A HANDBOOK BY HÅKAN KARLSSON WITH UPDATES FROM
PER-IVAR FRANSSON AND HÅKAN ÖSTERHOLM

Fiber Guide

Fiber analysis and process applications in the pulp and paper industry

Fiber Guide
SECOND EDITION
Fiber analysis and process applications in the pulp and paper industry

A handbook by Håkan Karlsson
with updates from Per-Ivar Fransson
and Håkan Österholm

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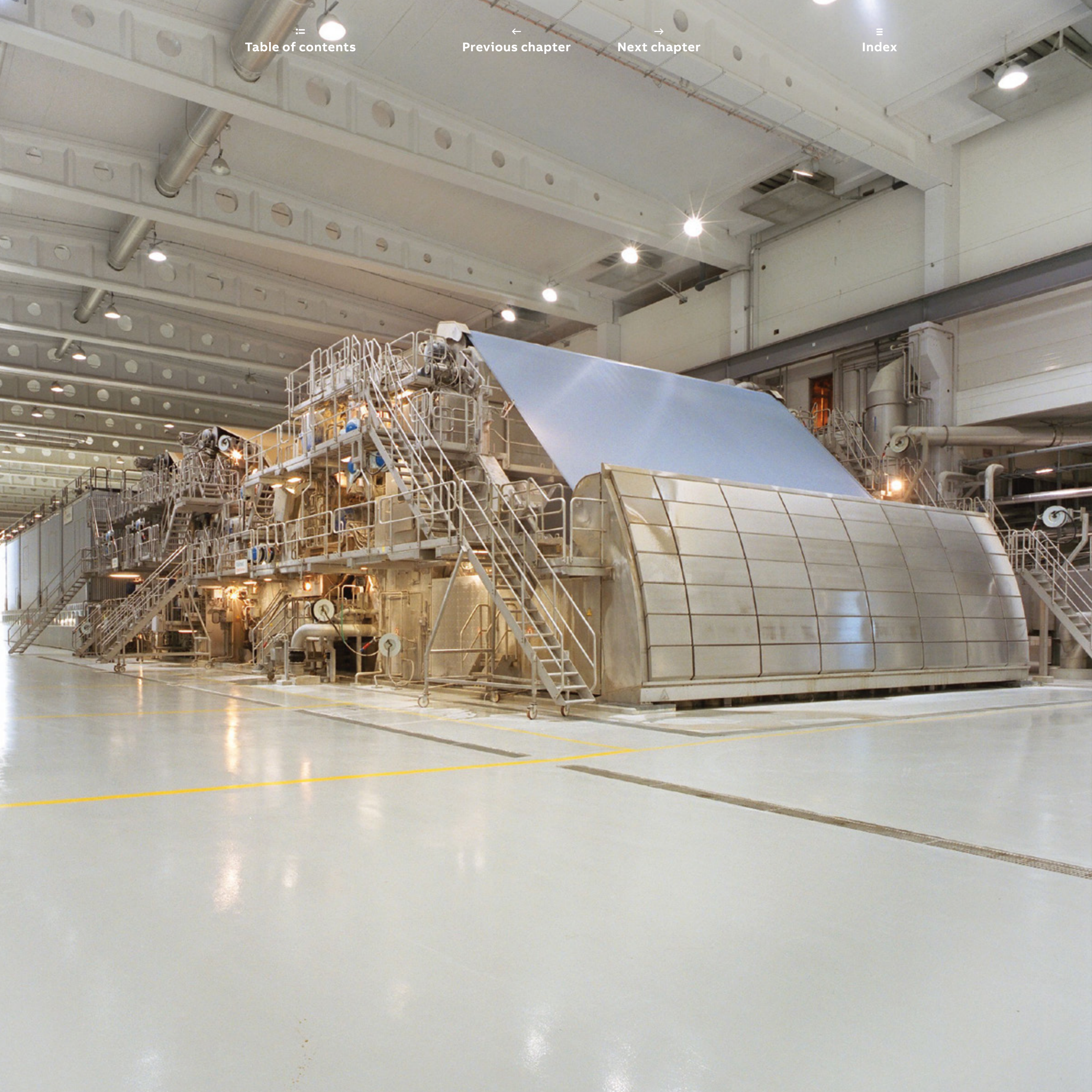

1. Acknowledgements

A lot of my experience and knowledge comes from STFI*, where I spent many, very active, and inspiring years with research and development work. Many results presented in this book are based on work done there – Thank you STFI.

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A special thanks to Therese Jost, who did a great job helping me to write this book. Finally, many thanks to the great staff at Lorentzen & Wettre, who have encouraged, supported, and helped me to write this book.

Håkan Karlsson, 2006

*STFI (Svenska Träforskningsinstitutet, 1945-2008), Then became Innventia AB (2009-2017), now RISE (Research Institutes of Sweden)

2. Background

The first quality sensors for online purposes using modern electro-optical and digital processor components (photodiodes and a microprocessor) came in about 1975. One of the first was an electro-optical shive analyzer, suitable for the design and optimization of screen rooms.

A few years later, systems for monitoring refining in mechanical pulping that combined measurements of optical fiber length, an optical shive analyzer and a freeness measurement were developed. Ways of measuring average fiber length and radius for online purposes were invented during the 1980’s.

All fiber analyzers at that time measured a projected length, and people were not fully aware of the importance of fiber deformations. But the industrial potential of these improved measurements was very evident. Since measurements of the distributions of fiber properties were required in combination with improved length measurements, RISE (now Swedish Pulp and Paper Institute (STFI)) started to develop the technology for this in the early 1990's.

In the late 90’s, the company Fibertracker AB[1], introduced the first commercial product to the market – the STFI Fibermaster. Its standard features were measurements of length, width, deformation, bendability, coarseness and fines, as well as detailed statistics about these properties.

Some years later, Fibertracker AB was acquired by Lorentzen & Wettre and the fast development of the online technique and new modules continued with the introduction of a new benchtop laboratory unit for fiber analysis, the L&W Fiber Tester[2].

Historically, Lorentzen & Wettre supplied the pulp and paper industry with a number of different products to evaluate the quality of pulp, including wood chips, classifiers, laboratory digesters, fiber fractionation units, handsheet machines, lab refiners and freeness testers. More semi-automated devices, such as the L&W Dynamic Sheet Former (DSF), which produced a paper sheet that closely resembled machine-made paper, were also developed at Lorentzen & Wettre.

1. Fibertracker AB was founded in 1998 by Håkan Karlsson and Per-Ivar Fransson (both from STFI).
2. For clarity, L&W Fiber Tester Plus is the most recent product model of the previous generations L&W Fiber Tester & STFI Fibermaster.

Measurements of fiber properties are now widely used online also for chemical pulps. Measurement of fiber properties by optical techniques are now a feature of standard laboratory equipment.

In 2011, Lorentzen & Wettre was acquired by ABB, who is proud to continue this long heritage of supporting the research and development of pulp measurements, most recently introducing ABB's L&W Freeness Online and L&W Fiber Online in 2017.

The purpose of this book is to support and motivate people working in all areas of the pulp and paper industry, by introducing new methods for paper making. The book gives a general overview, as well as detailed information, and experience about fiber analysis, and possibilities to use the new information in the pulp and paper processes. It is specifically written for people working with production of pulp and their developers, customers and suppliers.

Learn more about the products mentioned in this book

GO TO L&W PORTFOLIO

GO TO L&W FIBER TESTER PLUS

GO TO L&W FREENESS AND FIBER ONLINE

3. Introduction

The pulp that paper is made from, is more than a diffuse slurry of disintegrated wood. Pulp consists of fibers and each fiber is a fantastic basic building element. The cellulose fiber is strong and has a great bonding capacity of its own, and it can be used to obtain specific properties in a given paper grade. Paper should be regarded as an engineered product and the optimal use of the fiber is therefore of the greatest economic importance. It is also a renewable raw material.

There are many different paper and board grades, and therefore many different uses of fiber: packaging and liquid carton board, newsprint, fine paper, corrugating medium, security paper, cigarette paper, tissue, towels, filters, building elements, etc. Each grade has its own specific demands; the selection and treatment of fibers should be optimized for the specific grade's properties and processes.

For many years, pulp quality was determined by preparing handsheets and then performing paper testing in a “standard” way to assess the suitability of the pulp for sale or for internal use within the integrated pulp and paper mill. Chemical pulp quality was, and in many locations still is, determined by beating the pulp at specified intervals (PFI-mill) and then making handsheets at each interval to evaluate the development of the strength and optical properties.

Fiber length was determined by fractionation through screens with specified mesh sizes. Traditionally, for mechanical pulp (SGW, RMP, TMP, CTMP, etc.), freeness, shives or mini-shives content, linting propensity, fiber length, strength and optical properties were measured after handsheets had been made.

All of these methods were laborious, time-consuming, and prone to error as the pulp went through different operators and equipment. If a mill wanted to determine the quality of its market pulp, it could conceivably take several days before the beating, handsheet making, and testing could be completed. These methods do not lend themselves to process optimization, and pulp mills therefore had to rely upon the online sensors of the day, such as freeness and kappa number. Development in the electronic and computer technology sector have made new measurement methods available for the pulp and paper industry. New technology is used to achieve higher production, less discharge, improved quality (uniformity) and a better use of energy and raw material.

Operator-independent testing provides better accuracy in the measurements. Automatic methods allow for frequent testing and make it possible to follow the process in a way that was not achievable in the past with only manual tests. Feedback (and feedforward) for process control and a final check of product quality before delivery to the customer are also now possible.

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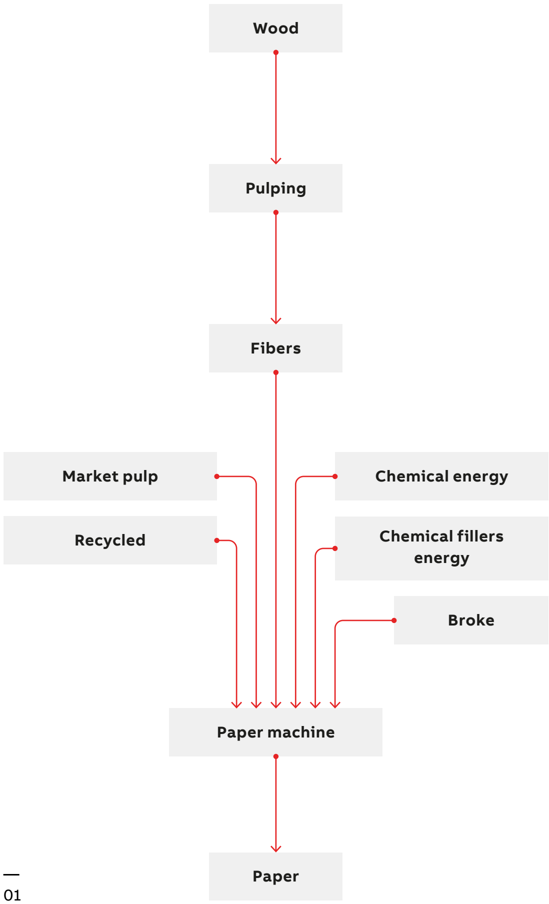
01
Papermaking starts earlier than in the paper machine. The most important cost item in the production of pulp and paper is the cost of fibers.



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01

The new techniques enable mills to think and work in new ways. The development in fiber quality measurements gives us a new language to communicate quality – the fiber language. This is key to more efficient papermaking (Figure 01).

Some people talk about a paradigm shift, which means that people must now have a broader view of what may seem like causal process interactions. How are the processes connected, and why does trouble or deviations from targets occur? In the past, it was usually sufficient if each person managed his or her own part of the process and if suppliers were the subject matter experts for their products. Now, generally speaking, everybody is required to know a lot about the whole system. Customers expect the supplier to not only understand the customer's process well, but also the problems of the customer's customer. Instead of customers and suppliers, you can consider them members of the same "departments".

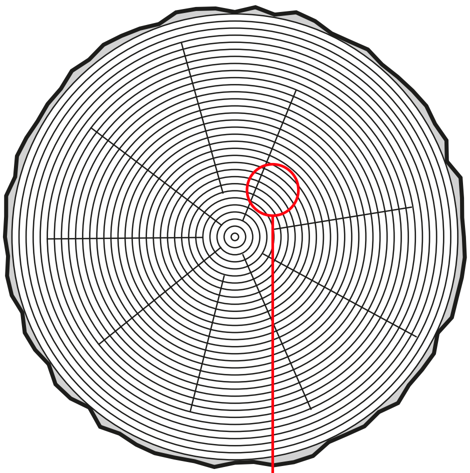
Understanding and speaking the fiber language is a useful tool for communication of quality all along the process chain.

