In all drying processes, flue gas and dry goods control have primary importance due to the danger of combustion and explosion. In this respect, indirect drying processes are less problematical. Depending on its structure in the moist state, the dried sludge takes on the form of fine granules or pellets. For direct and indirect drying, the heat requirement is 4.0–4.5 GJ t^{-1} of evaporated water.

10.2.3

Utilization and Final Disposal of Solid Waste

The current possibilities for material and energy recovery and final disposal of the different types of paper mill waste are shown in Figure 10.11. The dominant practice in the past for disposal was landfilling. Today, and in the future, energy recovery and material use of waste as in other branches of industry is gaining increasing importance.

Figure 10.12 shows how wastes of the German paper industry were utilized and disposed of in 2001. The largest share, at 36%, was utilized in the building materials sector, mainly in the brick and cement industry. The energetically utilized share was 35%. Internal power plants at paper mills had a utilization level of 26% and 9% was accounted for by external energetic utilization in power plants or waste incineration plants. 18% of residues were directed to biological utilization, of

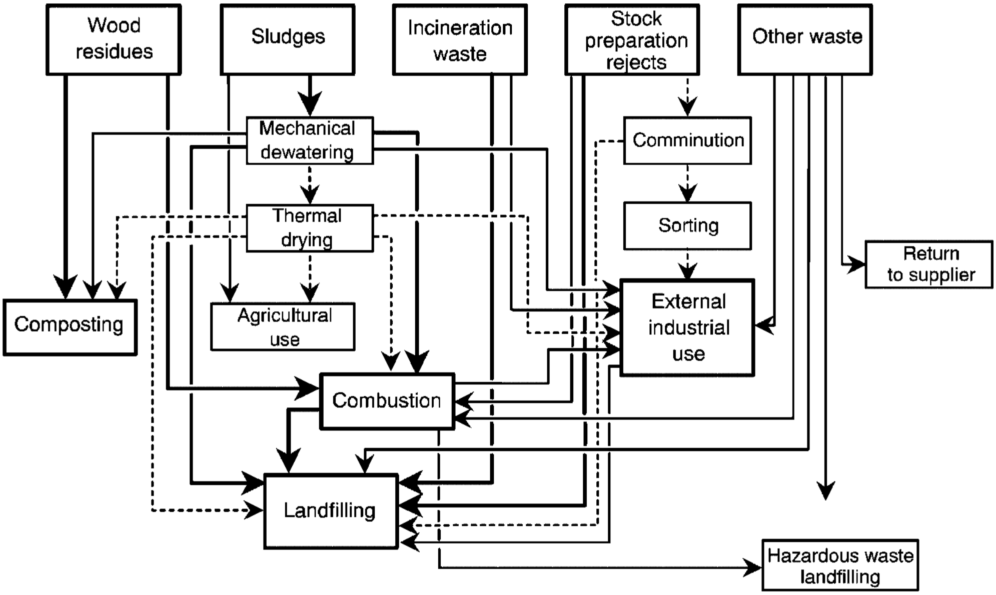

Fig. 10.11 Utilization and disposal of solid wastes of recovered paper processing [11].

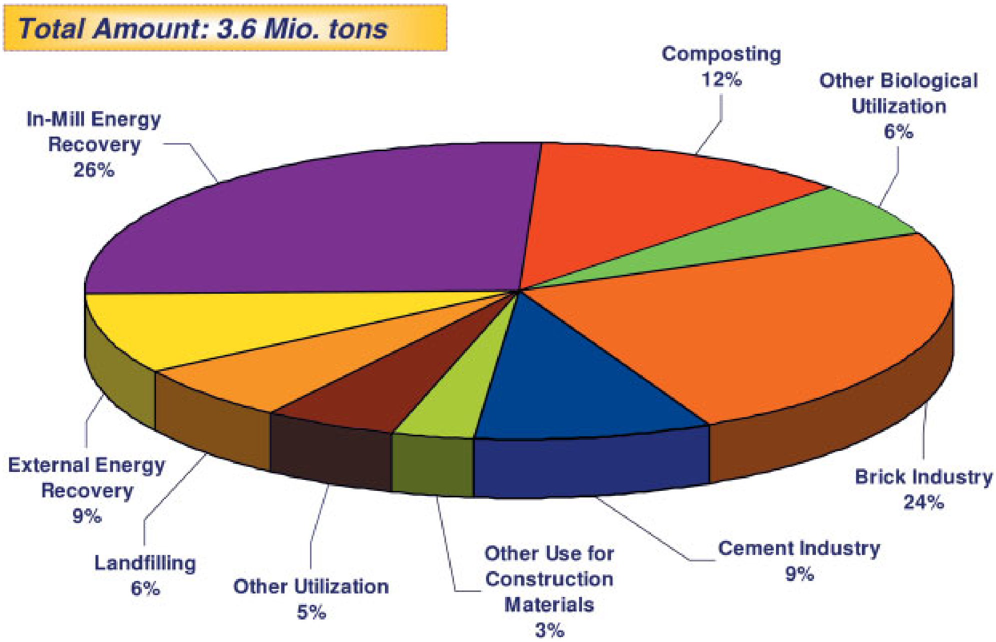

Fig. 10.12 Utilization and disposal of paper mill residues in Germany (2001).

which two-thirds were composted. The share of residues disposed of by landfilling had already dropped to just 6 %.

10.2.3.1 **Energy Recovery**

In the pulp and paper industry there is a long tradition of waste incineration. For example, consider the combustion of bark and wood residues. Recent years have seen a growing interest in the use of other types of waste such as sludges and rejects for energy production purposes. The reasons are:

- increased costs of fossil fuels and purchased power
- reduced landfill capacities and increased landfill costs
- more stringent environmental regulations governing the use of this waste in agriculture
- development of new combustion technologies with highly effective flue gas cleaning technologies.

Due to their heating values and low content of harmful substances, most types of waste from paper mills are suitable for energy recovery. Sludges and rejects are burned mainly in grate and fluidized bed combustion facilities. Burning of sludges is also carried out in multiple hearth incineration plants.

10.2.3.1.1 **Grate Combustion**

Grate combustion systems are especially suitable for lumpy fuels but not for most, paste-like, and finely grained fuels. With moist sludges for example, the retention times on the grate can be insufficient for complete combustion. Nevertheless, grate combustion systems are used in the paper industry primarily for co-firing of sludges with coal, bark or wood residues. Grate combustion with a stationary grate is shown in Fig. 10.13. Long reaction times for control processes and the difficult combustion control on the grate by the addition of air presuppose that the moisture content and ash content of the sludge vary only within narrow tolerances.

10.2.3.1.2 **Fluidized Bed Combustion**

Fluidized bed combustion results in good heat transmission and intimate mixing of air and fuel. Combustion is, on the whole, better than in grate furnaces, and emissions are therefore lower. Figure 10.14 shows the scheme of a stationary fluidized bed furnace. In fluidized bed boilers the combustion conditions can be controlled through regular temperature and pressure measurements, which is not the case with grates. Stationary fluidized bed furnaces as well as circulating fluidized bed furnaces offer very good operating conditions for low emissions of air-borne pollutants. The emissions of nitrogen oxides are especially low compared with grate combustion. Direct desulfurization is possible by the addition of basic sorbents such as limestone or dolomite into the body of the furnace.

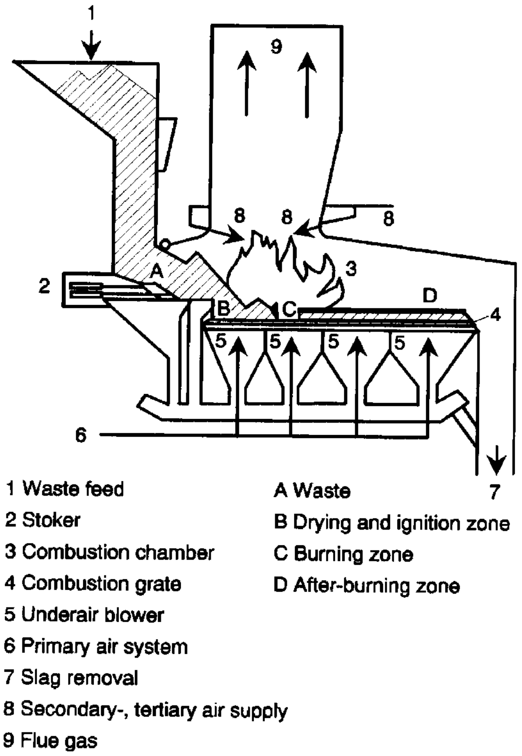

Fig. 10.13 Grate combustion with a stationary grate [11].

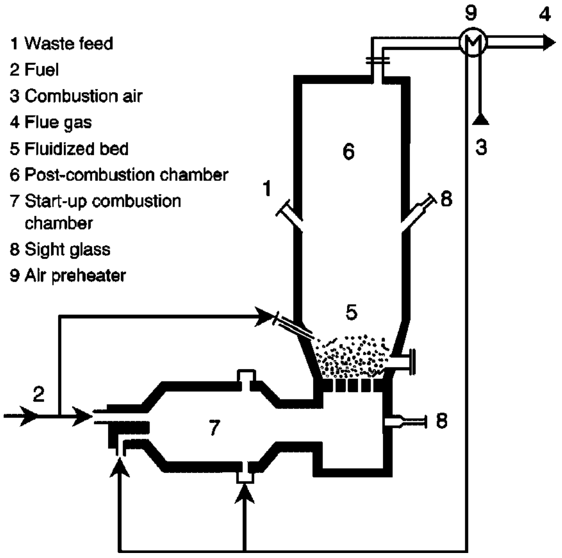

Fig. 10.14 Stationary fluidized bed combustion [11].

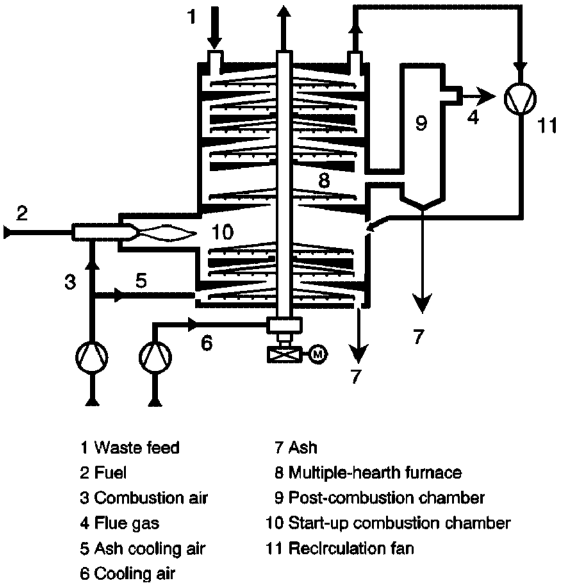

Fig. 10.15 Multiple hearth combustion [11].

10.2.3.1.3 Multiple Hearth Combustion

Multiple hearth combustion plants, as shown schematically in Fig. 10.15, are especially suitable for the combustion of moist and paste-like waste. They have been used for decades in the paper industry for energy production from primary and biological sludges, often together with bark. The flue gas purification plant downstream from the multiple hearth furnaces usually consists of wet scrubbers to remove dust and sulfur compounds. The flue gas finally enters the stack via a mist eliminator.

10.2.3.1.4 Choice of Combustion Technology

The choice of combustion technology depends on the operating conditions and the nature of the waste. According to today's knowledge, fluidized bed combustion is the most suitable for burning sludges and rejects. In fluidized bed combustion neither fluctuations of heating value of the fuel nor changing proportions of non-combustible components such as sand, metals or fillers have a negative influence on the combustion efficiency.

For fuels with a low heating value, such as deinking sludges, the stationary fluidizing is probably a more suitable option. Fuels with a higher heating value such as wood and bark are incinerated more effectively in a circulating fluidized bed. Due to the mechanical flow requirements of the fuel, producing a consistent grain size distribution by mechanical processing such as extraction of metals, shredding and grinding may be necessary. This requires consideration, especially when co-burning rejects with sludges.

For sludge and reject incineration in paper mills the following conclusions concerning flue gas emissions are possible:

- Emissions of solid particles, sulfur dioxide, hydrogen chloride, hydrogen fluoride and carbon monoxide are low compared with legal standards. Due to the high calcium carbonate content of deinking sludge this sludge should not release all sulfur as sulfur dioxide. State-of-the-art flue gas purification guarantees that no significant environmental impact arises.
- The emission of heavy metals is very low compared with the legal standards, especially for emission of cadmium and mercury.
- The emission standard of nitrogen oxides can usually be met by improved combustion control (temperature and oxygen level). Sometimes, the application of specific measures to remove NOx could be necessary.
- The stringent emission standard of polychlorinated dioxins and furans can be met without any additional measures in flue gas purification.

10.2.3.2 **Composting and Agricultural Utilization**

Nearly all types of paper industry waste are suitable for composting. These include fiber-containing sludges, deinking sludges, bark, wood residues, and biological sludges from effluent treatment plants. Rejects from recovered paper pulping and screening operations are not suitable or suitable only to a limited degree. With this type of waste, the content of plastic and other nonpaper components such as glass or stones has a detrimental influence.

In all cases, composting of residues from paper manufacturing requires the application of additives. With the exception of biological sludges, the sludges have an unfavorable carbon/nitrogen (C/N) ratio for microbial decomposition. They also have a dense structure that is unfavorable for composting. This requires the addition of structure-improving materials that are ideally also nitrogen carriers. Biological waste from households, garden waste, cuttings from trees and plants, straw, bark, and waste from animal husbandry are suitable as such components. The composting of fiber sludges and biological sludges, usually with bark, has been practised on an industrial scale for a long time.

The paper industry also has a long tradition of using sludges in agriculture. This is true especially for virgin fiber sludges and for biological sludges since the first biological effluent treatment plants started operation. With the exception of sludges from biological effluent treatment plants, sludges from the paper industry have a high carbon/nitrogen ratio and therefore contain only a small proportion of nitrogen. For this reason, they have only a limited fertilizing effect. The advantage of their use in agriculture relates to their soil enhancing properties. They not only contribute to covering the requirements of a humus forming organic substance but also improve the aeration and cultivation of the soil, increase the water retention capacity and prevent erosion.

Use of deinking sludges in agriculture is still controversial. In North America, no objections exist concerning their use as a soil improving material provided the material does not exceed defined contaminant concentrations or harmful substance loads. The situation in Germany is different. In general, the contaminant concentrations of deinking sludges are well below the valid threshold limits for municipal sewage sludge defined by legislation governing sewage sludge. The German Environmental Protection Agency still considers the agricultural use as unjustifiable for reasons of soil protection, including the irreversibility of numerous soil contaminants. The agency claims the ecological risk potential of deinking sludges is not sufficiently known. In the Biowaste Ordinance issued in 1998, the use of deinking sludges is also not allowable on soil intended for agricultural, forestry, or horticultural purposes.