4. Wood parts

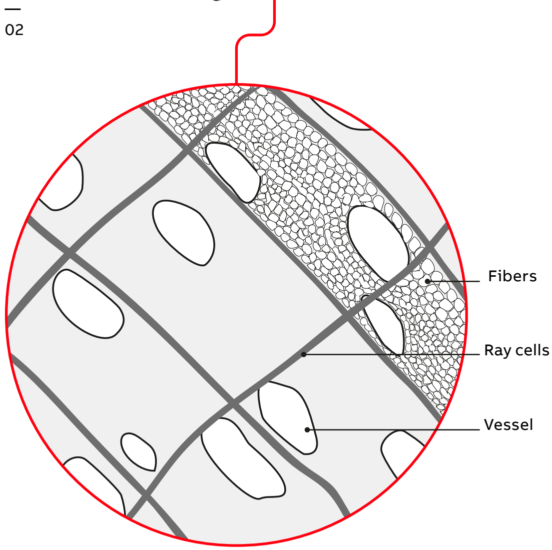
Generally, a tree consists of three parts: a crown composed of leaves and branches, a stem, and a root system. Figure 02 shows a cross-sectional sketch of a stem. It is a schematic diagram valid for both softwood and hardwood. The stem consists of bark (inner and outer), cambium, sapwood and heartwood. The bark is of no interest in papermaking.

The cambium is located between the bark and the sapwood. It is a thin layer of cells where cell growth takes place. The rate of growth varies with the seasons and the growth place, giving rise to the deposition of thin-walled fiber cells in the spring and denser thick-walled fibers in the summer.

The cambium is dormant during the cooler months of the year. This yearly growth cycle is responsible for the annual rings phenomenon, which also enables a tree to be aged by counting the number of rings (Figures 02 and 03).



02
Cross-sectional sketch of a mature stem with fiber annual rings and horizontal channels.

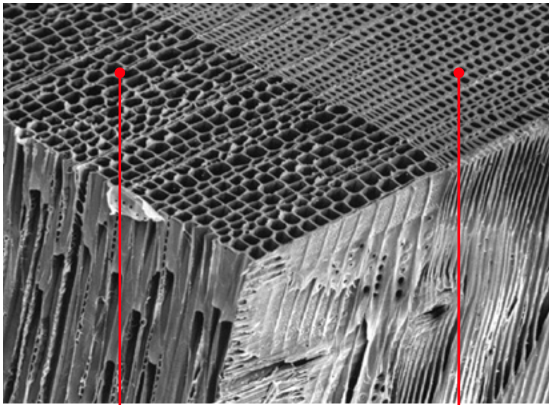


03
Cross-section of hardwood with annual rings, vessel cells and horizontal ray cell channels (cf. Figure 2.6)

The sapwood begins within the cambium layer. It provides structural support for the tree crown, acts as a food storage reservoir, and has an important function of water conduction up from the roots. The inner heartwood functions only as a mechanical support. In most species, the heartwood is much darker in color than the sapwood. Differences in structure of the wood capillaries make liquor penetration in the pulping stage more difficult in the heartwood than in the sapwood.

There are distinct differences between earlywood (springwood) and latewood (summerwood) in regions where the climate has seasonal changes. The earlywood has an open structure due to the fact that during springtime the growth is very intense and large amounts of water are transported through the fibers, making the structure very loose.

Earlywood fibers have a large diameter with a thin fiber wall and tend to collapse in the pulping process. Earlywood is succeeded by latewood, which has thicker fiber walls because of the slower growth during summer and fall. The earlywood is the lighter part of the annual ring, while the latewood is the darker part. These details can be seen in Figures 04 and 05 Latewood fibers in particular have to be beaten to develop strength.



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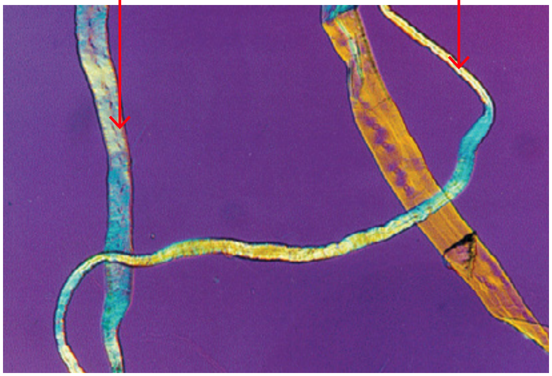
Detail of annual ring



— 05

Earlywood and latewood fibers. The wider, brown fiber is the earlywood.

5. Characteristics of wood

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06
A sketch exemplifying the structure of softwood. Earlywood and latewood fibers are evident. A resin channel can be seen at the top of the picture.

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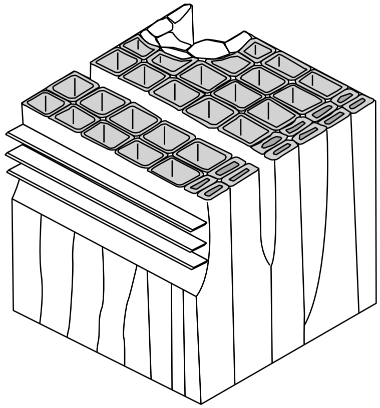
07
Sketch of a wood block exemplifying the structure of hardwood. The open hole is a vessel. The crossing channels include ray cells.

Wood for pulp making can be classified in two main groups: Softwoods (coniferous trees, such as pine, fir, spruce and hemlock) and Hardwoods (deciduous trees, such as birch, aspen, eucalyptus, acacia and oak).

5.1. Softwood
Softwood (Figure 06) is composed of up to 90% long, tapering cells called tracheids. These function both as support and water transportation. The hole in the middle of the tracheid is called lumen. The tracheids are connected to each other through pores. Apart from the tracheids, there are other cell types present, for example resin channels withholding resin, and ray cells. These cells are principally connected with lignin, forming a stable structure.

Ray cells are oriented in a radial direction from the outside of the tree trunk towards its center. They transport waste material (extractives) towards the heartwood and may be used for storage of various food substances. The ray cells accomplish horizontal transport of liquids across the annual rings. Fibers from softwoods are long and strong. The strongest papers are manufactured from chemical pulp made of softwood.



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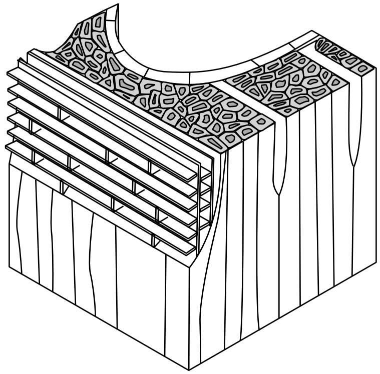

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07

5.2. Hardwood

Hardwoods have a more complex structure than softwoods, with different cells for water transport and support. Elongated libriform fibers function as support and are thick-walled in proportion to the diameter. Shorter, wider cells called “vessels” are responsible for water transportation (Figure 07).

Hardwoods also contain a vertical parenchyma system and a horizontal ray parenchyma system. Hardwood fibers are shorter and thinner, giving a better paper formation than softwood fibers. Hardwood fibers give paper a smooth printing surface and high opacity. Because there is less lignin in hardwood, compared to softwood, it is also easier to bleach the pulp to high brightness.

These qualities make the hardwood fibers suitable for use in printing paper, although this type of paper generally consists of a blend of hardwood and softwood pulps to meet both the strength and the printing surface demands of the customer.

The biggest difference between hardwood and softwood fibers is that the hardwood fiber is considerably shorter and thinner than the softwood fiber. Generally, hardwood contains more cellulose and hemi cellulose and less lignin than softwood, while the proportion of extractives, i.e. resin, is higher.

5.3. Geographical differences

In Scandinavia, the growth period is short but intense, particularly in the northern parts. It lasts from May to September-October, and the growth is idle during wintertime. It takes about 75 years for a Scandinavian spruce or pine to be ready to harvest, compared to a pine in the southern U.S., where it only takes 25 years for the tree to be ready to harvest. This is due to the warm climate all year round.

It takes only seven years for a eucalyptus tree to be ready to harvest when grown on a plantation in Brazil.

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08
Separating tree parts; the dark area is used by the sawmill.

5.4. Plantations

Monoculture tree plantations continue spreading throughout the tropics and sub-tropics, and field trials with genetically modified trees aimed at producing higher yields of a more uniform type of wood are in progress.

The seedlings are produced in nurseries, where they undergo rigorous checking. The parameters that are considered are: length, coloring, and physiological state of the seedling and consistency of the attached clod of earth. This result in a homogeneous and controlled structure of the wood produced at the plantations. Another advantage with plantations is the cost-effective and fast transportation of wood to the mills.

Among the most significant disadvantages of plantations are pests, diseases and fires. The more homogeneous a plantation is, the higher the risk of pests and diseases. These risks can normally be controlled through proper planning and management.

5.5. Differences in fiber properties within a tree

There are differences in fiber properties both between different tree species and within the same tree species. This leads to heterogeneity and time variations in the wood flow to the mill.

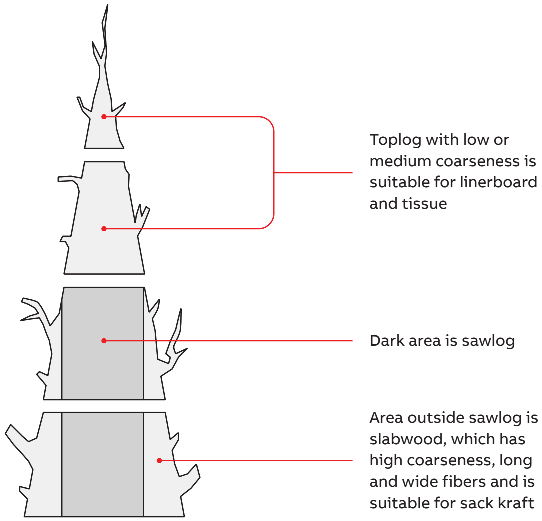
The usual way to process the tree is that the lower part of the stem and middle section of the stem go to sawmills, while the top section and thinnings become raw material for pulp and paper manufacturing (Figure 08). At sawmills, the outer layers of the stem become wood chips.

Three types of pulp raw material with different fiber properties are available:

- The top from older trees
- The lower, outer parts from older trees (sawmill chips)
- Young trees (thinnings)

5.5.1. Top and lower section of the stem

Juvenile wood comes from the first years of growth; it stretches to the top of the tree throughout its lifetime. There are fewer annual rings at the top of the tree, and the cambium has not yet reached its maturity stage, which means the wood is thin-walled, slender, and with relatively short fibers.



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08

The oldest parts of the tree are located in the lower section of the stem. The number of annual rings is at a maximum, as are the number of cell divisions that have taken place in radial direction. Fibers are longer in more mature wood. Therefore, there is a large variation in fiber dimensions, since the tree has both juvenile and mature wood.

5.5.2. Thinnings

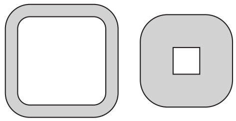
A stand of trees, or a contiguous community of mostly uniform trees, is often thinned several times during its lifetime. The trees are often about 30 years old at the first thinning. Wood from these kinds of thinnings has a considerable proportion of juvenile wood, with thin-walled and short fibers. Final cutting wood has, on the other hand, a large proportion of thick-walled long fibers.

5.5.3. Variations within a tree

The variations within a tree species depend on geographical locations, stands, variations between trees within a stand, variations between logs within a tree and variations within a log.

An understanding of the principal differences in properties between and within trees can be used to predict the kind of fiber properties that one can find in the above-mentioned assortment.

Even inside one tree there is a big difference in properties for different parts; from pith to bark, from ground level upward (fiber length increases from top to root) and differences due to growth rate. There are also differences between adjacent cells and within the growth ring. Fibers from earlywood have a large diameter, a thinner fiber wall and a shorter fiber length than latewood (Figure 09).



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09
Cross-section of earlywood and latewood fibers

Latewood fibers are thick walled and longer than earlywood. Table 1 shows differences between earlywood and latewood and amongst species. Fiber property models for different stands have been reported and can be used as tools to predict the fiber properties of logs. Effective sorting of pulpwood logs requires the detection of log diameter and number of growth rings, and also the position of a log within a stem. The advantages of the application of fiber property models are added value and cost savings, but there are also additional costs for wood procurement and mill handling.