10.2.3.3 **Use in Other Industries**

Rejects, deinking sludges, and combustion ashes of paper mills are used in many branches of industry for material and energy production purposes. The material use possibilities for deinking sludges and combustion ashes depend primarily on the composition of the inorganic components. The inorganic part of the deinking sludges consists mainly of calcium carbonate and clay. In the combustion ashes of deinking sludges, calcium oxide and sintered clay are primarily present. The aforementioned inorganic components also have use as raw materials in the construction industry. The primary use possibilities are therefore the following:

- cement production
- brick manufacturing
- concrete production
- mortar and sand lime brick production
- road construction.

10.2.3.4 **Landfilling**

Landfilling is the most commonly applied method worldwide for the final disposal of paper mill wastes. This situation will not change in many more remote regions of the world in the medium term. In contrast, landfill capacities have already become very limited in densely populated countries and it is becoming increasingly difficult to obtain authorization to open new landfill sites. Further development of landfilling techniques has dramatically increased costs for construction and operation of landfills. With the current technical state-of-the-art, operating a landfill site such that any annoyance to the population living nearby or environmental risk due to leakage, odors, fire and explosion risk can be largely eliminated.

Theoretically, the following possibilities exist for landfilling waste from paper mills:

- landfilling in monofill dumps for certain types of waste such as ash, sludge, and bark
- works-owned landfills where all in-plant waste is stored
- landfilling in public dumps where waste from other sources is also stored.

Depending on local circumstances and the types of waste concerned, pulp and paper mills sometimes use all three disposal methods. Because the waste from paper mills is not harmful, using municipal landfills is possible. To minimize leakage and maintain landfill stability, an extensive dewatering of sludges and rejects is necessary. Dry solid contents should be above 40%. The landfill of ashes from reject and sludge incineration does not require any measures beyond those governing the dumping of household waste.

10.2.3.5 **New Developments**

Besides extension of the processes to use waste material described so far, further possibilities exist for the use of waste from paper mills. These mainly concern fibrous sludges and deinking sludges. Only a small number of paper mills use these possibilities, or they have been limited so far to laboratory scale tests and pilot installations. New developments in the area of sludge use include:

- wet oxidation processes
- fermentation processes
- hydrolysis processes
- production of cat litter and adsorbent materials.

For ash use, filler recovery processes are under development that should permit the reuse of recovered fillers in the paper industry or other branches of industry.

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11

Paper and Board Grades and Their Properties

Otmar Tillmann

11.1

The Material Paper: a Survey

11.1.1

Introduction

The term paper refers to sheet material that is made essentially from fibers of plant origin. The characteristic feature of this nonhomogeneous material is its fiber network, which is usually arranged in layers containing pores of varying size. The properties of paper differ substantially from those of the fiber resources. These differences are illustrated in Table 11.1, which shows some selected material properties of wood, as the most important fiber source, in comparison with paper. As a result of the physical and chemical properties and the highly ordered state of wood fibers, wood is unsuitable for direct production of sheet material which could serve as writing material. The construction of paper, i. e., sheet material with properties that are optimal for writing, printing or packaging, is possible only after the breakdown of wood into its elemental fiber building blocks, their modification in the pulping process, and their controlled bonding in the papermaking process. Paper

Table 11.1 Comparison of selected properties of wood and paper.

Property	Wood	Paper
density, g cm^{-3}	0.3–0.5	0.5–1.5
Young's modulus, GPa	1.3	1.8–4.3
tensile strength, MPa	90–200	20–200
breaking length, km	7–30	1–8
strain to rupture, %	0.6–0.8	0.8–4
fiber alignment	ordered	random

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can be made with an extremely wide range of properties by varying the construction parameters: type of wood, pulping process, stock preparation, and papermaking process. This is illustrated in Table 11.2.

The wide range of paper and board properties that result from the construction parameters mentioned above can be increased still further by the use of additives such as mineral and chemical aids. For instance, the smoothness and brightness of printing paper can be increased by addition of inorganic pigments (fillers) [1]. Many special demands made on paper can be met by using suitable chemical additives, e. g., wet strength by using wet-strength additives or printability by using sizing agents [2]. However, paper produced with all these aids will never meet all conceivable requirements at a time. In each case only a few paper properties that are particularly important for the intended purpose can be optimized, as far as the other properties are concerned, concessions must be made.

11.1.2

Material Properties

The specific characteristic features of paper vary widely, depending on the type of paper. Nevertheless, there are a number of properties that are characteristic of all papers. These are inhomogeneity, hygroscopicity, anisotropy, and viscoelasticity.

Paper is an inhomogeneous material made from homogeneous elements: fibers, fillers, and air-filled pores. The homogeneous regions extend over a few micrometers (a few millimeters in the longitudinal fiber direction), corresponding to the characteristic dimensions of these particles.

A sheet of paper also exhibits other inhomogeneities, which can have characteristic dimensions of a few millimeters or centimeters. These are known as cloudiness and result from undesired fiber flocculation in the sheet forming process [3]. In this way, variations in caliper and density develop, and this leads to corresponding variations in transparency, the “clouds”. Finally, the production process can also give rise to inhomogeneities, e. g., due to stock pulsations in the headbox and in the sheet forming section [4]. Only betaradiographic measurements can give exact information about local mass differences. The existence of inhomogeneities must be taken into account in paper testing, e. g., by choosing the appropriate size of sample.

The most important characteristic of paper is its hygroscopicity, i. e., its ability to absorb or release moisture, depending on the ambient climate, until an equilibrium is reached. It is significant whether the state of equilibrium is established by absorption or desorption of water [5]. The equilibrium moisture contents of some types of paper at various levels of relative humidity are listed in Table 11.3.

As a result of the hygroscopicity of paper, physical paper properties, such as sheet dimensions, basis weight, tensile strength, strain to rupture, folding strength, bending stiffness, etc., are dependent on the ambient conditions [6]. With a change in the ambient climate, the full attainment of a new equilibrium moisture content of paper is a process which takes several hours. However, the change in the physical properties of the paper starts almost without delay and occurs very

Table 11.2 Selected properties of some grades of paper and board.

Selected properties of some grades of paper and board	Property	LWC, Mechanical paper	Newsprint	Wood-free offset printing paper	Bag paper	SC-A, Super-calendered mechanical uncoated magazine paper	Boxboard
basis weight, g m^{-2b}		54–55	45–49	81.4	69.7	45–60	286
caliper, µm^{c}		45–46	62–80	110	106	39–54	453
density, g cm^{-3c}		1.25–1.3	0.61–0.74	0.74	0.66	1.15–1.23	0.63
specific volume cm^{3} g^{-1c}		0.8–0.78	1.35–164	1.35	1.52	0.8–0.9	1.59
tensile strength, N^{d}	MD	36–40.9	26.5–30	64.5	78.5	36–42	245.5
	CD	14.6	12.6	25.1	53.5		80.5
elongation,%^{d}	MD	1.0–1.2	0.8–0.9	1.6	2.8	1.2–1.3	2.0
	CD	1.6	1.8	3.0	6.2		3.2
breaking length, km	MD	4.5–4.95	3.30	5.25	7.50		5.75
	CD	1.75	1.55	2.05	5.15		1.85
tear growth resistance, mNm m^{-1e}	MD	180	120	340	640		1200
	CD	250	170	410	630	200–230	2440
bursting strength (Mullen), kPa^{f}		100	50	150	350		550
Smoothness (Bekk)^{g}	fs	633–2460	71.4	18.2	6.1		22.9
	ws	600–2430	63.4	8.6	4.4		2.9
smoothness (PPS, 1 MPa)^{l}, µm		0.7–0.8				1.0–1.2	
roughness (Bendtsen),	fs	22	90	273	702		113
mL min^{-1h}	ws	20	114	469	838		> 500
specific bending stiffness, Nmm^{i}	MD	0.06	0.12	0.37	0.39		37.8
	CD	0.03	0.04	0.19	0.18		13.1
brightness,%^{j}	fs	73.1 (76)^{m}	55.9	84.6		66–67	81.5
	ws	72.3 (76)^{m}	56.3	84.6			
opacity, %^{k}		92–92.7	96.5	90.5		88–93	88–93

MD = machine direction; CD = cross machine direction; fs = felt side; ws = wire side; b, ISO 536; c, ISO 543; d, ISO 1924; e, DIN EN 21974, SCAN/P11:96; f, ISO 5758–01; g, DIN 53 107–00; h, 8791/2–90; I, 5629; j, 2470; k, ISO 2471; l, ISO 8791; m, brightness D65 R457 (UV).

Table 11.3 Moisture content of selected types of paper in equilibrium with various levels of humidity at 23 °C.

Type of paper	Basis weight, g m^{-2}	Relative humidity, %		
		20	50	75
newsprint	50	6.5	8.5	10.0
gravure printing	65	6.0	8.0	9.2
offset, mechanical	80	5.2	6.4	7.9
offset, wood-free	80	5.0	6.3	7.5
art paper, mechanical	120	4.1	5.7	6.9
art paper, wood-free	120	3.8	5.3	6.5

quickly at the beginning and slows down later. For this reason, paper should be processed in rooms in which the climatic conditions are favorable for the particular paper property required. The paper must be in equilibrium with the climate in the room and the climatic conditions must be kept largely constant. The testing of paper requires the establishment of testing climatic conditions (standard climate: 23 °C, 50% relative humidity, cf. Section 11.2.2.1).

Paper is an anisotropic material with regard to many physical properties. This anisotropy is due to the anisotropic properties of the individual fibers, which result from the fibrillated microstructure of the fiber rather than the fiber shape [7]. As a result of the fibrillated structure, the fiber can accept, for example, high tensile forces in the direction of the fiber axis with low elongation; however, even small tensile forces acting perpendicular to the fiber axis cause high elongations.

During drying the fiber shrinks in the axial direction by only about 1 to 2%. In comparison, shrinkage in the direction perpendicular to the fiber axis (radial direction) reaches about 30%. If the fibers in a paper sheet were completely randomly oriented sheet shrinkage in all directions would be equal and mainly governed by the low longitudinal fiber shrinkage. The more the fibers in a sheet are oriented in one direction the higher sheet shrinkage will occur in the direction perpendicular to the main fiber orientation. This is due to the increased influence of the larger radial fiber shrinkage. The fibers in a paper produced on a paper machine are not aligned randomly, the machine direction is usually preferred (anisotropy of fiber orientation). Furthermore the fiber mat is passed through the paper machine under tension, which prevents free shrinkage of the fibers during drying, mainly in the machine direction. Restraining forces in the cross machine direction are lower and nonuniform across the width, being smaller at the edges. This results in a nonuniform cross machine profile of shrinkage.

Both fiber alignment and shrinkage restraints are responsible for the anisotropy of the moisture expansion of finished paper, which is generally far lower in the machine direction than in the cross machine direction, the latter being nonuniform across the width. Both the above factors also affect the load – deformation properties (strain-to-stress) of paper, which are therefore also anisotropic (cf. Table (11.2)).

Many papers exhibit an anisotropy with respect to their composition in the normal direction (z-direction). The process technology of production on the fourdrinier wire is responsible for this phenomenon. On the wire side, substances (fillers and fines) that can pass through the wire are washed out, while on the other side, they are retained by the fiber mat. This results in different smoothness properties on the two sides of the paper, also known as the two-sidedness of paper. Two-sidedness of paper can be minimized by twin wire formers. A further anisotropy in the z-direction results from frozen stresses during nonsymmetrical drying of the web at the top and bottom sides. As a result of the in-plane anisotropy of the sheet, the machine direction must be considered and marked when taking samples for testing anistropic properties, such as strength. Two-sidedness is important in the testing of printability, for example. Therefore top and bottom sides have to be marked as well.

Finally, paper has viscoelastic properties [8, 9], i. e., it can be elastic like a solid or viscous like a thick liquid. The viscoelasticity is also a result of the superimposition of the properties of the individual fibers and those of the fiber network. The viscous flow of the individual fibers is caused by the sliding of fibrils at high tensile loads. The individual fibers exhibit elastic behavior at low tensile loads. In the fiber structure of paper, the sliding of fibers at fiber intersections results in a flow effect and the paper undergoes plastic deformation. A characteristic feature of viscoelasticity is the dependence of the onset of flow on the loading rate. Small loads acting over long periods of time result in flow, whereas large intermittently acting loads cause only elastic deformation. Therefore, in the determination of the tensile strength of paper, the time is fixed within which the tensile stress applied causes the paper to break.

11.1.3
Summary

The material paper has essentially four characteristic features: inhomogeneity, hygroscopicity, anisotropy, and viscoelasticity. These features must be taken into consideration in the testing of paper (cf. Table (11.4)). The magnitude of these features depends on the type of fiber, the fiber raw material, the pulping process, and on the process techniques used in stock preparation and papermaking. Consequently, there are a large number of variables in papermaking and many degrees of freedom are involved in the adjustment of the desired paper properties. Therefore, several different paths can usually be followed to obtain papers with comparable technical properties. This is of importance in the standardization of paper properties. Only the technical characteristics may be stipulated in each case, but not the process used to realize these characteristics, otherwise, there would be the danger of excluding new technologies and impeding technical progress.

Table 11.4 Characteristic material properties and their effect on testing conditions.

Property	Effect
inhomogeneity	sample dimensions, number of measurements
anisotropy	testing direction
two-sidedness	tested side
hygroscopicity	relative humidity, temperature
viscoelasticity	duration of test

11.2
Types of Paper, Board and Cardboard [10]

Paper and board are planar products made essentially from fibers that are mostly of plant origin, and different portions of fillers. Fillers are mainly inorganic substances, their content in the product may vary from zero to about 40%. Paper and board are formed by draining a fiber suspension through a sieve. The resulting fiber web is subsequently compacted and dried.

There are approximately 3000 kinds of paper and board products [11]. Most products with a basis weight up to 225 g m^2 are defined as paper. Above 225 g m^2, these products are usually called board, but the naming overlaps.

Depending on their use the paper and board grades can be divided into four main groups:
1. graphic papers
2. packaging paper and board grades
3. hygienic papers
4. specialty paper and board grades.

This classification has also been largely adopted by the Statistisches Bundesamt (Federal Statistical Office) of Germany in Chapter 48 of the “Commodity index for foreign trade statistics” [12]. The basis of this systematology is a “harmonized system for the marking and coding of merchandise” of the “council for tariff cooperation”.

11.2.1
Graphic Papers

The term graphic papers refers to a large range of different papers that are suitable for printing and writing and are made from virgin or recycled fibers or mixtures of them.

11.2.1.1 **Printing and Press Papers** [13]

Printing and press papers are divided into the following four subgroups:

1. newsprint
2. wood-containing natural printing papers
3. Wood-free natural printing papers
4. Coated printing papers (wood-containing and wood-free).

11.2.1.1.1 **Newsprint**

Newsprint represents an important subgroup. It consists primarily of a mixture of primary and secondary fibers (0–100 %). The primary fibers include groundwood and small amounts of chemical pulp, which are used to increase strength. The main field of application is newspaper production. Other uses are, e. g., paperbacks, calculating-machine rolls, and interleafing paper.