Table 1: Fiber dimensions in pulp for some different trees.

	Loblolly Pine (US)		Swedish Pine			
	Earlywood	Latewood	Earlywood	Latewood	Eucalyptus	Birch
Fiber length [mm]	3	3.5	2.7	3	1	1.1
Fiber width [µm]	45	35	35	25	16	22
Lumen diameter [µm]	32	12	30	10	10	16

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10
Cross-sectional sketch of a stem and how its divided into planks. The outer parts are processed into chips for production of pulp.

—
11
Fiber dimensions depend on species and origin of the wood.

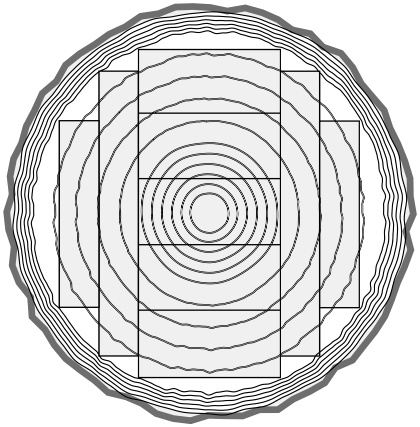
5.5.4. Sawmill chips

The parts of the log that are not used for making planks become chips. These chips are mostly produced from the outer layers of the stem (see Figure 10); therefore, the larger portion of the sawmill chips is from sapwood.

The sapwood chips are proven to have a considerably faster impregnation rate than those made of heartwood. Sawmill chips of pine are stiffer than those made of spruce because they have a thicker cell wall.

Since sawmill chips come from the outer part of the tree, these fibers are longer and wider than those from round-wood.

Spruce fibers are on average slightly longer and thinner than pine fibers. Wood chips from sawmills normally include longer and broader fibers than round-wood or thinnings. The two-dimensional fiber distributions move as indicated in Figure 11, depending on the mix of wood parts, pine and spruce.



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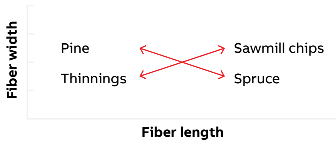

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12
Vessel cells from acacia, eucalyptus, and birch respectively. The first two samples show similar vessel cells, as they are both tropical trees, compared to birch which is a tempered zone tree.

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13
Stone cells

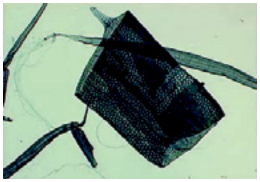
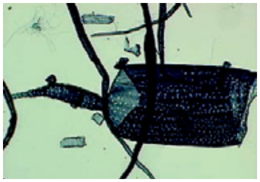
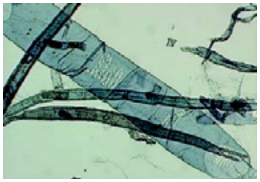
5.6. Other woodparts

5.6.1. Vessel cells

In softwoods, longitudinal tracheids function both for support and for water conduction. The cells have closed ends. Most hardwood species contain short, wide, open-ended cells called vessels, which function for water conduction, and closed-ended fibers that function for support. Vessel elements vary in size and shape between and among species and are normally much wider than the fibers (Figure 12). Vessel cells are not wanted in the pulp because they cause problems, such as vessel picking. In Nordic birch, about 9% of the wood volume is vessel cells. The percentage of weight is much less because of the thin walls of vessel cells.

5.6.2. Schlereids (stone cells)

Schlereids are present in Nordic deciduous trees and can cause problems in the papermaking process. They are a strengthening element in the tree and have thick, often lignified secondary walls. Schlereids are found in wood and bark and are called “stone cells” (Figure 13). They are roughly square and not elongated like a fiber. They are usually equivalent in width to a shive of several fibers. They can be mistaken for a shive. Schlereids are hard and highly lignified supporting cells that in paper cause holes, tears and fisheyes because fibers do not bond to them. Schlereids can be measured with a shive analyzer.

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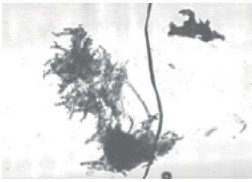

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5.6.3. Ray cells (parenchyma cells)

The horizontal structure of conifers is composed of narrow rays that are only one cell in width but often several cells high. There are two specialized types of ray cells: the ray parenchyma, present in all species; and ray tracheids, present in only certain species. Extractives are produced by the ray parenchyma cells. Ray tracheids are dead cells. Parenchyma cells affect the strength of pulp sheets negatively. Generally, most hardwoods have shorter parenchyma cells than softwoods. About 1–2% of the volume in Nordic softwood and about 5% of Nordic birch is estimated to be ray cells.

5.6.4. Resin acids

As mill waters are recycled, the concentrations of wood extractives increase. Of special concern is the resin acid because of its toxic nature and detrimental effects on the pulp and paper making process. Resin acids are released from wood during mechanical pulping processes, and high levels of these substances are associated with problems such as pitch deposits, reduced paper strength and decreased brightness. Resin acids are also known to be toxic to aquatic life. Pulp and paper mills using softwoods as a furnish release resin acids from wood chips into process waters, regardless of the pulping method.

6. Fiber origins

14
Twig of acacia

15
Twig of birch

Pulp fibers can be extracted from almost any vascular plant found in nature, but a high yield of fibers is necessary to give an economic profit. Today, pulp from virgin fibers is produced mostly from wood fibers (more than 90%). Depending on location and climate, pulpwood properties vary. The rest is produced from non-wood fibers like bagasse, straw and bamboo.

6.1. Acacia
Acacia is a fast-growing tree, which grows naturally in Western and Northeast Africa. It is raised on plantations for pulp production in e.g. Asia. They often have many small oval leaves and attach to the main stem by a leaf stalk called a leaf petiole (Figure 14). The fibers are short and suited for fine paper production.

6.2. Aspen
Aspen is a hardwood with brighter fibers than birch. It grows all over the world, e.g. Europe, Asia, North Africa and North America. Aspen is used to produce both chemical and mechanical pulp. The fibers are short with fine walls and suited for fine paper. Mechanical pulp from aspen is so bright that it can be used as a bonding layer in coated fine paper.

6.3. Birch
Birch belongs to the hardwood category, and it grows mainly in Europe, North America and temperate Asia. Their leaves may be toothed or pointed with serrated edges (Figure 15). The fibers from birch are much shorter than those from pine and spruce. They are mainly used in chemical pulp production.

14

15

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16
Twig of eucalyptus

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17
Twig of pine

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18
Example of dimensions of fibers (softwood and hardwood), vessel cells and a ray cell. In practice they all vary a lot in size and must be described with distributions (see Ch. 16 "Statistics and reports"). The smallest object to the right might be a fibril. Fibrils build up the layers of the fiber wall.

6.4. Eucalyptus

Eucalyptus is the world's fastest growing tree. It is raised in plantations where the climate is warm and humid, e.g. in South America, Southern Europe and Asia. Eucalyptus leaves are long and pointed with smooth sides and a leathery texture (Figure 16). The eucalyptus fibers are short and suited for fine paper production.

6.5. Spruce

Spruce fibers are, like pine fibers, relatively dark and long and grow all over the world. They are mainly used in the production of mechanical pulp. Mechanical pulp made from spruce has an ISO-brightness of 60–65%; a sufficient brightness for newspaper. For the production of many other grades, the pulp needs to be bleached to achieve the desired brightness.

6.6. Pine

Different species of softwood pine grow all over the world and can be identified by needles growing in clusters (Figure 17). Fibers from pine are relatively dark and long. They are used mainly in the sulphate process but also in the production of mechanical pulp. The high content of resin makes it difficult to use fibers from pine in the sensitive sulphite process.

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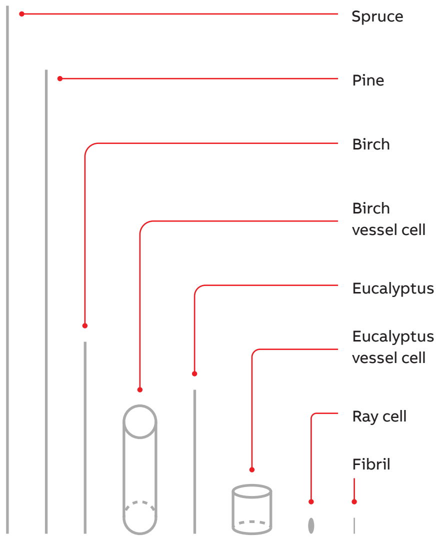

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16

Table 2: Properties of pulpwoods

Species	Fiber length (mm)	Fiber diameter (µm)	Fiber wall thickness (µm)	Coarseness (µm/m)
North America				
South Pine	3.6–4.9	35–45	5–10	230–300
Northeast region Spruce, Pine, Fir	3.3–3.5	25–40		
Northwest region Fir, Hemlock	2.5–4.2	30–45		
Redwood	6.1	50–65		
Aspen	0.7–1.3	10–27	2–3	86
Birch	1.2–1.85	20–36		
Beech	1.0–1.5	16–22	2–3.6	86–114
Oaks	1.40	14–22		
Red Gum	1.70	20–40		
Black alder	1.2	28		
South America				
Eucalyptus	0.9–1.0	14–16	4–4.5	80–90
Europe				
Pine	2.5–3.6	25–39	2.9–4.0	160–200
Birch	1–1.5	16–22	2–3.6	86–114
Spruce	2.5–3.5	24–59	2.9–6.2	
Asia				
Acacia	0.9–1.0	14		75–90
Balsam	3.5	35–40		

6.7. Non-wood fibers

After wood, cotton is the second most important fiber type. For example, linters, i.e. the fine, silky fibers combed away from the collected cotton, are used in security paper. Annual plants containing very long and strong fibers like flax and ramie are used mainly in textiles, but they are also found in cigarette and filter papers. Cotton must be extensively beaten to develop the desired properties.

Other non-wood fibers besides cotton include:

- **Bamboo** is classified as a tropical grass with a high content of long fibers and is a widely used paper source. Bamboo pulp is an important raw material for strong paper in Asia. An interesting feature of bamboo is that its fiber characteristics offer a wide range depending on the species; some bamboos have fibers similar to hardwoods, softwoods or an intermediate between the two.
- **Straw pulp** is manufactured by a relatively simple alkali cooking procedure. In addition to bast fibers, straw contains cells of different kinds of botanical character, of which many are thin walled and short.
- **Bagasse** is sugarcane residue left after extracting the juice and consists of short fibers. Its fibers are principally used as a raw material for unbleached wallboard.
- **Hemp** fibers are extremely long, which makes it hard to use them to produce a homogeneous paper sheet. Therefore, they have to be cut to the right size before pulp manufacturing. Hemp is an annual crop; and the wood components are therefore younger than the average tree fibers used in papermaking. There is a very special use for the hemp pulp, which partly explains the high price. Most of the mills that use hemp fibers are located in China and India and produce moderate quality printing and writing papers. In the western world, hemp is used in specialty papers like cigarette paper, filter paper (for technical and scientific uses), coffee filters, tea bags and security papers.
- **Mulberry paper** (known as Kozo in Japan) is made from mulberry tree pulp. The fiber is obtained from the inner bark of the mulberry. Mulberry contains long fibers, less lignin, high pentosan and high alpha-cellulose and is therefore a good raw material for papermaking. However, this chemical composition depends on the age of the mulberry tree. Mulberry paper is unique and is a good material for letters, security paper, business cards, wrapping paper, hand-made flowers, etc. Because of its special characteristics—such as strength, ink receptivity and stability—it can be used in many applications like paper for oil painting, filter paper, paper clothes and tea bags. The main pulping process applied in the production of mulberry paper is the kraft process.

6.8. Synthetic fibers

It has been predicted that a widespread use of synthetic fibers may eventually occur in the paper industry. An active interest has been evident in recent years, from both fiber producers and paper manufacturers. A lot of specialty paper products are currently being made from synthetic fibers. The advantages of synthetic or man-made fibers for papermaking fibers are summarized below:

- **Size:** Natural cellulose fibers vary considerably in size and shape, whereas synthetic fibers can be made uniform with a selected length and diameter. Long fibers are necessary for producing strong, durable papers. There are, however, limitations to the length of synthetic fibers that may be formed from a suspension in water because of their tendency to tangle and rope together.
- **Heat and chemical resistance:** Natural cellulose fibers have a limited resistance to chemical attack and heat. Synthetic fiber papers can be made resistant to strong acids and are therefore useful for chemical filtration. Papers can also be made of glass fibers. These papers have a great resistance to both heat and chemicals.
- **Influence of atmospheric conditions:** Natural cellulose fibers are hygroscopic; i.e., they absorb moisture from the air and reach an equilibrium that depends upon the relative humidity. Therefore, the moisture content of paper changes with the atmospheric conditions. These changes cause swelling and shrinkage of fibers. Synthetic fibers are not susceptible to these changes and can be used to produce dimensionally stable papers. Rayon swells and absorbs water, which needs to be considered when testing with rayon fibers.

While synthetic fibers offer many benefits, they can be more expensive than wood pulp. The cheapest man-made fiber (rayon) costs three-to-six times as much as an equivalent amount of wood pulp, whereas most of the true synthetics, such as the polyamides (nylon), polyesters, acrylics, and glass, cost 10–20 times as much.

This increase in cost does not prevent the use of synthetic fibers, but it limits their use to special products in which the extra qualities justify the additional cost.

Table 3: Properties of non-wood fibers

Species	Fiber length (mm)	Fiber diameter (µm)
Bamboo	2.8	15
Straw	1.5	13
Bagasse	1.7	20
Hemp	20	20
Cotton	20	20
Reed	1.2	12
Wheat	1.5	13
Rice	1.5	8.5

6.9. Recycled pulp

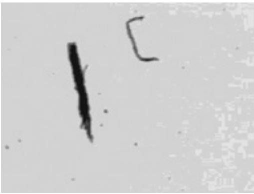
The definition of secondary fiber (recycled pulp) is any fibrous mass that has undergone a manufacturing process and is being recycled as the raw material for another manufactured product. Fiber substance and strength are lost during each recycling step. It is generally considered that a fiber can recirculate on an average of six-to-seven times, so it is necessary to sort and classify the material into suitable quality grades for an effective utilization of wastepaper.

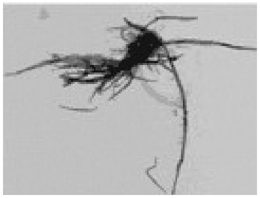
6.10. Contaminants

There are many contaminants that can affect the papermaking process (Table 4 on the next page), but we'll cover the most common.

6.10.1. Shives

Shives are fiber bundles found in pulp and paper. They derive from incomplete fiber separation during the pulping process. Shives are an important factor that can trigger web breaks and also reduce paper strength.





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To the left: a shive of 1.2 mm length (from DIP pulp), and a fiber as comparison. To the right: a fiber bundle that has separated during the pulping process but “bundled up” again.

6.10.2. Stickies

Stickies are troublesome contaminants found in recycled pulp. They originate from adhesives in tapes and labels, self-sealing envelopes, hot melts and latex used in the coating.

The best way to deal with stickies includes avoiding them (by selecting the source of pulp), removing them during the deinking of wastepaper, or use slotted screens. Since they escape the mechanical cleaning and screening, they end up in the paper machine, wire or in the end product, causing machine downtime or downgraded products.There is a pronounced problem in fine paper production, especially if the machine is fast and/or has a twin-wire former.

6.10.3. Dirt

Dirt is any foreign material in pulp. TAPPI defines dirt as “foreign matter in a sheet which, when examined by reflected (not transmitted) light, has a marked contrasting color and has an equivalent black area of 0.04 mm^2 (0.2 mm × 0.2 mm) or more." Dirt content of pulp, and particularly of recycled pulp, is important for its suitability to make fine paper. The standard procedure for measuring dirt content is laid out in TAPPI T213.

Table 4: Common contaminants in recycled pulp.

Contaminant	Originates from	Types of in-mill processing difficulties
Hot melts	Adhesives and coatings	Cleaning system cannot handle adequately, fouls equipment, causes defects in products
Polystyrene foam	Blocks, beads, etc. used in packing	Difficult to remove - sticks to rolls, indents sheets
Dense plastic chips	From blister packs and see-through packages	Breaks into small pieces, hard to remove, causes “shiner” in product
Plastic films	Laminated to paper	Slows down pulper process, causes product defects
Wet strength resins	Papers treated with resins	Does not disperse in pulper, can cause spots in product
Latex	Rubber latex as adhesive, lining or coating, including flying pasters and rubber bands	Degrades product, difficult to remove
Pressure sensitives	Miscellaneous uses; splicing rolls, case-sealing etc.	Sticks to wires and felts and deposits on wires, can cause web breaks
Waxes	Paper or paperboard laminates and coatings	Fails to disperse in pulper, degrades product
Asphalt	Paper or board laminated or coated with asphalt	Coagulates in pulping process, sticks to wires, causes black spots in product
Fibers	Vegetable and synthetic fibers used for rope	Causes product defects and web breaks

7. Fiber structure

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Illustration of a cell wall organization of fibers

7.1. Structure of the wood fiber wall
Every fiber has a complex inner structure and a chemical composition that determines its mechanical properties. The fiber structure contains layered walls. Figure 20 shows the different layers labelled: P (primary wall), S1 (secondary wall first layer), S2 (secondary wall second layer) and S3 (secondary wall third layer). The hollow region in the center of the fiber is called the lumen. The region between the fibers is called the middle lamella and consists mainly of lignin. The illustration shows the specific alignment of the cellulose fibrils in the secondary walls. Fibrils are an amassment of cellulose molecules, and their orientation can influence the characteristics of a pulp fiber.

7.2. Chemical composition
Wood mainly consists of three types of materials; cellulose, hemi cellulose and lignin (Table 5) . The relative composition in the wood varies in different species of trees (Table 6).

Cellulose is the main component of the fiber. It is a (carbohydrate) straight-chain polymer composed of glucose residues, and it is the structural material out of which the fiber is built. Cellulose is insoluble in most solvents, and it is resistant to the action of most chemicals except strong acids.

Cellulose is also very important to paper properties because the attraction between cellulose molecules in different fiber surfaces is the principal source of fiber-to-fiber bonding in paper.

Hemi cellulose is the second major component in a wood fiber. It is also a polymer, and it can be removed by mild chemical action. It is built up of branched molecule chains of glucose and other monosaccharides. The molecule chains are much shorter than in cellulose. Hemi celluloses are very important in papermaking because they promote the development of fiber-to-fiber bonding through their influence on the ability of fibers to take up water during processing and their direct participation in the bonding.

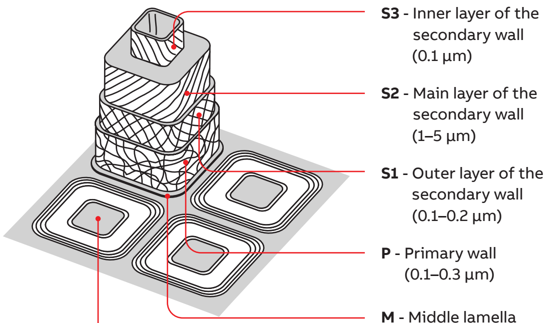

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Table 5: Distribution of chemical components in wood fiber wall. The middle lamella contains mainly lignin.

Wall layer	Lignin (%)	Cellulose (%)	Hemi cellulose (%)
Middle lamella	90	0	10
Primary wall	70	10	20
Secondary wall, S1	40	35	25
Secondary wall, S2	15	55	30
Secondary wall, S3	10	55	35

Table 6: Average compositions of softwoods and hardwoods (%)

Species	Cellulose	Hemicellulose	Lignin	Extractives and others	Vessels	Ray cells
Softwoods	42	27	28	3	No	Yes
Birch	45	30	20	5	Yes	Yes

The third major component in a wood fiber is lignin. Lignin is found between the fibers where it serves as a binding agent. It also occurs within the fiber wall. Lignin is very complex and does not dissolve in water or other common solvents, but it can be made soluble by chemical action. The purpose of all chemical pulping processes is to dissolve and remove lignin. However, there is no practical method for complete lignin removal by pulping. The residual lignin gives the unbleached paper a brownish tint, and if white paper is to be made, the remaining lignin must be removed by bleaching. Lignin prevents the formation of fiber-to-fiber bonds in paper, reducing its strength.

Besides cellulose, hemi cellulose and lignin, the wood also contains extractives (for example resin). These contaminants form unwanted dots on the paper. Chemical pulping and bleaching processes mostly remove these components. However, trace amounts do survive and cause problems in pulp and paper mills. Examples of problems are linting in offset printing and missing dots in gravure printing.

The compositions of softwoods and hardwoods differ from each other. Hardwoods contain more cellulose, skeletal polysaccharides, extractives and hemi celluloses than softwoods, and the lignin content is lower.

7.3. Degradation pattern

In chemical pulping, the middle lamella is dissolved during cooking. The primary wall and the first layer of the secondary wall (S1) are also affected but may remain after the digester depending of the yield. Mechanical refining will initially remove parts of these layers. For lower yields or after bleaching, these layers will be removed. The fibrils are strictly oriented in the secondary wall (S2) and, according to the literature, the fibril angle (relative to the fiber axis) is known to correlate well with mechanical properties of the sheet.

The fibril angle changes during the first years of the tree's growth and becomes more constant with age. The non-oriented layers P and S1 function as a kind of bond for the fiber. When these layers are removed, which happens in chemical pulping after some mechanical treatment, the orientation of the fibrils in the S2-layer affects the fiber shape. Small changes in the length of the fibrils affect the shape of the whole fiber.

In mechanical pulping, the lignin is softened at a high temperature, which helps to separate the fibers mechanically. Lignin rich parts will still be a part of the fiber fractions. More information about refining and degradation pattern is given in Chapter 9.

7.4. Importance of fiber properties

Paper properties depend strongly on the structure of the fibers that build up the sheet. The manner in which fiber properties affect sheet properties is described in Chapter 18 "Impact of fiber on products". The fiber length and other fiber dimensions are influenced by the method used to separate the fibers. To manufacture Stone Groundwood (SGW) for example, the fiber is shortened considerably. Chemical pulp is cooked, and in this process, a large amount of substances other than cellulose is removed by dissolution.

This leads to a decrease in the fiber wall thickness, resulting in collapsed fibers (two opposite walls are pressed together and completely or partly eliminate the lumen) and a greater strength in the paper. From a general point of view, long fibers enable good paper strength properties.

The curvature of the fibers has an influence on paper properties. Increased curvature contributes to a high stretch ability and tensile energy absorption, which is important in sack paper for example. Thick-walled fibers provide high bending stiffness but weak paper; thin-walled fibers provide low bending stiffness but good paper strength.

8. Manufacturing processes – an overview

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Papermaking starts with the selection of raw material

Fiber properties vary within single trees, between trees (depending on the growing situation) and of course between different species. Selection of wood is the start of the papermaking process.

In recent years, more attention has been paid to this early part of the process (Figure 21).

8.1. Table of symbols
Following is a presentation of the symbols that are used in the different process illustrations in this chapter.

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Table 7: to be referenced for process illustrations used in this chapter.

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Log preparation to create chips in a pulp mill.

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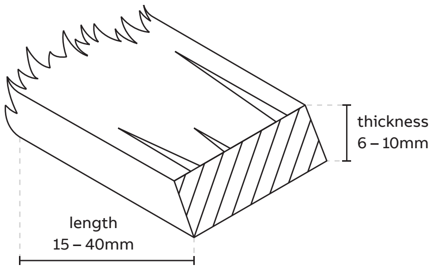
23
Typical dimensions of a wood chip.

8.2. Log preparation
Large amounts of wood are handled by the pulp mill, and the organization of the wood yard has a considerable impact on the final pulp quality. Chip damage means reduced pulp quality, and fiber losses have a severe effect on the economy of the mill. When the logs arrive at the mill, their weight or volume is determined. If the logs are frozen, de-icing is required in order to facilitate barking.

Sand and stones are removed in the de-icing step as well as after barking. This is done particularly to reduce the wear on the chipper knives. For that reason, a metal detector is also placed before the chipper infeed to detect any metal scrap. Thereafter the logs are reduced to smaller pieces in the chipper and passed on to storage.

8.2.1. Chipping
To promote a fast and uniform release of the lignin in wood, logs are cut into chips (see Figure 22). The width varies and is not of great importance but thickness and length are (Figure 23). The thickness of the chips is most important because it helps ensure that all the wood material can be efficiently impregnated with cooking chemicals. The average fiber length is reduced after chipping and depends on the chip length. Chipping is usually carried out in a chipper or reducer chipper. Before pulping, the chips are screened to ensure a uniform size distribution. Pin chips and fines are discarded and used as fuel. Oversized chips are reduced in size and fed to the refiner or digester.