Newsprint has a basis weight of 40–49 (in certain cases up to 54) g m^{-2}. It is machine-finished or supercalendered. Standard newsprint should have an ISO brightness of 57–60 %.

Improved newsprint has a high filler content and is calendered to obtain a more closed surface. It is used, e. g., for book and offset printing. The ISO brightness is about 10 units higher than the mean brightness of standard newsprint [14].

11.2.1.1.2 **Wood-containing Natural Printing Papers**

The term wood-containing indicates that these printing papers consist mainly of mechanical pulp along with chemical pulp, while “natural” refers to the fact that they are not coated. Fillers, e. g. kaolin or calcium carbonate, are used to produce high smoothness and good opacity. This important group of printing and press papers includes gravure printing paper, also called SC paper (supercalendered). Here SC-A+, SC-A, SC-B and SC-C are the subgrades (with decreasing quality demands).

Natural magazine papers have high lignin content, are filled and highly supercalendered. Their main use is the production of magazines and catalogs.

Gravure papers (SC-A. SC-A+) have the same properties as natural magazine paper, they are specially suited to gravure printing. ISO brightness is > 67 %.

Improved newsprint (SC-B, SC-C), improved for gravure printing containing up to 25–30 % recycled pulp has the same properties as natural magazine paper; ISO brightness is < 67 %.

SC offset paper has the same properties as natural magazine paper. The ISO brightness is > 67 % and the surface strength is optimized for offset printing.

Wood-containing thin printing papers have a basis weight of ≤ 45 g m^{-2}. They are used for telephone, railroad timetables, and address books.

Book papers are used in the production of books. They have a groundwood content of 5–20 %. The filler content depends on the desired specific volume.

Voluminous book papers are produced with a ≥ 1.4-fold specific volume compared with book papers.

Supercalendered writing papers are wood-containing natural papers that are sized and supercalendered. They can also be made from recycled fibers.

Machine-finished offset papers are supplied in sheets or rolls.

Wood-containing coating base papers and boards are intended to be further processed into coated papers or boards.

11.2.1.1.3 **Wood-free Natural Printing Papers**

Wood-free natural printing papers consist almost exclusively of chemical pulp. The proportion of fibers from mechanical pulp should not exceed 5 %. Wood-free printing papers do not yellow to any appreciable extent and have a high strength. This is the main difference between these papers and the wood-containing grades described above. The papers are uncoated and normally leave the paper machine in a machine-finished state. For certain printing processes these papers can be machine-finished or further calendered on a supercalender. This group of papers includes:

Wood-free, machine-finished natural printing papers with basis weights of ≤ 80 g m^{-2} (Group 1), 81–149 g m^{-2} (Group 2) and ≥ 150 g m^{-2} (Group 3).

Wood-free, supercalendered natural printing papers with basis weights as described for machine-finished papers.

Letterpress printing papers are particularly suitable for books (specific volume is ≥ 1.4 fold).

Wood-free bible, thin printing papers and thin letter papers can be rag-containing or rag-free. They are highly filled to give good opacity. The basis weight is in the range below 40 g m^{-2}.

Coating base papers for printing papers and boards are intended to be further processed into coated papers or boards.

11.2.1.1.4 **Coated Printing Papers**

These represent the largest group within the printing and press papers. Here the base paper is finished by the application of one or more layers of coating color to both sides of the paper web, which imparts a closed surface to the printing papers (see Chapter 7). These papers are supercalendered and supplied with a dull or glossy surface. They are described as wood-containing or wood-free, depending on the raw materials used. The wood-containing, coated printing papers represent the largest part and the LWC papers (light weight coated), in turn, make up the main part of this subgroup. Basis weight varies for LWC from 35–80 g m^{-2}, for MWC (medium weight coated) from 70–130 g m^{-2} and for HWC (high weight coated) from 130–170 g m^{-2} (basis weight figures include base paper plus coating weights if not stated differently).

Examples include:

Wood-containing, two-sided coated papers. Typical coating application is 5–13 g m^{-2} per side. Base paper basis weight is 29–36 g m^{-2}. Main areas of application are magazines, catalogs, and job printing with total basis weight of 39 g m^{-2} (ULWC).

Wood-containing LWC paper is coated on both sides; basis weight is ≤ 80 g m^{-2}. It is suitable for gravure printing and roller offset printing.

High weight coated (*HWC*) *papers* differ from other coated, mechanical pulp dominated paper grades in their higher coat weight. Traditionally they are produced at a basis weight of 100–135 g m^{-2}. They compete with coated fine papers in such end use areas as high-quality magazines, catalogs, and magazine covers as well as in the area of direct advertising. HWC papers can be double or triple coated.

Wood-containing consumer papers, coated on both sides have a minimum groundwood content of 50% and typical coat weight of 3–14 g m^{-2}.

Wood-free, two-sided coated papers (*WFC*). The coating application is 3–14 gm^{-2} per side and the basis weights vary between 55 and 170 g m^{-2}. The fields of application are magazines, catalogs, books, direct mail, labels.

Wood-free medium weight coated paper (*MWC*) is coated on both sides and has a basis weight of 72–120 g m^{-2} and typical coat weight of 12–25 g m^{-2}.

Art papers represent one of the highest quality printing papers and are used for illustrated books, calendars, and brochures. The basis weight varies from 100 to 230 g m^{-2}. Art papers are produced with matt or glossy finish. The coat weight varies from 20 to > 40 g m^{-2} per side. Art papers are almost exclusively available in sheets. They are triple coated, usually first with a precoater and thereafter with a double blade coater.

Pigmented papers, film coated offset (*FCO*), have a coat application of 5–10 g m^{-2} per side and basis weights of 45–65 g m^{-2}. Wood-containing or wood-free coating base paper can be used for their manufacture.

11.2.1.2 **Office and Administration Papers**

These papers offer a wide spectrum for very different areas of use, e.g., writing papers, papers for data printing, papers for forms, copy and duplicating papers, envelope paper, postcard board, self printing papers, refined papers for offset printing, blueprint papers, work drawing paper, bank notes, documents, and map paper. These printing and writing papers and the corresponding base papers are the papers that are used predominantly in offices, administration, and schools.

Examples are:

Data papers and boards are used for the manual, mechanical, electronic, and magnetic recording of data and its input and output.

Bookkeeping transparent paper is made from a highly beaten stock and is therefore transparent.

Account book paper or paper for bookkeeping machines is wood-free, highly supercalendered, and fully sized.

Paper for continuous forms is wood-containing or wood-free and often contains recycled fibers, usually machine-finished reeled paper.

Index board is wood-containing or wood-free, supercalendered, single-layered board that can also contain recycled fibers.

Writing papers are used almost exclusively for manual writing. They are supercalendered and can contain varying amounts of rags. This group also includes handmade papers, moldmade papers, bond, and air mail papers.

School writing paper is a machine-finished, highly sized paper with a basis weight of 60–80 g m^{-2}.

Air mail paper is light-weight (25–30 g m^{-2}) wood-free, often rag-containing paper with high opacity.

Carbon copy paper is well sized, has a basis weight between 23 and 30 g m^{-2} and is used in the copying of letters and manuscripts.

Carbonless copy papers contain color forming reagents, which produce a contour-true copy when subjected to pressure (exerted on underlying sheets).

Correspondence envelope paper can be made from a wide range of stocks, from 100 % recycled fibers to 100 % virgin fibers. This paper is used exclusively in the production of envelopes and mailing bags.

Kraft paper is used to make envelopes and mailing bags and is made from unbleached or bleached kraft pulp.

Envelope lining tissue is an intensely colored, sometimes dip dyed, wood-free tissue paper with a basis weight of 22–30 g m^{-2}. It is used for the lining of expensive envelopes.

Base paper for diazotype is wood-free, has a basis weight of 55 to > 200 g m^{-2} and is used in the making of blueprint papers.

Copying papers are used for copying and nonimpact printing. Basis weight varies between 70 and 90 g m^{-2} and ISO brightness between 80 and 96 %. The most important properties for a copying paper are smooth run in a copy machine and good dimensional stability. It must not show curling or cockling and retain dust when copying. It is mainly made of 90–100 % virgin chemical pulp fibers, but it may contain recycled fibers up to 100 %. The recycled fibers used are mainly from recovered newspaper, magazines and copying paper. Total filler content varies between 10 and 25 %.

Digital printing papers (*synonymous with electronic printing papers*) are a rapidly growing group predominantly made from chemical pulp. They are mainly uncoated, but increasingly coated, fine paper grades. The bulk of this paper is delivered in sheets.

The major categories of nonimpact printing the papers have to suit are electrical charge based methods, magnetic methods, thermal methods and ink-jet methods. The requirements vary by printing method. In *electrophotography*, the runnability of the paper is critical. The electrical conductivity as well as the electrical resistivity of the paper should be sufficient. Moisture content and friction are also important properties. Other required characteristics are good dimensional stability to avoid curl and cockle for example, surface strength and surface smoothness, especially for high resolution printing. Chemical properties of the paper surface such as surface energy are important for fixing the toners to the paper. In *ink-jet printing*, papers require characteristics that are matched with the inks and the ink drop size. First, ink-jet papers must be smooth. They must have sufficient and uniform porosity, with small pores, in order to absorb the solvent quickly and to counteract the spreading tendency. Dimensional stability is also important to avoid cockling and curling. Typical uses for digitally printed products are manuals, price lists, and various direct mail materials, but also low-volume paperbacks and hard-cover books. Black-and-white applications cover more than 80% of digital paper needs at present. Basis weights vary a lot, from 40 to as much as 400 g m^{-2} [10].

Copy base papers are wood-free. They can be finished to e.g., thermocopy, and photocopy papers with a wide basis weight range of 50 to 180 g m^{-2}.

Base papers for offset films are predominantly wood-free papers that are used for making paper offset plates.

Carbonizing base papers are carrier papers for a wax-bearing color mass. They are used for the production of carbon and blue papers (basis weight range of the coating is 10 to 14 g m^{-2}).

One-time carbon (OTC) base paper is used in the production of one-time carbon paper (basis weight range is 16 to 24 g m^{-2}).

Multiple carbon base papers are used in the production of multiple carbon or blue papers.

Base papers for nonimpact printing processes are predominantly wood-free and are specially suitable for nonimpact printing processes (thermosensitive, electrosensitive, thermostatic papers). Basis weights range from 50 to 180 g m^{-2}.

Blotting papers are wood-containing or wood-free, white or colored, and sometimes have veined fibers. They possess a very high absorbency and wetability. Basis weight range is from 35 to 350 g m^{-2}.

Security, banknote, and archival papers are wood-free and/or rag-containing or linters-containing. These heavyduty, nonaging papers are suitable for color printing and can be made resistant to forgery, e.g., by means of a watermark. Basis weights range from 60 to 80 g m^{-2}.

Map and nautical chart papers are wood-free, dimensionally stable, and are used for printing of maps and sea charts (basis weights from 70 to 120 g m^{-2}).

Letterpress board is wood-containing or wood-free and may contain recycled fibers. It has a basis weight of > 150 g m^{-2} and is supercalendered.

Picture postcard board is wood-containing or wood-free and is used for picture postcards (basis weights from 150 to 300 g m^{-2}).

Letter file cardboard is solid fiber board used in the production of files. It is multilayered, vat-lined or unlined and has a basis weight of 1000–2000 g m^{-2}. Special requirements are that it should be exactly planar, and have a precisely maintained moisture level.

Filing board is a special, tough board which is usually colored and supercalendered (basis weights from 130 to 900 g m^{-2}).

Ticket board is wood-containing or wood-free and often colored. It is used, e.g., for streetcar tickets, entrance and weighing tickets. Ticket board is produced in accordance with regulations issued by the railroad authorities.

Fancy cardboard can be pasted or unpasted and is often wood-free, e.g., ivory, bristol, and opaline board. It is used in the production of visiting cards, invitations etc. Basis weights range from 100 to 400 g m^{-2}.

11.2.2
Packaging Paper and Board Grades

11.2.2.1 Overview

A large number of grades of paper and board are available for packaging and are employed for many different purposes.

Packaging paper grades range from simple wrapping paper (WP, made from mixed recovered paper) to kraft paper, and are predominantly supplied in rolls. They are made from various virgin pulps (sulfite/kraft pulp), from recycled fibers or from mixtures of chemical pulp and recycled fibers. These grades are employed in the production of bags, beer mats, carrier bags, gift wrapping paper, etc. Some examples are:

For the foodstuff sector, for instance, special types of paper and board are produced which must fulfil the requirements of the food laws. These papers are also widely used in the nonfood sector, e.g., as coating papers. The possibilities of combination with each other and with other materials (plastics) are numerous. In this way, special packing materials can be produced for most packaging purposes. *Greaseproof papers*, e.g., are used for the packaging of butter, margarine, meat, and sausage. These papers include vegetable parchment and glassyne, and are provided with barrier polymers.

Kraft liner or *test liner*, and *corrugating medium* are the base for corrugated board production. Depending on their intended purpose (for the smooth surface or the corrugated inner layer of corrugated board), these papers are produced with varying strength, stiffness, wet strength, and printability.

Folding boxboard is ideally suited for the production of folding boxes because of its properties, such as good scorability, creasing ability, groovability, and printability. This board can be coated or uncoated; the former gives a better printed format.

Machine-made board (also solid fiber board) is produced almost exclusively from recycled fibers and is processed primarily into mailing boxes.

For all paper and board grades described above, the stock is adjusted to meet the requirements in each case.

11.2.2.2 Packaging Papers

11.2.2.2.1 Kraft Papers

In order to meet the high strength requirements, these papers consist of primary or a mixture of primary and secondary fibers of kraft pulp. They are used predominantly for packaging purposes.

Kraft sack paper (60–115 g m^{-2}), bleached and unbleached, includes kraft bag asphalt base paper which is used in the production of asphalt paper.

Extensible kraft sack paper (*Clupak*) corresponds to the kraft sack papers. It has a higher elongation (> 6%) in the longitudinal direction. It can also be used as base paper for plastic coating (45–350 g m^{-2}).

Secondary kraft sack paper (70–350 g m^{-2}) is made from at least 50 % unbleached kraft primary fibers.

Kraft packing papers (40–350 g m^{-2}), are made of slightly bleached, unbleached, or bleached fibers and must contain 80 % primary fibers.

Kraft tissue, bleached or unbleached, has a basis weight of < 30 g m^{-2}. It is a one-sided smooth or fluted kraft paper that is employed for wrapping glass or metal goods; it is also suitable for packing fruit, e. g., oranges.

11.2.2.2.2 **Sulfite Wrapping Paper (ZP)**

The stock composition of this paper is on average 70 % primary fiber pulp and not more than 30 % fibers from recovered sulfite or kraft paper. The basis weight is > 30 g m^{-2}.

Wrapping papers (*WP*) consist of mixed recycled fibers of varying composition; they may also contain chemical pulp (30 g/m^2–350 g/m^2).