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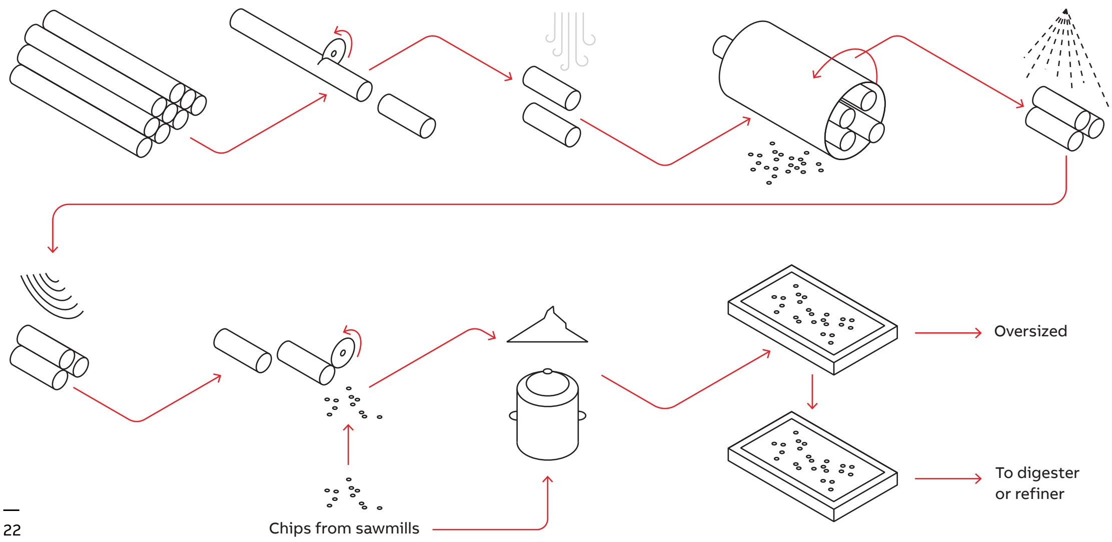

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8.3. Pulping processes

In a pulping process, wood is separated into fibers. This can be achieved mechanically, thermally, chemically or through a combination of these treatments (Table 8).

8.3.1. Mechanical Pulping

The principle of mechanical pulp making is to liberate wood fibers entirely by mechanical means. There are two fundamental mechanical pulp manufacturing processes: the groundwood and the refining processes. The pulps manufactured are called stone groundwood (SGW), refiner mechanical pulp (RMP) and thermo-mechanical pulp (TMP). The mechanical pulp manufacturing process is very high in energy consumption.

The advantage of mechanical pulp is the high wood yield—over 95%. The pulp also has a high opacity, which means that thin papers with good printing properties can be manufactured.

However, since the lignin is retained in the pulp, papers from mechanical pulps tend to yellow; a reduction in brightness as a result of aging or exposure to light.

Mechanical pulps are therefore used in short lifetime papers. Mechanical papers are weaker than those with chemical pulps, principally because the fibers are shorter and stiffer, resulting in less bonding points. Mechanical pulp is mostly produced from softwood, and is mainly used in newspaper, weekly magazines, some tissue products, and cardboard.

8.3.2. Online sampling

A number of process illustrations are presented in this chapter, with recommended marked positions for automatic sampling equipment like ABB's L&W Fiber Online. Besides the marked positions, manual sampling with benchtop equipment like L&W Fiber Tester Plus is recommended on each individual machine (refiner, etc).

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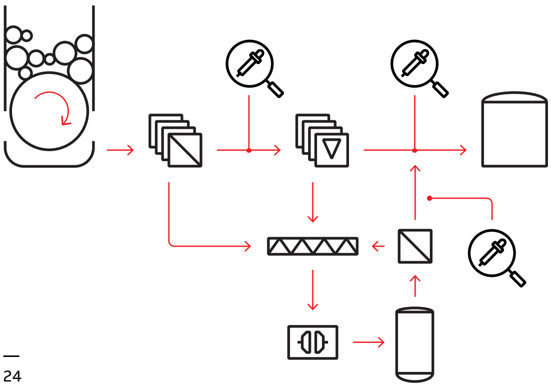
Table 8: General classification of pulping processes

Mechanical	Hybrid	Chemical
Pulping by mechanical energy	Pulping with combinations of chemical and mechanical treatments	Pulping with chemicals and heat
High yield (90–95%)	Intermediate yield (55–90%)	Low yield (40–55%)
Includes a significant number of fines and medium fractions – Weak paper	"Intermediate" pulp properties (some unique properties)	Long, pure fibers – Good strength
Softwood	Softwood and hardwood	Softwood and hardwood
Good print quality		Poor print quality
Difficult bleaching		Easy bleaching
Examples:	Examples:	Examples:
Stone groundwood	NSSC	
RMP	BCTMP	Kraft
TMP	CTMP	Sulphite

8.3.3. Stone groundwood pulping and pressurized groundwood pulping

The oldest method of mechanical pulping is the stone groundwood process (SGW), where a block of wood is pressed lengthwise against a roughened, revolving grindstone (with a diameter of 1.5 m and a rotation speed of 240–300 rpm) and the fibers are torn out and washed away from the stone surface (Figure 24). The water also cools the grindstone. While the principle is simple, it may be hard to achieve a uniform quality. The roughness of the grindstones must be carefully controlled, and the pressure against the grinding stone as well as the temperature and water flow must be checked.

Pressurized groundwood (PGW) is produced by a similar method where the grinder is pressurized with steam. This improves the fiber separation and the pulp gets better physical properties than SGW- pulp, and also less energy is required than in the SGW-process.



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SGW-process.
The pulp is screened in holed or slotted screens and in hydro-cyclones. The rejects are treated in a reject refiner. Fines content, length/width distribution, shives and freeness are of interest to monitor.

8.3.4. Refiner mechanical pulping

Refiner mechanical pulp (RMP), is manufactured by the defibration of chips or sawdust in a disc refiner. Softwood chips pass through a narrow opening between rotating metal discs that are 1.5 m in diameter. The defibration was initially carried out at atmospheric pressure but refining under increased steam pressure was later introduced.

The process usually involves two refining stages in a series, producing a longer fibered pulp than conventional groundwood. The pulp is stronger, bulkier and contains fewer fines, but it is somewhat darker in color than stone groundwood. The mechanical properties are also better.

8.3.5. Thermomechanical pulping

Thermomechanical pulp (TMP) is the most common type of mechanical pulp and is a modification of RMP. It involves steaming the raw material for a short period of time prior to and during refining (Figure 25 on the next page). The steaming has a softening effect on the chips, resulting in pulp with a greater percentage of long fibers and fewer shives than RMP. These long fibers produce a stronger pulp than either SGW or RMP.

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Simplified process illustration over the TMP-process. Two refining stages are used here (1, 2 or 3 stages can be used) followed by a latency chest and screening in two parallel lines. Rejects are treated in a reject refiner, which is also followed by a latency chest. Freeness, shives and fiber length are commonly measured online. Manual sampling positions are marked after the individual refiners.

8.3.6. Chemical pre-treatments

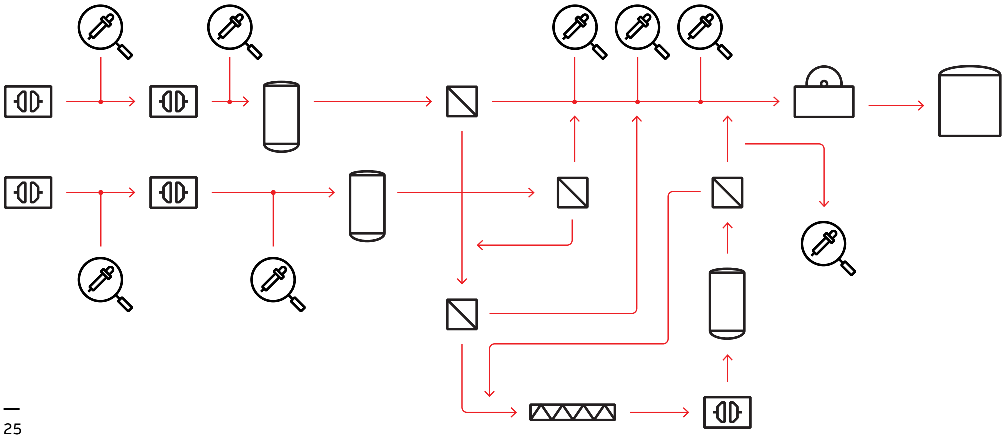
A thermomechanical pulp can be modified with small amounts of chemicals, usually sodium sulphite (Na_2SO_4), prior to defibration in a refiner. This pulp is called chemical mechanical pulp (CMP) or chemical thermo mechanical pulp (CTMP). Hardwoods such as birch and aspen can also be refined with these methods.

The additives usually result in an improvement in pulp strength, while the opacity and light scattering ability decrease.

If the pulps are bleached, they are called bleached chemical mechanical pulp (BCMP) and bleached chemical thermo mechanical pulp (BCTMP – Figure 26 on the next page).

There are many non-integrated BCTMP mills producing market pulp.

Refining is usually done at high consistency (30–40%), but it has also becomes more and more common to include low consistency refining in mechanical defibration systems.



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Simplified process illustration over the BCTMP process. The TMP process is combined with pre-impregnation stages and with bleaching after washing. Brightness, freeness, shives and fiber length are standard measurements.

8.3.7. Chemical pulping

In chemical pulping, the objective is to degrade and dissolve away the lignin and to leave behind most of the cellulose and hemi cellulose, i.e. the fibers. This is achieved by treating the wood chips at an elevated temperature in a solution containing the pulping chemicals until a certain degree of delignification is reached.

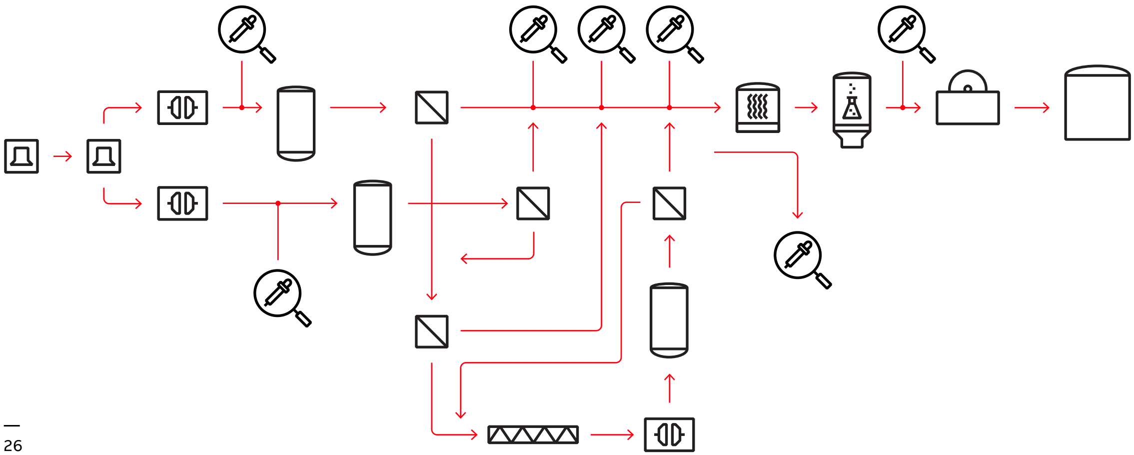
The process is referred to as cooking (Figures 27 and 28 on the next page). It is undesirable for the cooking liquor to boil, and thereby generate vapor, so it is performed in a pressurized system. After cooking, the pulping chemicals are recovered.

Almost all of the lignin is generally dissolved, but the amount of cellulose and hemi cellulose is also reduced. The yield of chemical pulp is low relative to mechanical pulping, usually 40–70%.
The two main procedures are the (alkaline) kraft process and the (acidic) sulphite process.

8.3.8. Kraft process

The most common method is the (alkaline) kraft process, which can be used with all kinds of wood. Advantages of the process are high chemical recovery and high pulp strength. Chemical recovery is an essential part of making the kraft process economically feasible. The kraft process involves cooking the wood chips in a solution of sodium hydroxide (NaOH) and sodium sulphide (Na_2S). The cooking process softens and dissolves the lignin that holds the fibers together in the wood.