Crepe packing material is a highly sized and creped packing paper of any stock composition (70–350 g m^{-2}).

Mixed soda pulp-paper is made predominantly from secondary fibers and kraft pulp (70–35 g m^{-2}).

Glassyne (20–40 g m^{-2}) is a highly supercalendered paper made from strongly beaten pulp. It is largely greaseproof, but not water resistant. The high transparency is achieved by intensive supercalendering. It is frequently colored. This paper is used, e. g., as wrapping paper for chocolates, covering paper in photograph albums, for dust jackets, envelope windows, and for packing high-quality preserves.

Supercalendered base paper for waxing is designed to be waxed and frequently contains titanium dioxide as filler. The waxed paper is often used as wrapping paper for candies (30–150 g m^{-2}).

Silicon base paper (30–160 g m^{-2}) is a supercalendered paper to be used for siliconization.

Greaseproof paper (40–200 g m^{-2}) is made resistant to grease primarily by using a special beating process (high fibrillation) and by the addition of auxiliary agents. In comparison with vegetable parchment, this paper is neither waterproof nor boilproof.

Parchment base paper (35–200 g m^{-2}) is unsized, highly absorptive and is made of 100 % chemical pulp fibers. It contains no chemical auxiliary agents and is employed in the production of parchment paper.

Vegetable parchment [15] is a highly waterproof, greaseproof, boilproof paper product of high purity. It is used in the packing of fats, also in combination with aluminum foil or with a plastic coating. Silicon-coated parchment paper has a wide range of applications, e. g., baking paper, antiadhesive papers, etc. Basis weight is 40–130 g m^{-2}.

Coated papers are often coated on one side and are suitable for offset and gravure printing. They can be painted, bronzed, and punched. They are waterproof and alkali resistant to prevent the detachment of labels in washing machines. They are used, e. g., as wrapping paper for chocolates, cigarettes, soap, and as dust jackets for books and records (70–20 g m^{-2} with a coat weight of 9–15 g m^{-2}).

Coated packaging papers (80–200 g m^{-2}) are bleached kraft papers having a one-sided matt or glossy coat and are suited for the production of bags and carrier bags.

11.2.2.2.3 **Corrugated Papers**

These papers include:

Kraft Liner (115–440 g m^{-2}). This covering paper is made of at least 80% kraft pulp, bleached or unbleached, and has a bursting strength per basis weight (bursting index) of 3.43 kPa m^2 g^{-1}.

Kraft-faced liner is a covering paper that does not have a specified stock composition, but it has guaranteed strength properties.

Two-layer paper is a double-layered covering paper.

Semichemical paper is corrugated paper made of at least 65% semichemical pulp.

Fluting or corrugating medium (80–200 g m^{-2}). The corrugated medium used for the production of corrugated board has no specified stock composition; however, definite strength properties are required.

11.2.2.3 **Board and Cardboard**

Paperboard grades can be classified into three categories: cartonboards, containerboards, and specialty boards. The classification used is shown in Fig. 11.1.

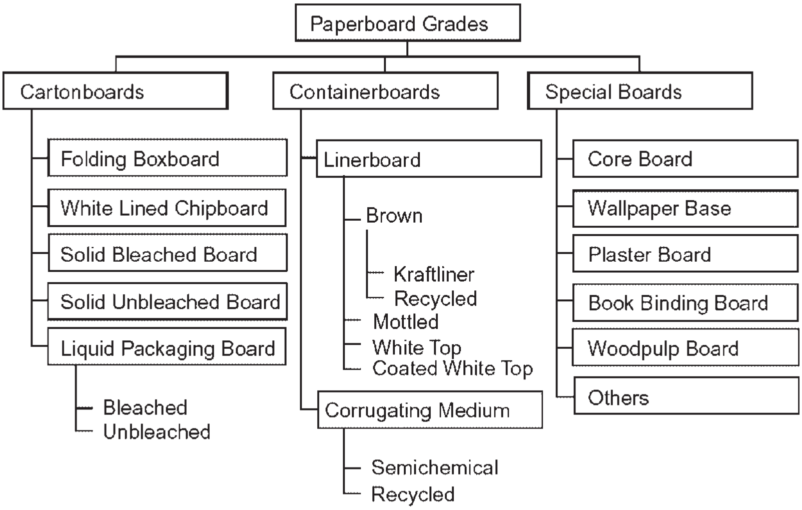

Fig. 11.1 Classification of paperboard grades.

As stated in the introduction the terms paper and board overlap as regards basis weight, so many linerboard and corrugating medium grades have a basis weight lower than 100 g m^{-2}, and recently even down to 80 g m^{-2} and less. Products with basis weight > 600 g m^{-2} are usually called cardboards. Most of the paperboard grades are multiply products like folding boxboard and liquid packaging board whereas corrugating medium is very often a single-ply product.

Paperboards are very often used for packaging, but again there are exceptions like plasterboard. Because of their function in the packages, strength properties are most often very important for paperboards. Cartonboards are mainly used for consumer product packaging such as food, cigarettes, milk, and pharmaceuticals. Containerboards (corrugated boxes) are used in many packaging applications starting from simple transportation containers and ending with multicolor printed display containers for stores.

The following board types are included in the group of folding boxboard:

Coated pulp board made from bleached chemical pulp is usually used for folding boxes.

Cast coated pulp board is used for high-grade packaging and for folding boxes, fine pasteboard boxes, paperback covers, etc.

Chromo board, chromo duplex board, chromo triplex board have very different stock compositions, depending on their intended purpose.

Artificial chromo board, triplex board, a gray core can also be used in this case.

Other machine-made boards in the cartonboard group include:

Mechanical pulp board which has a light or gray core. It is used, e.g., in the production of paper plates and round cheese boxes.

Brown mechanical pulp board is made predominantly from recycled fibers and has a brown colored cover and reverse. It is used for the production of mailing boxes.

Chipboard consists predominantly of recycled fibers and is employed for the production of mailing boxes, box lining, etc.

Pasted board consists of two or more layers of mill board that have been pasted together in the dry state.

Sheet-lined board is made from mill board. It may also be pasted, is lined on one or both sides with paper, and is used for high-grade packaging.

Mill board is made by winding one or several fiber webs on a press roll. Thus, high basis weights and the production of especially stable packaging material are possible.

Cartridge papers and boards are usually made from recycled fibers and are used in the production of cartridges, special cartridges, cardboard tubes, and containers such as detergent drums.

Board for cups is a single layered hard board consisting of bleached pulp and is used for the production of drinking cups, etc.

11.2.3
Hygienic Papers

The major component of all hygienic papers is tissue. The term “tissue” describes products made from lightweight, dry creped (sometimes wet-creped or noncreped) papers such as toilet paper, kitchen towels, handkerchiefs, facials, napkins, hand towels, wipes. Such kind of products are made from a one-ply, semi-finished, wet-laid tissue base paper, that is predominantly composed of natural fibers. The origin of the fibers may be virgin or recycled. Usually the basis weight of the base paper before creping is 10–20 g m^{-2} which is increased during creping by 10–20%. Tissue is usually used in multiple layers because of its low basis weight. Cellulose wadding and crepe paper also belong to the group of tissue papers whereas nonwovens (predominantly air-laid products) do not.

11.2.3.1 Cellulose Wadding

This is a loosely structured, highly absorbent fiber product. It is made from virgin fibers. Its use includes the production of sanitary towels, surgical artificial cotton, patients’ sheets, and packing cotton.

11.2.3.2 Tissue

Tissue is made of virgin or recycled fibers (or a mixture), with fine, soft creping and closed formation. The basis weight is < 27 g m^{-2}. Tissue has to meet a wide variety of requirements, for instance surface softness, liquid absorbency, tensile energy absorption as shown below. The highest quality tissue is made on machines with a through-air drying system (TAD, Section 6.11.4) or other soft tissue producing systems. Tissue is employed in the production of :

Toilet paper (*bathroom tissue*) is the biggest single product made from tissue. It is made in one, two, three or five plys with or without moderate wet strength, because this type of tissue has to disintegrate in the sewage system. Toilet paper should be smooth and can be embossed, unprinted or patterned, tinted, purely white or off-white.

Kitchen towels are the second biggest product for the consumer sector. Kitchen towels usually have a basis weight of 20–24 g m^{-2}. Sheets are 220–280 mm wide and 250–280 mm long. The number of sheets to a roll is normally between 54 and 100.

Most kitchen towels are two-ply. Good wet strength and high water absorbency behavior are the most important functionalities.

Facial tissue and handkerchiefs have the lowest basis weight of 14–18 g m^{-2}. The surface is often made smoother by light calendering or softening additives. Facial tissue is usually two-ply while handkerchiefs are two- or three-ply. Because of the high quality requirements, the base tissue for most facial tissues and handkerchiefs is made either entirely from pure chemical pulp or from a mixture of pure chemical pulp and selected recycled fiber. Handkerchiefs can be one-, two-, three-, or four-ply and must have good air permeability, absorbency, wet-strength and burst strength.

Serviettes can be one-, two-, three- or four-ply. The size and type of fold vary greatly.

Diapers and sanitary towels covers have additive functionalities which are supported by a special water absorber.

11.2.3.3 Crepe Paper

Crepe paper is a single-layered, highly absorbent hygienic paper made from groundwood and/or secondary fibers. The basis weight is $> 27\ \mathrm{g\,m^{-2}}$. The most important uses are toilet paper, paper handkerchiefs, and cleaning rolls.

11.2.4

Paper and Board for Technical and Specialty Uses

This group of paper and board covers a wide range of grades. The most important subgroups comprise base papers for decor, priming and barrier foils, body, coating and soakage base papers and base papers for wallpaper, papers for electrotechnical purposes, drawing paper, photographic base paper, cigarette paper, filters and filter layers and special cardboards for the various branches of industry, e. g., pressboard (pressspan), car body and shoe cardboard. All these papers and boards have a common requirement; they must exactly fulfill defined quality criteria according to the use. *Chromatography papers* are porous, absorbent special papers made from linters without the addition of sizing or filling agents. They are often acid washed and contain silicon compounds to render them hydrophobic.

Reagent and indicator papers are high-grade special papers used for impregnation with test reagents and indicator dyes.

Household filter papers are wood-free special papers that give a defined rate of filtration. They must comply with food laws. They are used, e. g., for coffee filters. The rate of filtration and the separating ability depend on the degree of fiber beating.

Analytical and industrial filter papers are usually made from cotton, dissolving pulps, glass microfibers or other artificial fibers. They possess a uniform stock distribution and, thus, a homogeneous pore size. Analytical filters are acid washed and are made without paper making additives. Filter layers with a basis weight of up to about $750\ \mathrm{g\,m^{-2}}$ are produced to withstand special stress, e. g., in the beverage industry. Filter layers of this type, that are also used for sterilization filtration, must comply with food laws. For industrial use, the paper and filter layers may also be impregnated with melamine-urea resins or similar compounds.

Filter mass is made from soft-cooked, highly bleached pulps or from rags or linters and is used in the form of flocks for industrial filtration.

Cable and condenser paper (capacitor tissue paper) is stiff, nonporous paper made from pulp and is usually impregnated with artificial resins. These papers contain neither fillers, metal impurities, nor salts. The absence of pores is achieved by fine beating of the pulp fibers and by supercalendering. Cable paper must exhibit high strength in the longitudinal direction. The thickness of condenser paper is 0.006–0.012 mm and the basis weight is 6–7 g m^{-2}. These papers must meet IEC regulations [16].

Pressspan is a single-layered, highly rigid product that is made from pure pulp and couched in the wet state. When used in the electrical industry, the pulp must be produced with a high degree of electrochemical purity.

Building papers and boards include: *roofing felt base*, a wool-felt board (reclaimed wool) impregnated with tar/bitumen and used to produce roofing sheets. *Felt and wool-felt board* made from recycled fibers and rags. They are used as the base material for textile floor coverings and as insulating material in various fields, predominantly in the automobile industry. They are also employed as separating layers on flat roofs that are covered with a plastic foil. *Gypsum liner board* used for the production of gypsum wallboards (building plates).

Covering papers and cardboards, this general term describes various papers and cardboards that are used as protective coverings. These single-layered or multilayered materials can be made from various raw materials. They are used, e. g., as covering papers in road construction.

Substrate papers, saturating base papers, and coating base papers. Substrate papers are used in many different technical systems as manufacturing aids. They are frequently removed from the finished product at the end of the production process, rewound and reused in the same process. *Saturating base papers* must be absorbent and have wet-strength and often also resistance to organic solvents. *Coating base papers* must be moisture resistant and stable to organic solvents. One or both sides of the paper are treated with various solutions or dispersions, which represent the requirement for the desired coating.

Raw material for artificial leather is tough kraft paper that is not dyed and is usually moisture resistant. It forms the web base for the production of artificial leather.

Base paper of vulcanized fiber is absorbent, voluminous paper made from cotton rags, cotton linters, and refined pulps.

Photographic base paper. A suitable base paper for the production of photographic paper is a moisture resistant, dimensionally stable, chemically neutral chemical pulp paper that is free from traces of iron or copper. Today, papers coated with a thin polyethylene foil on both sides have replaced barite paper. This paper is used for the uptake of light-sensitive emulsions.

Saturating base paper (overlay paper) is made from special pulp and has basis weights of 15–40 g m^{-2}. It is highly porous, free of dirt, and protects the underlying decor in the production of laminated products.

Decor base paper is a soakage base paper made from bleached or unbleached kraft pulp; it is used for resin absorption in the production of laminated plates.

Base papers for abrasive papers are tough, sized papers made from kraft pulp and are coated with an abrasive.

Calender bowl paper is strong, compressible, heat-resistant paper used for the manufacture of calender bowls.

Technical drawing paper. This group includes the following: *Opaque drawing papers* are fine look-through papers made from pulp and have good sizing and hardness. Erasability is the most exacting demand. *Translucent drawing paper.* A distinction is made between natural transparent paper and paper made transparent by chemical treatment. Natural transparent papers are made from pulp, linters, or mixtures of the two by intensive beating of the fibers. They are well sized and exhibit good surface smoothness and look-through. Opaque papers are rendered transparent by soaking them in a solution of synthetic resin. *Sketching papers* are wood-containing or wood-free, machine finished, sized natural papers with a basis weight ≥ 80 g m^{-2}. *Art drawing papers* and board are suited to special drawing and painting techniques, e.g., watercolor paper. The latter has a rough surface which accepts water colors but does not allow their penetration. This material also has good erasability.

Base paper and board for wallpaper. This is the general name for papers and boards that are suitable for the production of wallpaper [17]. They can be single- or multilayered, couched or pasted, wood-containing or wood-free, coated or uncoated. They may contain recycled fibers and may have a woodchip coat. Strip-off wallpapers or preglued wallpapers can also be produced.

Papers for tobacco products. Imitation cork paper is a brownish yellow colored paper used for the production of cigarette tips. It has an imitation cork imprint and joins the filter to the tobacco stick. *Filter encasing paper* is used for the production of acetate and/or cellulose filters. *Cigarette paper* has a high filler content and a basis weight of 18–28 g m^{-2}. To control the smoking properties, this paper has a porosity that is suited to the type of tobacco and contains additives that regulate burning. *Cigar or cigarillo casing paper* holds the chopped tobacco together and serves as the inner casing.

Long-fiber paper is used for tea bags and artificial sausage skin and is made from fibers having an average length of > 3 mm. The addition of synthetic fibers is permitted.

Binding papers are tough, wood-free papers that are frequently embossed.

Cover paper and board is tough, elastic, durable, wood-free white paper or board that has a linen finish and is specially suited to the production of covers for brochures, paperbacks or similar products.

Bookbinding board is press rolled or mill cardboard that is pasted or unpasted and has high rigidity, dimensional stability, and perfect lining ability.

Car body cardboard is a hard cardboard used predominantly as shaped parts in automobile manufacture; it is usually capable of being cupped.

Leather fiberboard is an especially tough hard cardboard that is flexible and resistant to moisture.

Suitcase board is an embossed hard cardboard used in the production of luggage.

Flong is a coated cardboard (solid board) made from very high-grade stocks (rags). It is processed with fillers and is completely knot-free and can be subjected to hot embossing. It is used to produce the matrices for high-pressure dry stereotyping.

Cardboard for beer mats is a highly absorbent groundwood cardboard that may be pulp covered. It can be punched, embossed, and printed.

Base papers for chart paper have a basis weight of 30–130 g m^{-2} and are usually filled and sized. They have a refined surface and good dimensional stability.

Gardener, flower, and decoration crepe. Gardener's crepe is a white or colored, highly expandable paper that has longitudinal grooves and serves as decorative flowerpot wrappers. *Flower crepe paper* is wood-free and is used to make artificial flowers. *Decoration crepe paper* is flameproofed by impregnation with chemicals and is used for decorations of various types.

Board for playing cards is made of two or three layers pasted together. It is coated on both sides, has a supercalendered surface, and is sometimes linenized. The basis weight is 280-340 g m^{-2}.

Album board is used for photograph, stamp, and other albums and is often wood-free and voluminous.

Hot setting paper and hot sealing paper are coated on one side, become sticky on heating and can consequently be fixed to another material.

Insect resistant or insecticide paper is resistant to insects. It can kill insects by means of volatile components or by contact.

Antitarnish paper is an impregnated or coated paper that protects other materials against corrosion by releasing substances in the vapor phase or by direct contact.

Photographic protective wrapping (black photo) paper is lightproof, black-dyed, chemically neutral paper that can be folded without breaking and is suitable for wrapping photographic film.

Sterilization paper is a wood-free paper that, even when coated, can tolerate sterilization processes and is used for packing sterilized materials.

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12

Testing of Paper and Board [1–4]

Otmar Tillmann

12.1

General Aspects

The proper selection of relevant analysis and test methods for raw materials, intermediate or final products obviously has importance for the success of a testing program. Process and product analysis are the main areas for a large variety of very heterogeneous testing methods. Process analysis tries to define the control variables of the process that allow it to run smoothly and produce products with the necessary properties. The aim of product analysis is to define the properties that relate to the use of a specific product or material. The test results obtained should be representative for all of the paper from which the sample has been taken. Reliable, representative measuring results require

- representative sampling as far as quality and quantity are concerned
- adequate sample preparation
- calibrated measuring equipment
- careful, accurate measuring.

A straightforward process for cut-size and reel paper is described in ISO 186 (2002).

As a result of its hygroscopic properties, paper and board must be tested under standard climatic conditions and the samples must be conditioned in this climate for at least 4 hours before testing (sample conditioning). In ISO 187 (1990), the preferred climate for paper testing is specified as 23 °C and 50 % relative humidity. In the following the most relevant test methods for paper and board testing will be described.

12.2

Basic Properties

The basic properties of paper include the dimensions and the mass. In the case of sheet material such as paper, the *basis weight* m_A is determined in accordance with

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ISO 536 (1995). The value m_A is the ratio of the mass m to the area A of a sample.

$$m_A = \frac{m}{A}$$

Another basic property of paper is the *caliper*. As paper is compressible the caliper must be defined in terms of the measuring instrument. ISO 534 (2003) specifies an instrument with two parallel planar measuring surfaces of 200 mm^2 which act on the sample with a surface pressure of 100 kPa. The resulting distance between the surfaces is the caliper D of the paper.

The ratio of the basis weight to the caliper is the *density* of the paper. The reciprocal density is the *specific volume*.

The *moisture expansion* of paper, i. e., the change in dimensions with changing ambient climate, is also a basic property. According to DIN 53 130, the moisture expansion (ME) is the ratio of the change of length ΔL of a sample paper strip, resulting from a change in the ambient climate from 23 °C/45 % relative humidity to 23 °C/83 %relative humidity, to the original length L_0. The temperature can also be 20 °C in each case.

$$\mathrm{ME} = \frac{\Delta L}{L_0}$$

The moisture expansion test is standardized in ISO 8226–1 (1994) and ISO 8226–2 (1990).

12.3
Composition and Chemical Paper Testing

The *fiber composition* of paper is determined with a light microscope (fiber microscopy). Due to the varying fiber morphology, both the fiber raw material and the pulping process can be determined. Chemical dyeing methods are used for contrast enhancement and quantitative determination of fiber composition (ZM IV/ 55/74; TAPPI T 401 om-93, Harders-Steinhäuser, Faseratlas).

The term *moisture content* refers to the amount of water in the paper in equilibrium with a defined ambient climate. It is determined gravimetrically in accordance with ISO 287 (1985). A dry sample is produced by drying the paper to constant weight at 105 °C. The moisture content is expressed in percent, based on the moist sample.

Chemical testing is used to determine the components of paper. This is of significance in papermaking for quality control and process control. Another important field of chemical paper testing is the control of papers for the packaging of food.

The entire spectrum of analytical methods used for the chemical testing of paper ranges from gravimetric methods to spectroscopy, electrochemical and enzymatic methods, as well as sensoric tests on taste and odour and microbiological tests.

Most of the testing methods to determine the composition are destructive. The components to be determined must be extracted with water or organic solvents. For example, the resin content of paper is determined gravimetrically in the extraction residue by using an organic solvent as an extracting agent.

The inorganic fillers contained in paper are determined as residue on ignition (ash content). In accordance with ISO 2144 (1997), the sample is ignited at 900 °C until no change in weight is observed. The ignition residue is then determined gravimetrically and expressed as a percentage of the original weight of the sample. Other ignition temperatures are used for chemical pulp (575 °C) and filter papers (800 °C) (DIN 54 370 (1999). Determination of $CaCO_3$ is calculated from the difference in weight loss between 575 °C and 900 °C (CO_2). X-ray microanalysis is employed for the quantitative determination of the types and amounts of fillers. Elements such as calcium, magnesium, and metals in trace amounts can be analyzed by atomic absorption spectroscopy. For the determination of organic substances in paper extracts, IR spectrophotometric and chromatographic methods are applied, e. g., gas chromatography for volatile components and high performance liquid chromatography for thermally sensitive constituents.

Other chromatographic methods are used for the determination of chlorides, nitrates, and sulfates, or for the differentiation and characterization of dyes and optical brighteners.

Apart from the analytical methods mentioned above, the sum parameters are of special importance. These include the ash content, pH (ISO 6588, 2003), electrical conductivity of aqueous extracts (ISO 6587, 1992), and the resin content of paper.

Apart from the ISO standards mentioned above, other standards for chemical testing of paper are, e. g., the ZELLCHEMING, SCAN, and TAPPI test methods.

12.4
Strength Properties

Tensile strength and *strain at rupture* are determined as values characteristic of paper strength (ISO 1924, 1992). The tensile strength together with the sample width gives the tensile strength per unit width, measured in N m^{-1}. Together with the sample thickness the tensile strength can be expressed in kPa. The *tensile index* results from tensile strength per unit width (expressed in N m^{-1} divided by grammage).

In paper technology, the *breaking length* is also of some importance as a calculated value. It is the length of a freely suspended paper strip of any constant width and thickness that just breaks at the point of suspension due to its own weight.

The breaking length L is calculated from the tensile strength force F_B of the paper measured in N, the basis weight m_A, the width of the strip w, and the gravitational constant $g = 9.81$ m s^{-2}.

$$L = \frac{F_B}{m_A \cdot w \cdot g}$$

The *bursting strength* is important in the characterization of packaging papers. The bursting strength of paper is determined in accordance with ISO 2758 (2001) and that of board in accordance with ISO 2759 (2001). In the testing instrument, the free area of the sample stretched in a circular frame is exposed to increasing pressures until it ruptures.

Packing materials are also characterized by their bursting strength. For instance, set values are stipulated in DIN 55 468 Part 1 (1999) for the strength of corrugated boards, and are used for classification. The same standard specifies set values for the *puncture resistance*. This strength property is determined, mainly for cardboard and corrugated board, by measuring the resistance offered by a sample to the penetration of a pyramidal body (ISO 3036, 1975 and DIN 53 142–1, 2003). There is also a puncture test method available (DIN 53 142–2, 2003) which describes a linear penetration of the pyramidal body.

To determine *tear resistance* (Elmendorf), a sample is torn with the help of a pendulum device starting from a predetermined cut. The work required for a tear of a given length is measured. The test is described in ISO 1974 (1990).

Z-directional strength refers to the ability of paper or board to resist tensile loading in a direction perpendicular to the plane of the paper (*z*-direction). After exceeding the *z*-directional strength of the paper, a break in the paper structure occurs in the sheet but not at its surface. The *z*-directional strength is therefore not equivalent to the surface strength or linting tendency of the paper. Many test methods to measure *z*-directional strength of paper are available. Some methods have also been standardized, TAPPI UM 584, TAPPI UM 403, TAPPI UM 527, and TAPPI UM 528.

The *z*-directional strength (DIN 54 516, 2004) is determined by measuring the maximum force per unit sample width required to split the sample.

The *crush resistance* of paper under compressive stress is measured as the short span compression strength. To prevent the sample kinking, the free span length must be very small (typically 0.7 mm). The resistance measured according to DIN 54 518 gives the ultimate crushing load per unit width.

The flat crush resistance (ISO 3035, 1982) and the edge crush resistance (ISO 3037, 1996) are used to characterize the strength of corrugated board. In the former test, a circular sample of corrugated board is exposed to increasing pressure between two parallel planar plates until the corrugation collapses, and the maximum load is measured. In the second test, the load is applied in the direction of corrugation starting from the edge of the sample. The edge crush resistance is used in DIN 55 468 Part 1 for the classification of corrugated boards.

The *folding strength* is an important property of both packaging and graphic papers. It can be determined either as described in ISO 5626 (1993) as the Schopper double fold value, or as described in ISO 5626 (1993) as the Köhler-Molin folding endurance value. The sample is subjected to specified tension in both cases. The Brecht-Wesp pressure folder functions without tension. A sharp fold in the sample is produced between two rolls and is repeated up to fifty times in the same position. The ratio of the tensile strength of the folded sample to that of the unfolded sample is the folding strength.

12.5
Load-Deformation Properties

Not only the strength properties, tensile strength and strain to rupture can be determined in the tensile strength test (ISO 1924, 1992), but also the *tensile energy absorption, TEA,* which is especially important for bag paper. The TEA value represents the nonelastic portion of the deformation energy and thus that portion of dissipated energy which should be high in the case of bag paper.

The resistance to flexural stress is measured as the *bending stiffness* under approximately pure elastic deformation, as defined in DIN 53 121. This test is usually performed with a two-point beam method. To guarantee elastic deformation, maximum bending angles, which depend on the span length and the sample thickness, are specified. This may be circumvented by the resonance length method (ISO 5629, 1983) in which the resonance length of a free sample strip is measured. Resonance is generated via a clamp vibrating at 25 Hz.

Deformations in board and cardboard can also be produced by creasing. Testing the properties of *creases* requires defined production processes, e.g., DIN 55 437 Part 1. In Parts 2 and 3 of this standard, methods are described for the manual folding of the creases and for the visual evaluation of the folding or the technical evaluation of the creases with a folding-moment tester.

12.6
Surface Properties

A large number of methods are available for evaluating the topography of paper surfaces. The Bekk *smoothness* is determined according to ISO 5627 (2002) as follows. At a defined pressure difference, the time in seconds is which a specified amount of air requires to flow radially inwards between the paper surface and a ring-shaped glass plate and on into a vacuum chamber is measured. The smoother the surface of the paper, the longer the pressure equalization takes. The determination of *roughness* according to Bendtsen (ISO 8791/2–90) is related to the Bekk method for the determination of smoothness. In this case, however, the direction of the air flow is reversed and the magnitude of the air flow is measured. The air escapes under defined conditions between the measuring ring of the measuring head and the paper surface under constant overpressure. For a general description of roughness or smoothness, see ISO 8791–1.

Sometimes the *topography* of the paper surface is described using profile measurements laser scanning. The scanning profilometer uses point sensors in conjunction with high precision *x*- and *y*-stages to capture profiles and 3D data. The stages move the sample under the sensor and the sensor passes the captured height data to the computer for evaluation.

Another surface property of paper is the *abrasion resistance*. The mechanical abrasion resistance of surfaces is determined in the friction wheel process (DIN 53 109–93). In this process, the amount of abrasion which is obtained by abrading the conditioned or wet sample with an abrasion wheel of defined quality under defined conditions is measured.

12.7
Optical Properties

An object, e. g., a paper surface, is termed white when the illumination intensity and the absorption capacity of the surface are independent of the wavelength. Deviations confer a more or less pronounced color shade on the surface.

In the paper industry, a special process is used to characterize the *brightness* because this is one of the most important optical properties of paper. The determination of the reflectance factor (ISO brightness) is based on ISO 2470 (1999). For this test, a filter is used which has an intensity maximum at a wavelength of 457 nm. The reflectance (blue component) measured in a reflectometer under specified conditions is known as brightness. It is expressed as a percentage of the brightness of a white standard.

Another optical property of paper is its *transparency*, i. e., a measure of its light transmittance. It is calculated from the reflectance factors R_0, R_w, and $R_{(w)}$, which are determined in accordance with DIN 53 147 (1993). The reflectance factor of the individual sheet on a completely black background is R_0, R_w is the reflectance factor of the individual sheet on a white background, and $R_{(w)}$ is the reflectance factor of the white base.

Most white papers and paperboards, and therefore also secondary fiber materials, currently contain an optical brightener. Brightness measurements for such materials depend on the relative proportion of UV radiation in the illuminant used for the determination. The standard test methods for ISO brightness have not defined the standard illuminant for use in the determination. The relative amount of UV has also not been defined. As a result, widely different R457 reflectance factors exist for the same kind of fluorescent material. The problem has recently been solved. A revised ISO method, ISO 2470, states that the UV radiation of the illumination must correspond to the relative amount of UV in the standard illuminant C when measuring fluorescent objects.