As a result, the fibers are readily separated when the pulp is expelled from the digester. Strong paper products are manufactured from kraft pulp, but the unbleached pulp has a dark brown color. The yield of unbleached kraft pulp is 65–70% (used in bags and linerboard), bleachable kraft pulp has a yield of 47–50%, and bleached kraft pulp has the lowest yield, 43–45%, and is used in white papers.



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Continuous digester, unbleached pulp. The pulp is washed and screened after the digester and different kinds of mechanical refining are often carried out in the pulp mill. Kappa number, shives content, fiber properties and freeness are of interest to monitor.

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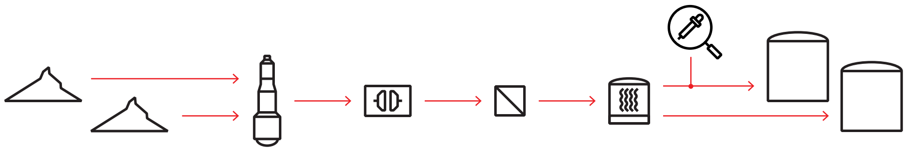
Batch cooking. Five batch digesters are here followed by a buffer. The pulp is screened before entering the oxygen reactor and a new buffer. A bleach sequence is performed before the final pulp storage. Brightness, shape factor, fiber width and length, vessel cells (HW) are monitored.



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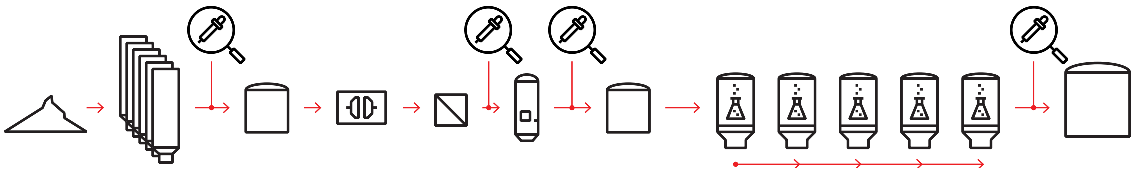

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8.3.9. Sulphite process

Sulphite pulps are lighter in color than kraft pulps and can be bleached more easily. The yield is in the region of 48–51%, but the resulting paper is weaker than that made with kraft pulp. The (acidic) sulphite process works well for softwoods such as spruce, fir and hemlock, and hardwoods such as poplar, birch and eucalyptus.

Resinous softwoods are more difficult to handle. Sulphite pulping makes the lignin water-soluble. Due to its sensitivity to wood species, weaker pulp, greater difficulty in chemical recovery and long cooking time, sulphite pulping is not used much today.

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NSSC cooking. A continuous digester combined with high consistency refining. The shives content before refining can be as high as 12%. Kappa number, shives and fiber dimensions are important measurements.

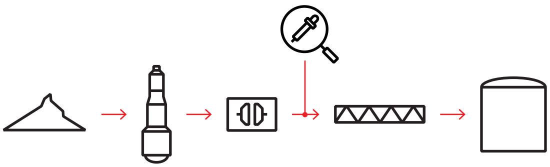
8.3.10. Advantages of the two major processes for chemical pulping

- Kraft process:
  - Produces highest strength pulp
  - Handles wide variety of species
  - Tolerates bark in the pulping process
- Sulphite process:
  - Produces bright pulp that is easy to bleach to full brightness
  - Produces higher yield of bleached pulp than the kraft process
  - Produces pulp that is easier to refine for papermaking applications

8.3.11. Semi-chemical pulping

Semi-chemical pulping combines chemical and mechanical pulping. The wood chips are partially softened or digested with chemicals, and the rest of the pulping process is carried out mechanically, most often in disc refiners.

Semi-chemical methods include pulp yields in the range of 55–90%. The NSSC process (neutral sulphite, semi-chemical) is the most common used semi-chemical process. It is mainly applied to hardwood chips.



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The NSSC process utilizes sodium sulphite cooking liquor, which is buffered with sodium carbonate to neutralize the organic acids liberated from the wood during cooking (Figure 29). An optimal balance between cooking and refining results in the least amount of fiber loss for the best economy. The shives content is quite high. As a prime example, NSSC- pulp is suitable for the center layer in corrugated containerboard.

8.3.12. Dissolving pulp

Dissolving pulp is a chemical pulp intended primarily for the preparation of chemical derivates of cellulose. It is utilized for chemical conversion into products such as rayon, cellophane, cellulose acetate, cellulose nitrate and carboxymethyl cellulose. Dissolving pulp is made by either a modified kraft or a modified sulphite process.

The purpose is to produce fairly pure and uniform cellulose. Lignin and hemi celluloses are considered to be contaminants and are therefore removed. The major raw material is softwood, but some hardwood is also used.

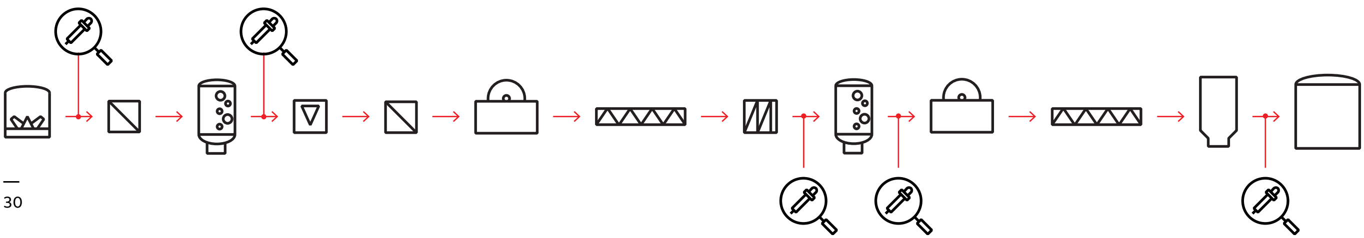
30
A recycled fiber plant with its different operational stages. Measurements of residual ink, brightness, fines content, ash.

8.3.13. Recycling and De-inked Pulp (DIP)
The paper industry is the sole user of recovered paper as a secondary raw material. According to Fisher Solve, recycled fibers make up 57% of the total fiber consumption in the pulp and paper industry. Wastepaper consists of different types of paper that has been collected after use, i.e. corrugated fiberboard, magazines and newspapers. The different operating stages of a recycled pulping process are described below (Figure 30).

When recycled wastepaper arrives at the mill, it is sorted and cleaned. For example, if newsprint is to be manufactured, the recycled paper has to be separated into individual fibers and cleaned from mechanical impurities, stickies and printing ink. The process consists of two steps: loosening the ink from the fiber surface and separating the ink from the process water. The paper bales are fed to the slusher and tumbled in water. The paper is torn and turned into pulp by moving slowly through the slusher. Chemicals needed to remove the printing ink are added to the slusher.

Thereafter, the pulp passes through screens and the ink particles are removed from the pulp through flotation. The principle for flotation is to inject tiny air bubbles into the pulp suspension. The suspension is then allowed to flow slowly through a basin; the air bubbles rise to the surface, and on their way, they will capture hydrophobic ink particles, which are gathered on the surface and removed as foam. The separation is not completed in one step and it is therefore repeated. To remove the remaining ink-particles and plastics, the pulp is heated and dispersed, and then bleached and washed.

Recycled pulp fibers do not reach the same strength as virgin pulp fibers, since they have been dried once before. Decent properties can be achieved through beating, but a larger number of fines is also released, hampering the drainage on the wire. The recovered paper is usually a mixture of various fiber types or paper grades. Recovered paper contains a certain number of contaminants and other detrimental substances. Nevertheless, recycled fibers must meet defined quality criteria for a given furnish, just as virgin fibers.



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8.3.14. Bleaching

Bleaching of pulp involves removal or modification of the colored components in pulp with the aim of increasing its brightness. Unbleached pulps display a wide range of brightness values. The sulphite process produces the brightest pulps (65, according to ISO brightness), whereas those produced by the kraft, soda, and semi chemical processes can be quite dark. Mechanical pulp brightness is mainly a function of the wood species and condition; species are generally selected to provide brightness in the 50–65% range.

8.3.15. Bleaching of chemical pulps

There is an essential difference between the bleaching of chemical pulps and mechanical pulps. The bleaching of chemical pulps is usually a multi-stage process where the lignin is oxidized, decomposed and finally eliminated from the pulp fibers. This results in less chromophores in the pulp. In the bleaching of mechanical pulps, the lignin is not decomposed and removed from the fiber; instead oxidizing or reducing chemicals attack the chromophores in the lignin. A large amount of lignin is therefore still present in the pulp, but the pulp is brighter.

Unbleached chemical pulps, mainly kraft pulps, have a dark brown color, as a result of the large number of chromophores in the pulp, which are mainly found in the residual lignin. Numerous paper products like printing and writing paper, food board, etc. require a bright pulp, as the requirements for a smooth surface with good printability and other related properties are high.

Bleached chemical pulps are found in a number of paper products such as fine paper, board, tissue, liner, etc., and most of the chemical pulp produced is bleached. The bleaching process results in a brighter pulp with higher cleanliness with respect to a low number of shives, dirt and extractives. The bleaching process also removes bacteria, which is a necessity for food and liquid packaging board.

Bleaching is usually carried out in a step-wise sequence utilizing different chemicals and conditions in each stage, with washing in between the different stages. The generally used chemical treatments are listed in Table 9 on the next page. Usually chlorination and extraction are carried out in a sequence, where chlorinated lignin compounds are first formed and then solubilized in a subsequent extraction stage.

The intention is to delignify the pulp, since very little brightening takes place through the CE sequence. The oxygen stage is used mainly for delignification.

Sulphite pulps and hardwood kraft pulps are bleached more easily than softwood kraft pulps because of their lower lignin content. A brightness level of 89–91% in a softwood kraft pulp can be achieved with a bleaching of six stages. A CEDED, CEHDED, or OCEDED sequence can be employed. Lower brightness levels can be achieved with fewer stages.

Table 9: Symbols for bleaching stages.

Bleaching stage	Symbols	Comment
Treatment with acid	A	
Chlorine	C	Phasing out due to environmental concerns over dioxin formation. Not very selective, carbohydrate degradation also occurs.
Chlorine dioxide	D	Expensive but selective.
Alkaline extraction	E	Removes fragments of lignin. The effluent is highly coloured.
Hypochlorite	H	More selective than elemental chlorine.
Oxygen	O	Least selective for lignin. Cheapest to use.
Hydrogen peroxide	P	Highly corrosive. Becoming more common with the elimination of chlorine.
Chelating stage	Q	
Peracetic stage	T	
Treatment with water	W	
Enzyme stage	X	
Dithionite	Y	
Ozone	Z	

8.4. Paper manufacturing

Different pulps are used to optimize the properties of the fiber mix fed into a paper machine. If the paper machine has only one layer, various paper requirements still have to be satisfied. Long fibers give strength. Short fibers give better formation and a more even surface. It is necessary to use broke. Other components can also be included in different situations. The quality of the different components and of the blend determines the quality of the paper and also the runnability on the machine.

8.4.1. Refining

Refining, or beating, involves a mechanical action carried out in continuous conical or disk-type refiners, where the flow is parallel to the bar crossings. The goal is to modify the pulp fibers in an optimal manner to meet the demands of the particular papermaking furnish. As a result of refining, the fibers are more flexible and conform more readily, and the surfaces are modified to improve the bonding. But refining also lowers the drainage capability of the pulp, reducing the production rate and increasing energy consumption. It can also cut fibers.

Some paper properties are improved with beating but others deteriorate. An optimal balance has to be reached.

31
Mixing and beating of pulp to get certain paper properties. Brightness, blend (fiber dimensions), fines content, shape factor and freeness are of interest.

32
Paper machine wet end. Fines and fillers are partly circulated, depending on the retention. Shape factor, fines, blend (fiber dimensions) are of interest.

8.4.2. Blend chest

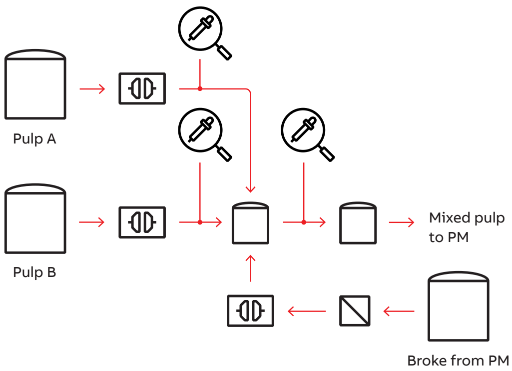
Figure 31 shows how pulp A and pulp B from different storages are refined separately. After refining the two components are mixed in the blend chest. Broke from the paper machine is also recirculated and mixed in the blend chest. Different mixes are used for different grades; the broke may come from earlier grades.