The *opacity* is a measure of light-tightness. It is defined in ISO 2471 (1998) as the ratio of the reflectance factor R_0 to the reflectance factor R_∞. Both reflectance factors are determined in accordance to DIN 53 145 (2000). R_0 is measured as the reflectance factor of an individual sheet on a completely black background and R_∞ as the reflectance factor of an “infinitely” thick stack of the same paper.

12.8
Printing Properties

The printing properties of paper result from complex interactions between printing ink, printing process, and paper. Practice-oriented printability tests must be performed to evaluate these properties. Test printers are also suitable for this purpose. Instruments for offset printing, gravure printing, and flexographic printing can be used with standard printing inks under laboratory conditions to test the dry pick resistance or the wet pick resistance of papers. Missing dots, mottling and ink penetration properties can also be tested. Conversely, the behavior of various printing inks towards standard papers can also be evaluated.

Using an image analyzer for testing printed image and printing process has increased during the last decade. This is due to the improved capability of the analyzers and because the importance of the quality of the printed image has increased. The image analyzer and its use in paper testing has already been mentioned earlier in connection with paper tests. The image analyzer is used to measure the uniformity of paper (print mottle, number of missing dots, and properties of dot), surface properties of paper (fiber rising, picking, and contact angle measurement), and many other properties of paper, i. e., width of cracking at the fold.

Furthermore, defined proof copies produced with the test printers can be used to test full ink coverage, color density, color gloss, shade, abrasion resistance, stacking ability, and contact yellowing.

More reliable results obviously come from tests that closely simulate the actual printing process. That is why tests developed for full-scale printing machines give the best predictions of the actual printability properties of a paper [5].

12.9
Behavior towards Liquids

The behavior of liquids towards paper is characterized by the processes of wetting and penetration. In both cases, the characteristic physical property is the *surface tension*. This value can be measured directly and tensiometrically in the case of liquids and indirectly, via the contact angle of test liquid droplets, in the case of solids such as paper. A liquid wets the surface of paper only if its surface tension is lower than that of the paper. The same holds for the wetting of the capillary walls upon penetration of liquids into the capillaries of the paper.

If the *wetting* and the *penetrating capacity* of liquids are to be changed, the surface tension of the paper must also be changed. This is achieved, for instance, by sizing the paper, a process which must fulfill the requirements regarding printability with aqueous inks. According to DIN 53 126 (2001), paper is considered to be printable if a standard ink line drawn with an adjusted drawing pen has neither run nor penetrated into the paper after 24 h.

The *water absorption* W_A (Cobb) (ISO 535, 1991) refers to the amount of water that is absorbed by a certain area of paper on one-sided contact for a specified exposure time. The time of exposure to water must be chosen such that a sufficient amount of water enters into the fiber matrix, but does not penetrate to the opposite side of the sample.

In the determination of *grease permeability* (DIN 53 116), red-colored palm kernel oil is used as the testing agent. The passage of fat through the sample under specified conditions is then evaluated.

12.10
Exclusion of Gases and Vapors

As a rule, papers have only a limited ability to exclude gases and vapors. Of particular importance are the air permeability (e. g., for filtration properties) and the water-vapor permeability.

There are two standardized test methods available for the determination of the mean *air permeability*: the Bendtsen method (ISO 5636-3, 1992) and the Schopper method (ISO 5636-2, 1984).

A gravimetric method for the determination of *water-vapor permeability* is described in ISO 12572 (2001). This method is suitable for building materials. For foils, laminated paper and board also DIN 53 122-1 (2001) is recommended.

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13

Book and Paper Preservation

Manfred Anders

13.1

Introduction

Most modern paper lacks the durability and permanence that has characterized its use since its earliest application in recording the history of man and his civilization. Although fundamental papermaking techniques have changed little in nearly 2000 years, two innovations in the 19th century, namely (i) the use of alum as a component of size, and (ii) the replacement of cotton fiber by wood pulp, are responsible for this predicament.

There has been an unbelievable development in the production of documents since the invention of printing with movable letters by Gutenberg. Within a short period of time, the necessary fibers for paper production could no longer be supplied by rags. After an intense search wood was discovered as an alternative. Ground wood pulp was used and later also chemical pulp, whereas in the latter the lignin is removed in a chemical process and so a "woodfree" pulp is produced.

The beginning of industrial paper manufacture dates from the middle of the 19th century, and with the development of paper machines, a new sizing method which could be integrated into the mechanical process became necessary. The sizing of paper is necessary for its writing property, otherwise it would act like blotting paper. The "sizing in the mass", wherein rosin is precipitated onto the fibers by means of acid-forming alum or aluminum sulfate in the pulp, was part of the mechanical paper manufacture until the 1980s. Today, a pH neutral and synthetic sizing agent is used. Papermaker's alum easily forms sulfuric acid on exposure to water in air; in turn this acid easily catalyzes the depolymerization of cellulose. Further, cellulose from wood pulp is more susceptible to this attack than linen- or cotton-derived fiber. Today it is accepted that the inherent acidity of such papers accounts for 85–90% of the destruction in book papers, resulting in a half-life for fold endurance of an estimated 7.5 years [1].

William Barrow was one of the first to describe the problem and correctly identify the cause at the Virginia State Library [2] beginning in the 1930s. Prior to his work, book and paper conservators relied as much on art as on science. While

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highly skilled, these professionals often selected materials and treatment without adequate consideration of the long-term consequences.

The discovery and the use of wood pulp (1840 by Keller) and acid sizing, mostly with alum or aluminum sulfate (1807 by Illig), are the main reasons for the current problems of deterioration of books in libraries und archives. Even at that time it was known that acid-sized wood pulp paper was not as stable against aging as traditionally made rag paper. Today the books most threatened by deterioration are those that were made in the last 150 years and not, as many people may assume, the older works from centuries ago.

There has been a fundamental change in papermaking in recent years. The development of synthetic sizing enables the industry to produce paper with neutral to slightly alkaline pH. With calcium carbonate as a filler, this paper has a sufficient alkaline reserve against acid contaminants from the environment. The paper has a better aging permanence than previous modern papers.

The main cause for paper deterioration in libraries and archives is the acid catalyzed hydrolysis of cellulose, the ingredient that gives permanence to the paper. The aging permanence of paper is closely connected with the acid concentration in the paper. The priority in preservation measures is in most cases the deacidification of acid paper. Today, more than 70 years after Barrow's pioneering work, mass deacidification of books and archive materials has become a commercial reality.

13.2
Mechanisms of Paper Deterioration (Fig. 13.1)

13.2.1
Paper Deterioration by Aging

The aging mechanisms can be divided into biological, physical and chemical processes. While using and storing paper appropriately, only the chemical processes are decisive. Paper nearly universally involves cellulose, although its source and methods of processing have evolved steadily throughout the centuries. As production costs dropped significantly, the application of paper dramatically expanded so that its traditional applications, particularly its use in books and official records, were dwarfed by other functions. Such widespread use of paper reduced the emphasis on permanence.

The sizing of paper continues to be the predominant cause of paper deterioration. In the early 1800s, about the time of Robert's invention of the fourdrinier machine for continuous paper manufacturing, gelatin sizing was abandoned in favor of alum or alum-rosin blends. Papermaker's alum, $Al_2(SO_4)_3 \cdot 18\ H_2O$, is easily hydrolyzed by water to form sulfuric acid. Acid catalyzed hydrolytic attacks cause degradation of cellulose by random scission of the hemiacetal links, leading to breakage of chain linkages (Fig. 13.2). Even a few scissions per molecule cause a substantial loss in physical properties [3]. In 1851, the discovery of the soda process

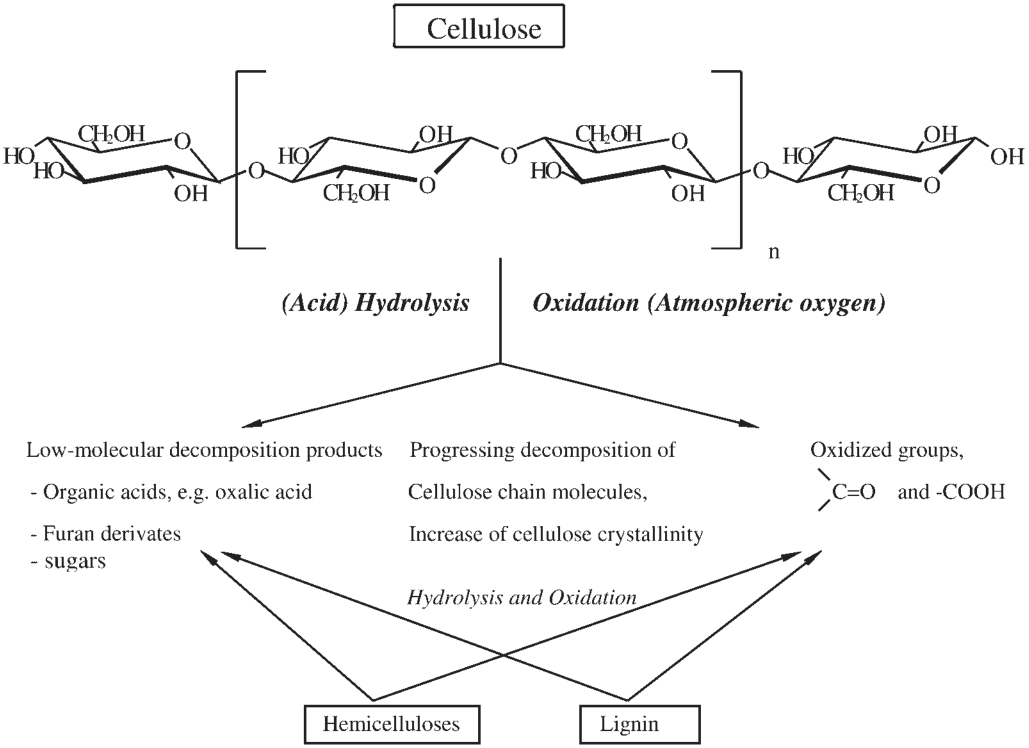


Fig. 13.1 The main decomposition reactions of paper fibers.

for separating cellulose from wood added a further dimension to the problem since paper derived from wood pulp is more susceptible to acid attacks than the cotton cellulose obtained from linen and rags.

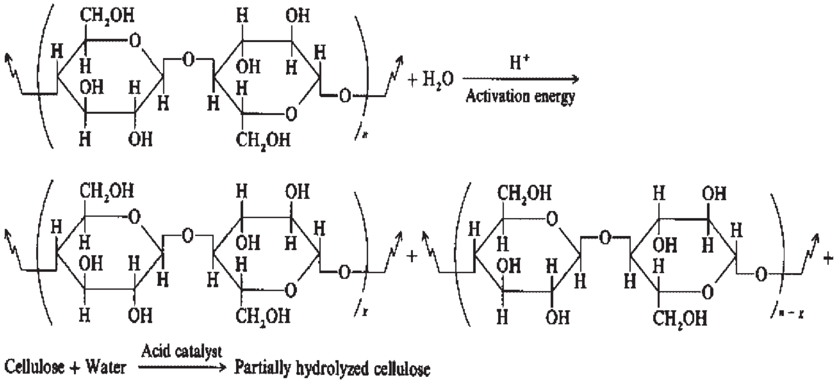


Fig. 13.2 Acid catalyzed hydrolysis of cellulose.

The lack of paper permanence is attributable to both internal and external influences [4]. In addition to sizing materials, internal factors include the type of fiber, coatings, and the presence of acidic and metallic compounds. External variables are the conditions during storage and use. Heat and humidity accelerate the deterioration of paper, and atmospheric pollution is frequently the source of external acid attacks. A comparison of identical volumes stored in the New York Public Library and the Royal Library in The Hague proved the importance of proper storage, as the New York books were found to be in a far more advanced stage of deterioration [5].

It was not until 1926, when Gösta Hall from Sweden developed a satisfactory method for accelerated aging [6], that researchers had the means to simulate the effects of the natural aging process. Although Edwin Sutermeister of the S. D. Warren Company recognized as early as 1901 that stable paper should contain an alkaline filler, it was left to William Barrow of the Virginia State Library to pull the disparate elements of early researchers together in a scientific analysis of the problem [7].

As acid catalyzed hydrolysis of cellulose is responsible for up to 90% of paper's loss of permanence, researchers have concentrated on deacidification as the primary solution to the impermanence of modern papers. Paper deacidification involves introduction of a strong base to convert acid species to their corresponding neutral salts, and the establishment of a neutral buffer to protect the paper against future acidcatalyzed damage. The first recorded attempt to neutralize paper was by Arthur Church at the Victoria and Albert Museum in London who, in 1891, advocated the immersion of paper in a methanolic solution of barium hydroxide [8].

Subsequent attempts to develop effective deacidification focused on aqueous techniques which offered the additional benefit of modest strengthening through re-establishment of hydrogen bonding. Otto Schierholz, working for the Ontario Research Foundation in Toronto, secured a patent in 1936 for his work which involved dipping paper in a solution of alkaline earth bicarbonates [9]. In 1943 Barrow described a two-step process, involving immersion in a calcium hydroxide bath and subsequent treatment with calcium bicarbonate. Commentators differ as to whether Barrow was aware of the earlier Canadian work. Further refinement of the technique included the 1957 development by James Gear et al. at the United States National Archives of a one-step process involving magnesium bicarbonate, and the use of the more soluble magnesium hydroxide by scientists at the Library of Congress in 1978. While effective and proven, these techniques involve painstaking care as they are applied to single sheets.

13.2.2
Oxidative Deterioration Processes

Although the above mentioned acid catalyzed hydrolysis is the main cause for the deterioration of cellulose and the connected loss of permanence, the influence of oxidation cannot be neglected. The oxidative damage is much more complex in its

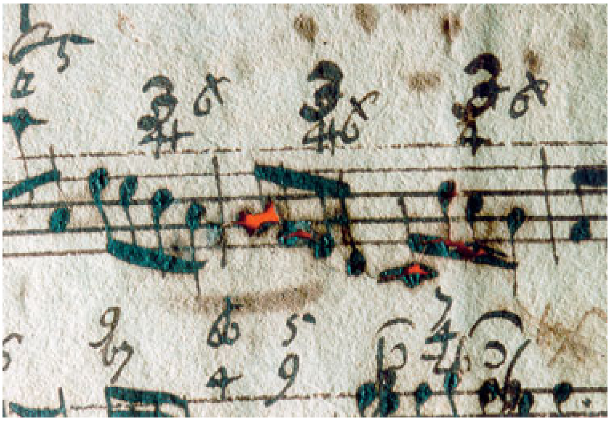



Fig. 13.3 Approximately 200 years old manuscript attacked by ink corrosion.

various chemical reactions, synergistic effects and secondary reactions and not at all completely researched.

Cellulose can be oxidized not only by various oxidants like pollution gases from the air (ozone, NO_x, etc.) and bleaching agents in the wood pulp production, but also by atmospheric oxygen. In the oxidation by atmospheric oxygen an additional activation or catalysis is needed.

Acids as well as bases have a catalyzing effect. The catalysis by heavy metal ions is really effective. A well-known example of this mechanism is the ink corrosion which leads to a total destruction of paper in the area of ink due to the excess of iron ions in the ferro-gallic ink and the acid. Some of the most valuable manuscripts are affected (Fig.13.3 and 13.4). Temperature and electromagnetic radiation, especially UV rays, have an activating effect.

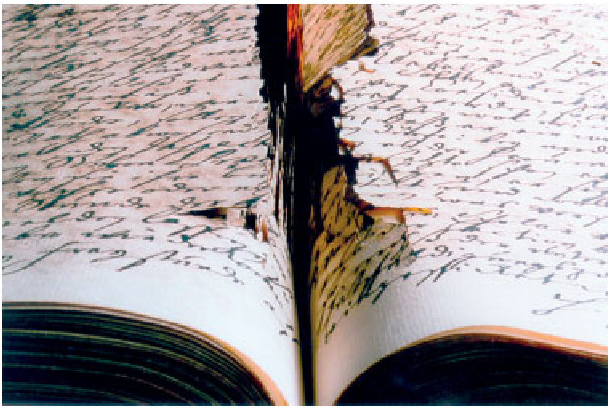


Fig. 13.4 Approximately 200 years old manuscript attacked by ink corrosion.

The observed reactions are often summarized under the term "autoxidation" as reaction products of such oxidation processes: organic acids like ethanoic acid, formic acid, oxalic acid etc., cause a further acidification of the paper. Due to these oxidation processes the acid catalyzed hydrolytic deterioration of cellulose is accelerated.

13.2.3
Alterations due to Paper Aging

13.2.3.1 Yellowing

Paper ages by becoming yellow and brittle. An intensification of the yellowing is observed with continuous aging. There are various reasons for the yellowing of paper. Many of the reaction products of the aging processes, such as oxidation products, condensed furan derivates etc. are dark colored. More and more of these colored reaction products are produced with continuous aging. In wood-containing, i.e. lignin-containing papers, the yellowing is extremely intense.

13.2.3.2 Embrittlement of Paper

The alterations in paper that result from aging can be seen most obviously on the basis of the angles of cracks after a strain-to-crack measurement. The ratio between individual fiber strength and the bonding strength between the fibers changes during the aging of paper. The strength of individual fibers decreases due

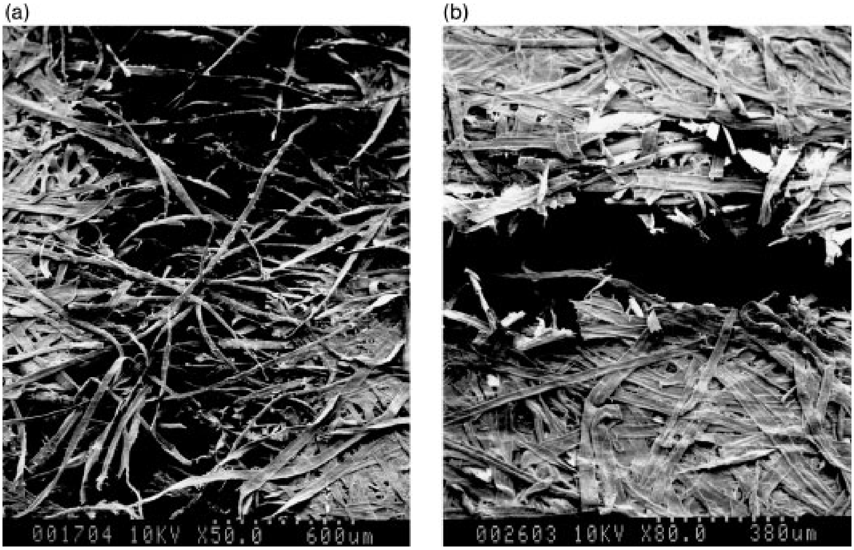


Fig. 13.5 Scanning electron microscope pictures of the angles of cracks of non-aged (a) and aged (b) paper after a strain-to-stress measurement.

to the shortening of cellulose molecules as the result of deterioration mechanisms in the course of aging. On the other hand the inter-fiber bonding is strengthened by linking reactions and salt bonds: the fibers are linked one to the other inflexibly and strongly. The fiber-fiber bonds are developed on the fiber surface so that the structure of their surface, where an increasing number of reactive groups are developed by oxidation processes, is decisive. As a consequence of aging inflexible bonds between fibers are created. In the case of a mechanical strain the attacking forces cannot be spread to nearby fibers because the fibers are linked inflexibly. During a mechanical strain, like in tearing, in an aged paper the deformation energy is spread less in the paper but concentrates on individual fibers that are already weakened and then break.

If new paper is torn the fibers slide apart without breaking. This can be shown with pictures from a scanning electron microscope of the angles of cracks of aged and non-aged paper after a strain-to-stress measurement (Fig. 13.5). The fibers of the new paper only slid apart whereas in the aged paper they broke. This means that the fiber-fiber bonds in new paper and the individual fibers in aged paper are the mechanically weaker points.

13.3
Development of Mass Deacidification Processes

13.3.1
Overview

There are many statements in literature about different deacidification systems and agents, its advantages, use and also comparative examinations [10–16]. In the treatment a long-term acid protection (exogenous influences) is to be achieved and therefore an additional alkaline buffer is deposited in the paper [17–23]. In the following the most important methods are introduced.

On the one hand the deacidification systems can be divided into *single sheet methods* and *mass deacidification methods*. On the other hand the methods can differ in the polarity of the solvents used. Polar solvents have a swelling effect on cellulose, or rather paper, and can dissolve some of the colors and inks and therefore mostly nonpolar solvents are used in mass deacidification systems. Single sheet methods with water as a treatment medium are the classical methods.

Mass preservation is designed to meet the needs of national and major research libraries and archive groups. With a mean collection deterioration rate of 4.7 % [24] and limited resources, a treatment based on painstaking manual work is inconsistent with the need. Further, greater emphasis has been placed on nonaqueous and gas-phase deacidification techniques to compensate for some of the intrinsic limitations of aqueous methods.

Nonaqueous deacidification systems contain a deacidification agent and an organic solvent that serves as the carrier. The solvents offer the advantage of rapid penetration and drying. The latter is particularly important in minimizing the obvious appearance of treatment, most notably cockling. Liquid techniques can function economically over a broad treatment range. The approach of Church in the late 19th century was updated by Baynes-Cope in the mid-1960s [25]. This followed his experimentation in 1961 with a magnesium methoxide solution which, while quite effective, was impractical in terms of preparation and storage. Independently, Richard Smith from the University of Chicago developed a process that utilized a magnesium methoxide compound which was dissolved in a mixture of methanol and chlorofluorocarbons (CFC) [26]. This overcame many of the problems associated with earlier approaches regarding stability and ease of use.

Ethanolate and propanolate of magnesium which are dissolved in the appropriate alcohol and a nonpolar halogenated hydrocarbon can also be used as deacidification agents. By transformation of the magnesium alcoholate in the appropriate carbonates (alkoxy magnesium carbonate) using (dry) carbon dioxide, a further improvement of the solubility and permanence could be reached.

13.3.2
History of Commercial Mass Deacidification

In the last 25 years some mass deacidification processes have been developed, by national libraries and companies, which could not gain acceptance. A short description of the most important follows:

In contrast to procedures working with solvents, a vapor-phase approach offers prospects for minimal preselection and maintenance of document integrity because no solvents are involved. At least one researcher likened this approach to a “fountain of youth” among deacidification methods [27]. Gas-phase processes work best on a substantial scale because the facilities characteristically have high capital intensity.

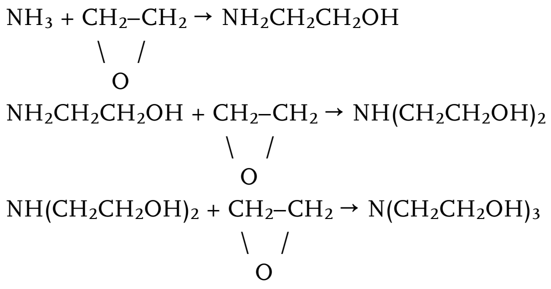
Early attempts at gaseous deacidification included the work reported in 1962 by Kathpalia at the Nehru Library in New Delhi, involving exposure of books to high concentrations of ammonia [28]. The compound proved to be too weak a base to neutralize completely strong acid and the ammonia buffer was highly impermanent. At about the same time, Barrow working in the United States and Baynes-Cope in England combined ammonia and short-chain amines, including butylamine, diethylamine and piperidine, and observed similar results – a short term alkalization that was reversed as the amine left the treated paper.

A more promising approach was advanced by Langwell who placed cyclohexylamine carbamate impregnated sheets in books [29]. The active compound diffuses into the book paper to neutralize acidity, but no alkaline reserve is established and the neutralization is reversible. Finally, morpholine treatment was promoted by Kusterer and others working at the Barrow Laboratory in 1977. Besides the lack of permanence, significant discoloration was observed in the paper of treated books. Kelly and Williams at the Library of Congress designed a mass deacidification process in 1977 that utilizes diethyl zinc (DEZ) [30]. The compound easily diffuses between the pages of closed books, neutralizing the acidity and establishing a uniform, controllable reserve of zinc oxide.

13.3.2.1 **BPA Process**

Book Preservation Associates (BPA) was formed in 1988 as a wholly owned subsidiary of ETO Sterilization, a processor of spices, medical products and cosmetics. In the BPA process books or other library materials are placed in closed boxes in a vacuum chamber. The pressure is reduced and the books are exposed to ammonia for 6 h. The chamber is then purged and evacuated. Ethylene oxide is introduced and the materials are held for 12 h at nearly atmospheric pressure. The chamber is alternately purged and evacuated up to 25 times before treated materials are removed. The total cycle time is 24 h [31]. Books are placed in an aeration room for two days to permit off-gasing of the ethylene oxide before being returned to libraries.

The process was designed to create high molecular mass, primary, secondary, and tertiary amines within the cellulose matrix of the book paper. The in situ generation of amines, together with free ethylene oxide, neutralizes acidity and establishes an alkaline reserve of ca. 1%. Ethanolamine generation during treatment is described as follows:



$$NH_3 + \underset{\substack{\backslash\ \ /\\ O}}{CH_2{-}CH_2} \rightarrow NH_2CH_2CH_2OH$$

$$NH_2CH_2CH_2OH + \underset{\substack{\backslash\ \ /\\ O}}{CH_2{-}CH_2} \rightarrow NH(CH_2CH_2OH)_2$$

$$NH(CH_2CH_2OH)_2 + \underset{\substack{\backslash\ \ /\\ O}}{CH_2{-}CH_2} \rightarrow N(CH_2CH_2OH)_3$$

Developers of the process reported that the mono-, di-, and triethanolamines are formed in approximately equal amounts with a modest dominance by the monoethanolamine. The reaction depends on the ratio between reactants and is adjusted intentionally. BPA personnel report that the pH drops approximately 1.5 points in the two months following the treatment.

The process could not gain acceptance on the market because of the inadequate alkaline reserve (no depot effect of the deacidification) and further side effects. Nevertheless new attempts are being made in Japan to try to use this process again after some alterations.

13.3.2.2 **The DEZ Process**

The DEZ process was developed by the Library of Congress in Washington over more than 15 years, progressing from simple laboratory experiments to an operating small-scale commercial unit. Much of the latter work was in cooperation with Texas Alkyls, one of three major producers of compounds such as diethyl zinc (DEZ). Akzo secured an exclusive license for the DEZ Process and tried to commercialize the technology.

As strong alkylating agents, metal alkyls react easily with acids to form the corresponding neutral salts. DEZ also reacts with residual water in the paper to form a stable, permanent buffer of zinc oxide. Unlike most other processes, the neutralization of existing acidity is independent of the formation of the alkaline reserve. Thus highly acidic and neutral paper are both provided with an optimum alkaline reserve. The key reactions are summarized below [32]:

$$H_2SO_4 + (C_2H_5)_2Zn \rightarrow ZnSO_4 + 2\ C_2H_6$$
$$2\ CH_3CO_2H + (C_2H_5)_2Zn \rightarrow Zn(CH_3CO_2)_2 + 2\ C_2H_6$$
$$H_2O + (C_2H_5)_2Zn \rightarrow ZnO + 2\ C_2H_6$$

The buffer established by the DEZ process is more neutral (saturated solution with a pH of 7.3–7.5) than that of magnesium or calcium salts used in other deacidification methods.

The process consists of three steps: pretreatment, permeation, and post-conditioning; the total cycle time is 55–60 h. Akzo operated a treatment facility near Houston, Texas, with a capacity of about 40 000 books per year. Owing to its high reactivity, liquid DEZ is dangerous if mishandled. Poor design and operating procedures on the part of an earlier contractor threatened to halt further development of the process because of the inoperative first pilot plant. The issue of safe handling was fully resolved in the second facility. Nevertheless the process did not become accepted and was stopped.

13.3.2.3 **The Wei T'o Process.**

Wei T'o Associates, developers of a nonaqueous liquid deacidification process, derives its name from an ancient Chinese god regarded as the protector of books. The National Archives of Canada operated a treatment facility in Ottawa with a capacity of about 40 000 books per year until 2002. The process is based on the work conducted by Richard D. Smith, a graduate student at the University of Chicago in the mid-1960s. In 1989, Union Carbide acquired the exclusive rights of the process and intend to market the technique as part of a paper preservation service unit.

The deacidification agent is methoxymagnesium methyl carbonate carried in a solvent system composed of methanol, trichlorotrifluoroethane (Freon 113) and dichlorodifluoromethane (Freon 12). The CFCs have been replaced by perfluorocarbons. Books are placed in wire baskets and dried to a moisture content of 0.5 %. The pretreated materials are immersed in the treatment solution for 1 h under modest pressure. Drying is initiated by evacuating the chamber and recovering the solvents. Final drying is performed under vacuum. During this stage the deposition of the magnesium compounds occurs. Careful control of pressure regulates the evenness of deposition [33].

Following deposition, the active agent reacts with water from the air to form a mixture of intermediate magnesium compounds [8]:

$H_3COMgOCOOCH_3 + 2\ H_2O \rightarrow Mg(OH)_2 + 2\ CH_3OH + CO_2$
$H_2O + CO_2 \rightarrow H_2CO_3$
$Mg(OH)_2 + H_2CO_3 \rightarrow MgCO_3 + 2\ H_2O$
$MgCO_3 \rightarrow MgO + CO_2$

These magnesium compounds react with strong acids to form the corresponding neutral salts. For example, magnesium hydroxide converts sulfuric acid to magnesium sulfate:

$Mg(OH)_2 + H_2SO_4 \rightarrow MgSO_4 + 2\ H_2O$

Magnesium sulfate is also generated by the reaction of magnesium carbonate with acid:

$MgCO_3 + H_2SO_4 \rightarrow MgSO_4 + H_2O + CO_2$

Residual magnesium hydroxide, carbonate and oxide form the alkaline buffer that protects paper from subsequent acid attacks.