8.4.3. Additives

Chemicals are added to the furnish for various reasons and they can be categorized as functional additives or control additives. Examples of functional additives are dyes, sizing agents, strength aids and fillers. Examples of other functional additives are fillers like kaolin and clay. Sizing agents help to repel water, and strength aids are polymers that bind to the fibers to improve strength. Examples of fillers are kaolin clays and titanium dioxide. Examples of control additives are drainage aids and retention aids. Drainage aids increase the rate of water removal and retention aids help to retain fines.

8.4.4. Paper machine

A paper machine consists of a number of components with different functions: The headbox is a pressurized flow box from which the diluted pulp slurry is evenly spread out onto the moving wire to form a web. Several headboxes may be used. The cross-machine profile is controlled by sectionalized slice screws and/or by sectionalized dilution across the headbox. The speed of the water jet relative to the speed of the wire orients the fibers more or less in the machine direction. The wire allows water to be drained and retains the fibers. Twin-wire machines are common and several single wires and headboxes can also be used on the same machine. Fines and fillers can pass through the wire and have to be bonded to fibers or flocs to be retained on the fiber web (more on this later in the book). Special chemical systems are used for this purpose. Figure 32 shows the water circulations. Fines and fillers build up in the circulations, depending on the retention.



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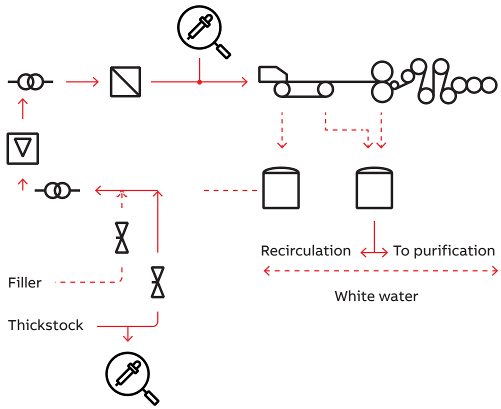

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This is a dynamic system, and this causes problems when changes are made to a different paper grade. The drainage properties are important for the runnability of the machine. The paper web enters the press section in order to remove water that has not been removed on the wire. Pressing is an energy-efficient way of getting rid of the water. The structure of the web influences the efficiency of the press section. The remaining water has to be removed by drying the paper on steam-heated hot cylinders, which uses energy. In the dryers, the web can be more or less restrained. Restrained drying often gives a more uniform web and often better quality but for some paper grades, free drying is an advantage. The fiber properties also have an influence.

8.4.5. Post-drying treatments

One example of a post-drying treatment is calendering, which is the passage of paper through one or more nips formed by a set of iron rolls. The primary objectives of calendering are to get a smooth surface, reduce sheet thickness to the desired level and even out caliper variations. Many printing paper grades require a more even surface, which can be achieved by applying a surface coating. This is done online or offline.

9. Fiber/Process

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33
Chemical pulps give better bonding, but lower light scattering, and lower yield than mechanical pulps.

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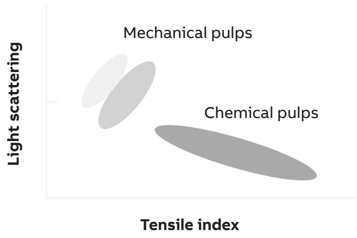
34
TMP fibers (magnification 100×)

Chemically separated fibers are flexible and have a high bonding potential. At the same time, they are not damaged and have kept their length in the separating process. They make strong paper.

Why then separate fibers mechanically? Because mechanical pulp has a high yield and a high light scattering power. Refining increases both tensile index and light scattering power. This is not the case for chemical pulps; refining increases tensile index but reduces light scattering power (Figure 33).



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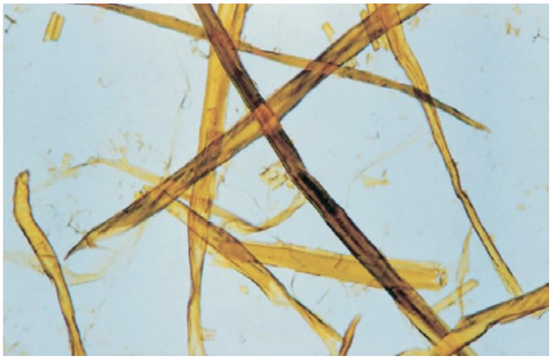
9.1. Mechanical pulps

Fibers from the Thermomechanical pulping (TMP) process are stiff and wide with high lignin content. A medium fraction and fines can be seen in Figure 34. Ray cells can also be seen in the picture; they are shorter and narrower than the fibers. Other parts of the fines are derived from the cell wall. Bigger flakes and more fibrillated material can also be seen.

Refining causes deformation of the fibers. The fiber deformations in mechanical pulps are called “latency” because there is a latent strength associated with their removal. By heating the fibers up to 85°C for a period of time, the curliness of the fibers is removed.

The shape factor, also known as form factor, is an important measure of pulp quality and is a measure of straightness of the fibers (projected length, divided by the true length). For mechanical pulp, it seems to be proportional to temperature.

After removal of latency, the fibers are quite straight and even when heated to a certain temperature, the shape factor seems to stay at that level. If the latency changes, the drainage properties of the pulp change.



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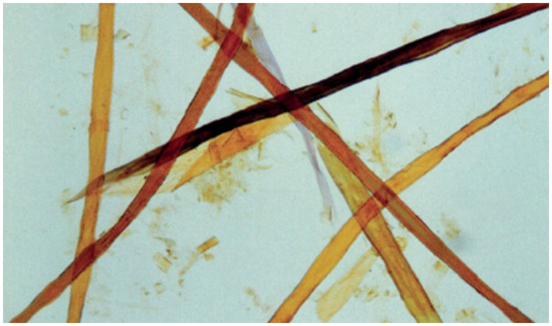
34

If the latency is removed before determining the CSF (Canadian Standard Freeness) number, this source of instability is removed (Reference to P52 and P78). However, the CSF value will then be different in the actual pulping process. Fiber analysis makes it possible to measure deformations very accurately. This makes it possible to avoid hot disintegration of the pulp before measuring the CSF value.

CSF still seems to be the most accepted measurement of quality for mechanical pulp, although greater accuracy, better repeatability and less maintenance is desired by users. For a simple product, with only one type of fiber having few and similar grades, a standardized drainage measurement may be sufficient. Today it is very common that different kinds of fibers are used and mixed to produce more advanced products, meaning that a simple measurement is of limited value.



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35
CTMP fibers
(magnification 100×)

Freeness is to a great extent a measure of the fines content. The problem is that the drainage resistance comes from ray cells, particles with poor bonding potential, and fibrillar material with good bonding potential. Another reported result from refining of TMP is split fibers, which appear to be generated in first stage refining—especially in earlywood fibers. The amount of split fibers has been reported to be up to 30% of the total. A split fiber wall will yield a more flexible fiber. The stiffness of mechanical fibers is much higher than for chemical fibers and the reason why chemical fibers produce much stronger paper than mechanical fibers.

Unseparated fibers (shives) are also present in mechanical pulps, and it is of great importance to keep these under control. TMP is often made from spruce, which requires less refining energy than pine. Thick-walled, Southern U.S. pine is also used in the TMP process, generally with three-stage refining.

Chemical thermo mechanical pulp (CTMP) fibers are similar to TMP fibers, but they are one step closer to chemical fibers with more narrow fibers and less medium fraction and fines (Figure 35). The fibers are deformed a lot in refining of mechanical pulp, but the treatment at a high temperature reduces the deformation to a large extent, but not entirely.

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36
Shape factor measured on pulp taken directly from two parallel refiners and dissolved in cold water, and on pulp taken later in the process.

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37
The average fiber width decreases faster after 3.3 MW because of fiber cutting.

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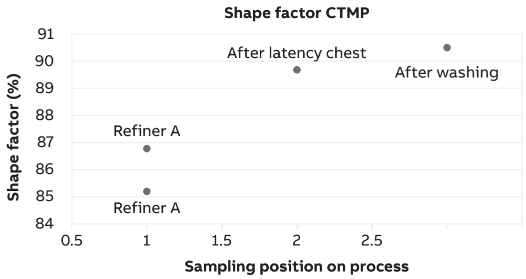
38
A cut fiber

Figure 36 shows that two investigated refiners worked differently. After latency removal, the fibers were quite straight. The same effect with respect to shape factor occurs in the reject refiner. Deformed fibers are found after the refiner, when pulps are sampled and diluted in cold water. After latency removal with hot water, the fibers are straightened out. Fiber length and fiber width decrease with increased refining energy. The development of fiber width is shown in Figure 37; at 3.3 MW, both fiber length and width decrease due to the cutting of fibers (Figure 38) and the generation of smaller particles.



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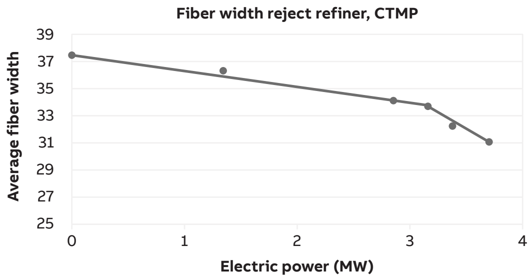

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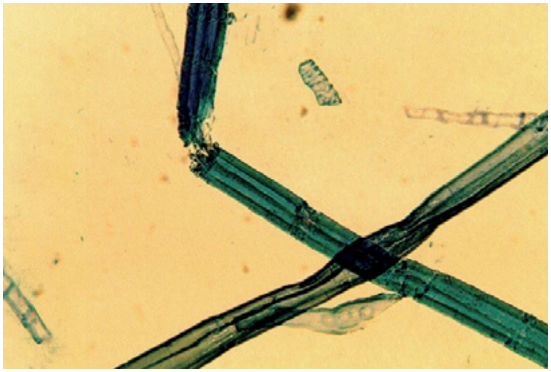

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9.2. Unbleached kraft pulp

Fiber deformation can occur when the pulp leaves the digester, but unbleached pulp fibers are generally still quite straight, although the shape factor can drop after a limited amount of refining. Further refining can straighten the fiber again. High Consistency (HC) refining is often used in the production of sack kraft paper. It introduces deformations of the fiber, which leads to an improved stretch in the sheet with improved Tensile Energy Absorption (TEA) as a result.

Low Consistency (LC) refining improves swelling of the fibers. Some of the fiber properties achieved in HC-refining are lost in LC-refining. There is always a balance (optimization) between properties. Both HC refining and LC refining reduce the number of shives significantly. Some primary fines can be seen in Figure 39 on the next page. The purpose of refining is to improve bonding strength without cutting the fibers too much.

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39
Unbleached
kraft pulp fibers
(magnification 50×)

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40
Bleached softwood
fibers from chemical
pulp (magnification 50×)

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41
Bleached softwood
fibers from chemical
pulp (magnification
100×)

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42
Birch fibers with vessel
cells from chemical pulp
(magnification 50×)

9.3. Bleached kraft pulp

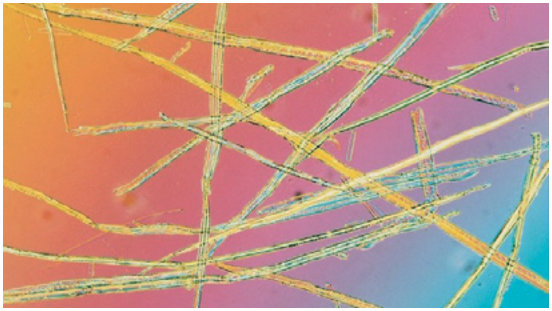
Refining energy needed to develop strength is different for individual fiber species. Hardwood fibers need less specific refining energy than softwood fibers. Bleached pulp always contains very deformed fibers. Mechanical treatment in combination with the chemical treatment seems to cause these deformations.

The deformations are created in the process. Some of the deformations seem to be reversible and some irreversible. The reversible deformations can be “healed” by a proper beating of the fibers.

9.4. Softwood and hardwood fibers

Figure 40 shows bleached softwood fibers. Compared to the unbleached fibers (Figure 39) we can see a lot of deformed fibers. Figure 41 shows softwood fibers at 100 times magnification, where more details of deformations can be seen: both local kinks and softer bends.