Similar chemistry is practiced by the Bibliotheque Nationale at its treatment facility in Sable sur Sarthe/France. The unit has an annual capacity for 60000 volumes. However, the French process uses ethoxymagnesium carbonate as the deacidification agent.

13.3.2.4 **The British Library Process**

The British Library has achieved excellent results in its effort to deacidify and strengthen book paper in a bulk process that has been under development since 1980. The method involves graft copolymerization techniques initiated by low-intensity γ-radiation. This work has been performed by the Industrial Chemistry Group of the University of Surrey under British Library supervision and sponsorship.

Short-chain monomers, in particular ethyl acrylate and methyl methacrylate in a volume ratio of 5:1, are introduced in liquid form without solvents in a closed system. Low-intensity γ-radiation polymerizes the monomers under ambient conditions. Additionally, the liquid monomer mixture has been modified to include an amine-substituted alkyl methacrylate to neutralize acidity and establish a buffer against future acid catalyzed hydrolysis [34]. The presence of a small amount of a diacrylate leads to cross-linking and hence strengthening of the paper.

Paper strength, as measured by fold endurance, is enhanced by a factor of 5 to 10 and a gain in weight of 15–20% occurs. No dimensional changes in treated books have been observed. Researchers have concluded that the polymer is deposited within the cellulose network of the paper as well as on and between the fiber surfaces. The treated books retain their original appearance and pages do not stick together at the prescribed polymer deposition levels. This process also could not be realized, residual monomer contents and further problems brought this project to a halt.

13.3.2.5 The Lithco Process

In 1988 Lithco started developing a nonaqueous deacidification technique. Magnesium butoxytriglycolate, the active ingredient, is solubilized in Freon 113 as a ca. 10 % solution. Later heptane was used as solvent instead of Freon 113. The company marketed the process for its ability to both deacidify and strengthen book paper.

The process consists of three steps: preconditioning, impregnation, and postconditioning. Books or other library materials are dried rapidly by dielectric heating to a moisture content of ca. 2 %. The documents are immersed in the deacidification solution for deposition of the neutralization agent. Finally, excess solution is drained, excess chemicals are rinsed out, the solvent is removed under vacuum, and the books are removed. Total cycle time is less than 5 h.

The butoxytriglycolate ligands are intended to interact with cellulose to strengthen the paper through hydrogen bonding. Similar chemistry based on zinc compounds has also been explored by Lithco on a more limited basis. Additionally, the company utilizes dielectric heating to speed the drying during both the first and last steps [35].

Early work was conducted in a demonstration unit capable of processing 20 standard bound volumes per batch. Lithco commissioned a larger pilot unit with a capacity for 1000 books per day in May 1990. In practice the stabilizing effect through the monobutyl-triglycolether could not be observed. The opposite could be observed more often: due to the oleagenous substance a loss in permanence occurred. This process also did not become accepted and therefore was stopped.

13.4
Current Commercial Processes

13.4.1
Papersave Process®

The Papersave process® was developed by Battelle (Frankfurt) and is often called the Battelle process in older literature. The inventor was Jürgen Wittekind. In this mass deacidification process, titanium magnesium ethanolate (METE) dissolved in hexamethyldisiloxane (HMDO) is used as deacidification agent. Titanium ethoxyl has the task of dissolving the magnesium ethoxyl in the form of a titanium magnesium double ethoxyl in HMDO. The magnesium alcoholate performs the deacidification. The advantage of this process is the use of the nonpolar solvent HMDO in which nearly no component of the documents is soluble. The addition of alcohol as a solubilizing agent, as in other processes, is not necessary because of the production of the double alkoxide. Only the alcohols that are set free in the hydrolysis of the deacidification agent can become a problem in some cases.

The Papersave Process® comprises three steps: (Fig. 13.6 and 13.7): First, the books, which remain in a closed treatment chamber during the entire process, need pre-drying. The normal moisture content of 5–7 % is temporarily decreased

Fig. 13.6 Chamber of the Papersave Process® mass deacidification plant with a capacity of 60 tons per year.

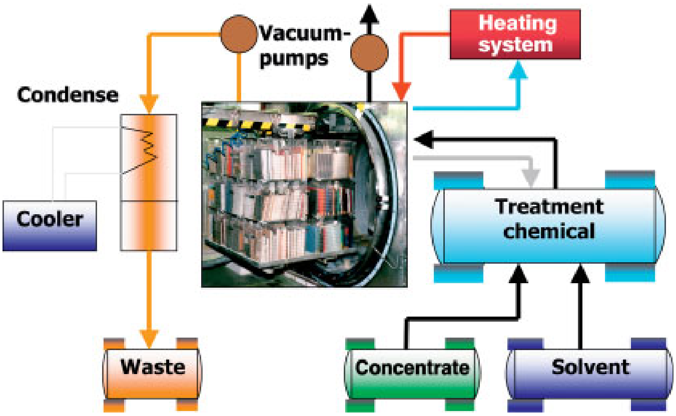


Fig. 13.7 Schematic of the Papersave Process® mass deacidification plant.

to less than 1%. The drying process takes place under vacuum conditions accompanied by a mild heating to not more than 120 °F (50 °C). Due to optimisation of the drying technology, the previously used microwave technology has been replaced by a more favorable method.

Secondly, deacidification follows the pre-drying. The books are impregnated with an alkali solution. The treatment chamber is completely flooded with the treatment chemical. The deacidification chemicals are alcoholates of magnesium and titanium dissolved in hexamethyldisiloxane. Due to the previous drying, the closed books standing in the chamber absorb the solution like a sponge.

Thirdly, the books are again dried after the treatment solution has been drained. The solvent absorbed during impregnation dries away while the deacidifying chemicals (magnesium and titanium compounds) remain in the paper.

The entire process takes three days. After the books have been removed from the chamber, they regain lost humidity and return to their normal moisture content. This process is finished after approximately three weeks. During this period the books exude alcohol due to the reaction of the treatment chemicals with water. Therefore, the treated books are stored in a well-ventilated room before being returned to the customer.

By this treatment the following results are obtained: The acids contained in the paper are completely neutralised by the magnesium compounds. The pH of the paper after treatment is raised to between 7 and 9. The pH of some papers can exceed 9 for a short period after treatment. In the following months, the pH of the paper decreases to levels below 9 due to the transformation of magnesium alcoholates and magnesium hydroxides in magnesium carbonate. After neutralisation of the acids, 0.5–2 wt.% of superfluous magnesium carbonate remains in the paper and serves as the alkaline buffer. Thus, acids subsequently formed or introduced into the paper by environmental influences can be neutralised within the paper.

This process has proven itself in practice during the last 10 years and is offered by ZFB GmbH (Center for Book Conservation) in Leipzig/Germany which works on the conservation and preservation of library and archive goods. The company was founded in 1997 by hiving off the section Center for Book Conservation from the German Library in Leipzig. Battelle (Frankfurt) was taken over by ZFB in 2001. In Switzerland a Papersave deacidification plant with a capacity of 120 tons per year was also opened in 2000, operated by Wimmis Nitrochemie under license from ZFB.

13.4.2
The Bookkeeper Process

This is a liquid, nonaqueous process that employs a perfluorocarbon carrier to deposit a submicron dispersion of magnesium oxide. No alcohol is involved and a surfactant is employed to keep the neutralization agent evenly distributed in the fluorocarbon solvent. The technique was developed by Koppers Chemical Company in 1981, who transferred the rights of the process to Richard Spatz in 1987. Book Preservation Technologies, in which Spatz is a principal, continues the development of the method.

Books are placed open on a supporting grate which is loaded into a treatment chamber. No predrying is required. The chamber is flooded with the treatment solution and the grate is mechanically agitated so that the pages are exposed and completely wetted. Books are subsequently removed from the chamber and placed in an air dryer, from which the solvent is condensed and recycled [36]. The total process time is 5 h or less. The process can be operated in batch or continuous mode. The Bookkeeper process relies on the migration of paper acid to the magnesium oxide for neutralization to occur.

The treated books show partially a dusty layer of magnesium oxide and damage because of the intense mechanical strain during the deacidification process. Today this process is used in the Library of Congress (Washington) in America and is also offered commercially in the Netherlands.

13.4.3
Magnesium Oxide Dust

An automated process for the conservation of single sheets was evolved in the Federal Archive of Lower Saxony in Bückeburg as a consequence of a development of the PTS (Papiertechnische Stiftung) in Munich/Germany. The aqueous process consists of three treatment stages:

1. Fixation of the writing and printing substance by means of a polyamine condensation product and a poly-condensed aromatic sulfonate (development of this system by works in Stuttgart [37]).
2. Deacidification and generation of an alkaline reserve with an aqueous magnesium bicarbonate solution.
3. Sizing with cellulose ether (MC/CMC) for the increase of permanence.

All processes are carried out in dippings. The most progressive plant works with only one dipping which combines all three chemical systems. The system is run today by the company Neschen AG.

13.4.4
Aqueous Processes

13.4.4.1 Bückeburger Process

The companies Libertec and SOBU from the area of Nuremberg (Germany) offer a paper deacidification by means of a nonaqueous process. In this process fine magnesium oxide particles are blown into the opened books as dust which is then fixed in the paper by humid air. The books are clamped individually into a gadget and then treated. The treated books show an irregular deacidification and a dusty coating on the paper, especially in the book fold.

13.4.4.2 The Austrian National Library Process

Work on an effective deacidification process for bound newspapers began in the Austrian Library in 1973. The technique, which has been in regular operation in Vienna since 1987, involves immersion in an aqueous solution of calcium hydroxide and methyl cellulose. Borax is then used as deacidification agent.

The process steps include: preparation, treatment, drying and rebinding. Covers are removed from bound newspapers, and the materials are placed in a vacuum chamber. Following immersion in the treatment solution, the paper is shock frozen at –30 °C to prevent the formation of large crystals that would damage the paper web. Final drying consists of freeze-drying to avoid the pages sticking together. Treated papers show no significant change in dimensions and permit the use of the original covers [38]. Although testing and preselection is required, the

Library has successfully applied the technique to various other archival materials. The current capacity is 3000 bound volumes per year.

13.5
Strengthening Old and Brittle Paper

13.5.1
Overview

There are some successful new possibilities in the deacidification of paper up to mass deacidification processes by nonpolar solvents (for example the Papersave Process®) whereas no new achievements have been reached in the strengthening of paper, especially not in nonaqueous treatments. The experiences of paper makers are only of limited use in the strengthening of old papers because the papers cannot be changed in structure and compound during restoration or preservation.

The chain deterioration of cellulose during paper aging is irreversible and cannot be cancelled. A renewing of the fibers is not possible but there are possibilities to stabilize brittle paper and the following measures are worthy of consideration:

1. Elastic "conglutination" (sizing) of the paper texture with macromolecular substances (cellulose ether, gelatin).
2. Formation of macromolecules in the paper texture by polymerization, for example the Parylen Process. Here the most commonly discussed method to accomplish only strengthening involves the gas-phase deposition of poly-*p*-xylylene. Paralyne is the generic name for the various members of the polymer series of *p*-xylylenes developed by the Nova Tran Corporation. The technique is capable of establishing a thin, durable coating of the polymer on the paper. No deacidification is accomplished, however, and the high cost of treatment has discouraged widespread use.
3. Inserting or applying a stabilizing matrix, normally a thin stabilizing paper.

13.5.2
Preservation of Originals by (Mechanical) Paper Splitting (Leipzig Paper Splitting Technique)

If a work has to be maintained as an original because of its value, even if the paper is seriously damaged, then deacidification is not sufficient. In these cases a stabilization of the paper is necessary. This can only be achieved be preservational techniques like wet treatment, leaf casting (if parts are missing), application of thin stabilizing material [39] or paper splitting.

Paper splitting [40] was developed at first as a manual technique for preservation and new permanence of highly damaged paper for valuable works by Günter Müller, Jena/Germany. The Center for Book Conservation GmbH in Leipzig developed a paper-splitting machine (Fig. 13.8) The machine includes a laminating

Fig. 13.8 Paper splitting machine in the Center for Book Conservation in Leipzig.

unit, a splitting unit and a removing unit. First the binding has to be removed from the book i.e. the single sheets have to be separated. In the laminating machine the sheets are embedded in gelatin between two carrier sheets. The carrier sheets in roll form are spread with gelatin by means of sizing machines. In the splitting machine the composite of original sheet and carrier material produced in the laminating machine is pulled apart, i.e. it is split. Then, a thin but sturdy core paper (often with an alkaline buffer) is brought in between the two sides and glued together with the halves of the original paper with cellulose ether (for example methyl cellulose) mixed with calcium carbonate as deacidification agent and alkaline reserve. After that the split sheets are supplied to the removing unit where the carrier sheets are removed by means of an enzyme (protease). Finally the stabilized sheets are bound again.

Even despite occasional ethical doubts the paper-splitting process is often the only practicable method for highly damaged paper, for example paper that is an advanced stage of damage by micro-organisms or ink corrosion.

13.6
Commercial Prospects

The need for paper deacidification is enormous. It is reckoned that between 70% and 80% of the library and archive collections consist of acid paper and are therefore exposed to a dynamic deterioration process. The reaction is self-accelerating because the acid deterioration is an autocatalytic process. This means that in the course of the deterioration process more and more acids are produced. The acids in the paper can be neutralized and an alkaline reserve can be deposited. With that the acid conditioned deterioration reaction in paper can be stopped effectively but cannot be cancelled. If the deterioration is too far advanced, more complex preservation processes than mass deacidification (for example paper splitting) are needed so that the paper can be used again. The earlier the acid corrosion is stopped the easier and cheaper is the treatment. An early deacidification is therefore the most effective method to save money in the preservation of documents.

Most collections are in the property of public institutions and it is unsure how much money will be available for the preservation of these important cultural assets. This uncertainty makes it more difficult for the private sector to act and plan economically.

The most compelling evidence for the need for mass deacidification is the substantial involvement of national libraries in the development of treatment methods. Research libraries and archive groups universally seek a low-cost option that will permit preservation of collection materials in their original form. Current deacidification techniques represent a viable and cost effective preservation solution to the problem of acid paper. Although, it is currently difficult to define costs in order to make convincing comparisons among processes, mass deacidification is unquestionably far less costly than reformatting options such as microform. In addition, users of research libraries and archives collections continue to prefer original format materials.

More than one mass deacidification method will be adopted by the library and archives community. The problem is so big and the needs are so diverse that a single institution may well choose to pursue multiple treatment options.

The aim of new developments is to evolve technical less complex methods with less expensive chemical systems. A further aim is, in addition to the deacidification, to achieve more improvements in the paper, e. g. strengthening, protection against oxidation and protection against microbial infections, by the use of additives.

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