The deformations in bleached hardwood pulps are similar, as can be seen in Figure 42. It is a birch fiber, with typically long vessel elements (the wide objects are vessel cells). Hardwood fibers are more sensitive to refining than softwood fibers.



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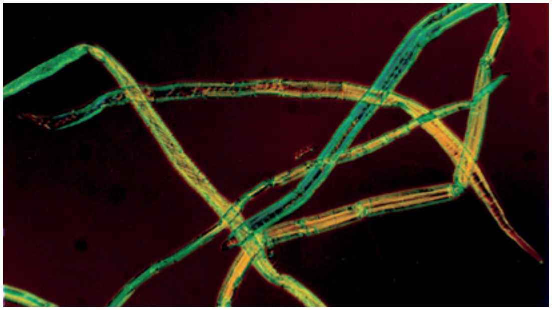

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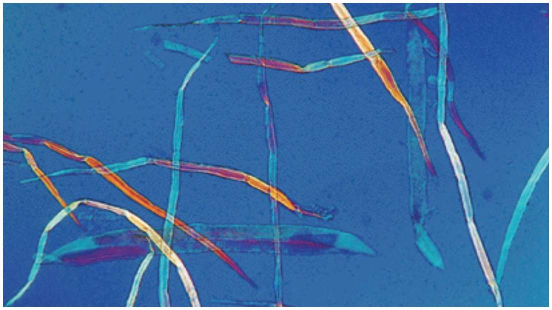

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43
Fibers at different stages in the process

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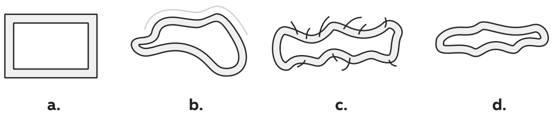
44
Deformations along the pulping process line

9.5. After bleaching

The shape factor is a key quality factor for industrial chemical pulps. A high shape factor is in most cases positive for the paper strength and means straight fibers. Fiber deformation is always found in chemical pulp. The deformations increase through the process (Figure 43).

A main drop in the shape factor often occurs in the oxygen delignification stage, and the shape factor continues to decrease during bleaching. The most striking feature of the case shown in Figure 44 was that a considerable decrease of shape factor was seen already before the O2 stage. This phenomenon may be because wash liquid containing residual products from pre-bleaching was washed out from the diffuser, causing the fibers to be more sensitive to mechanical treatment in the process.

Fibers at different stages in the process



a.Tree structure.
b.Middle lamella and parts of the outer layers (P, S1) are removed.
c. After refining the fibers are fibrillated and starts to swell (to some extent).
d. After drying the fibers are partly collapsed. Fiber collapse also takes place earlier in the process.

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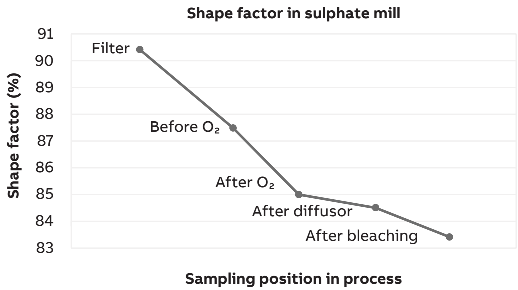
43

9.6. After refining

If a pulp is beaten in a PFI Laboratory Mill (used in the laboratory for the beating of chemical pulps under standardized condition), the shape factor will improve significantly (Figure 45 on the next page). However, if the same pulp is beaten in an industrial refiner, the result is seldom as good. The improvement in shape factor also gives a corresponding improvement in tensile index. The difference in tensile index between PFI and industrial beating is explained by the difference in shape factor.

One way to characterize refining is by using the specific edge load. It is easier to straighten the fibers and obtain a straightening of the fibers similar to that in PFI refining using a lower-specific edge load. PFI mill is known to have a fibrillation effect on the fibers. The difference in effects of each type of refining can be seen in Figures 46 and 47.



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45
PFI beating represents a kind of ideal beating, showing the strength potential for a pulp.

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46
Bleached sulphate, PFI beaten (magnification 100×)

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47
Bleached sulphate, beaten in an industrial refiner (magnification 100×)

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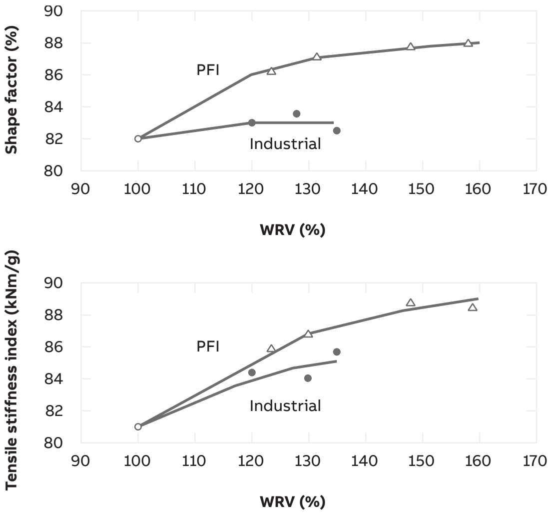
48
Shape factor vs. Water Retention Value (WRV) with Kraft pulp (Mohlin, RISE).



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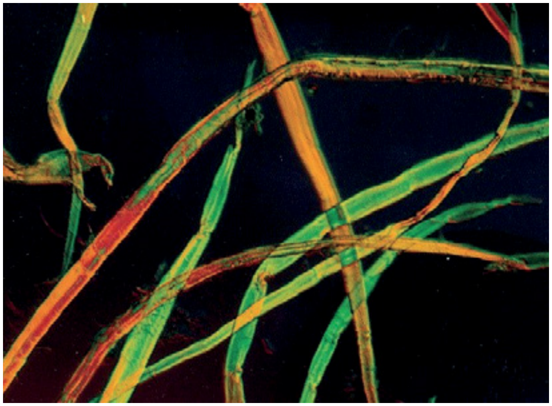

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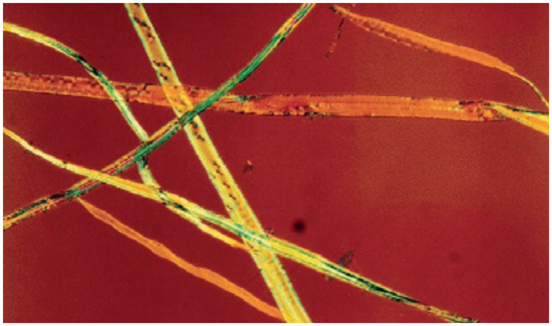

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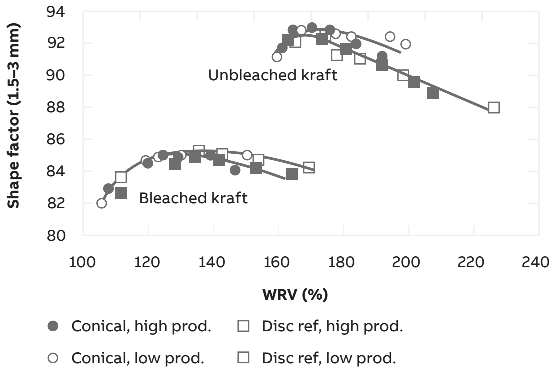

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9.7. Swelling

Modification of the fiber wall is the most important effect of beating; the fiber becomes more flexible and more fibrillated. Swelling increases sheet strength. Hemi cellulose is considered to play a central role as a swelling factor in the fiber. Hemi-cellulose and amorphous cellulose can be found between the crystalline parts of the fiber wall. Because of its structure, the fiber will swell mainly in the plane of the cross section not along the fiber axis. The swelling is prevented by the primary wall, the outer secondary wall, areas with string hydrogen bonds and lignin with a hydrophobic character, and a layered mix with the cellulose.

Water is retained by the fiber bound to internal and external surfaces (hydrogen bonds), in the lumen, in pores in the cell wall and within capillary forces on the fiber surface. Swelling decreases with increasing temperature.

Partial disintegration of the fiber wall during beating allows the fiber to swell. The swelling explains why reversible fiber deformations can be healed during beating. The healing can be measured as an increase in shape factor. A slight increase in fiber diameter is often seen as well. This is similar to a balloon effect, when the fiber wall swells. But most of the swelling enlarges the fiber wall towards the lumen. The swelling can also be local at a specific deformation point of the fiber.

9.8. Screening of shives

To evaluate a screen or a screening system, the efficiency of shives removal relative to the reject rate of the screen should be compared with the long fiber yield relative to the reject rate of the screen. A combined fiber and shive analyzer is an efficient tool in such evaluations.

9.9. Fractionation of fibers

How can expensive fibers be better utilized? One way is to separate the long fiber fraction from the pulp and use the long fiber fraction for reinforcement purposes in one production line, where improved strength is important, and use the short fraction for fine paper production in another line, where formation and surface uniformity is more critical than strength.

In a recycled pulp mill, the problem can be the opposite. The fines fraction may only reduce production efficiency and not contribute to the strength of the paper. Then it can be optimal to separate out the fines fraction and perhaps be able to burn it. An online measurement system can be used to optimize this process.

Fractionation with hydrocyclones separates particles with respect to surface area and density. High-density particles will go into the rejects and particles with a large area will be accepted. A very special application would be to separate earlywood and latewood. Attempts have been made to do this kind of separation with hydrocyclones.

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49
Fractionation scheme – fine fraction represents the earlywood fraction, and coarse fraction represents the latewood fraction.

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50
Formation index is a measure of local variations in the grammage of the sheet. Increase of average fiber length causes an increase of flocculation on the forming unit.

Earlywood fibers and latewood fibers have very different properties and different bendabilities and cell-wall thicknesses. The accepts are rich in with flexible earlywood fibers (fine fraction) and the rejects are rich in stiffer latewood fibers (coarse fraction), see Table 10. The process is illustrated in Figure 49.

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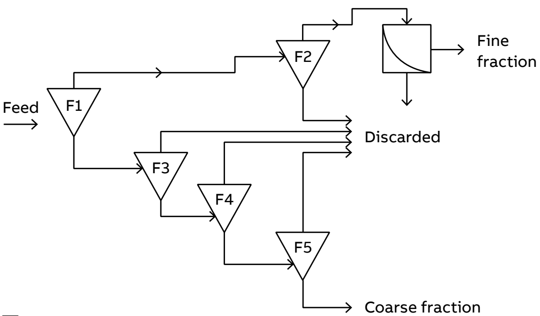
Table 10: Results from fractionation

	Length (mm)	Width (µm)	Shape factor (%)
Fine fraction	2.66	36.0	85.7
Coarse fraction	2.85	35.7	85.3



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9.10. Fiber orientation

Do the fiber properties affect the fiber orientation in the sheet? The fibers will always have a tendency to more or less line up in the machine direction on a paper machine because of speed differences between jet and wire.

This tendency may be less for shorter or more deformed fibers.

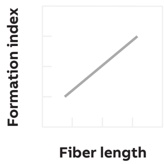
9.11. Wet web stretch

In general, the most critical point for runnability in a paper machine is after the press section, where web breaks are most common. The wet web stretch depends on the straightness of the fibers. It occurs before the paper has dried enough to form hydrogen bonds, which make the paper stay together when dry. Increased curliness means increased wet web stretch.

9.12. Formation

Chemical long fibers are used as reinforcement pulp. However, their impact on the strength of the sheet is not always completely clear. Formation index is a measure of local variations in the grammage of the sheet. Longer fibers cause more or bigger flocs on the wire, and an uneven sheet may have a lower strength with the same conditions in the process (Figure 50).

However, flocculation can be reduced with a lower consistency during forming and improvements of the dewatering elements on the wire.



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10. Traditional testing of pulp

Physical tests on pulp and paper are carried out for various reasons, e.g. as a production control, as a value indication of the paper properties between a seller and a buyer and, of course, for functional reasons. The main reason for pulp characterization is to ensure a stable pulp quality, since different kinds of fibers have different effects on the physical properties. Pulp characterization is also a tool for improving existing and developing new products of the resultant paper. However, it is not possible to use results from the pulp characterization to predict the properties of a paper made on a specific paper machine.

To ease the communication between researchers, producers and customers, standard test procedures have been agreed upon and issued by the pulp and paper industry. Standardized tests make it possible to compare results in one laboratory with results from other laboratories. Some institutes responsible for standardization:

- ISO — International Standardization Organization
- SCAN — Scandinavian Pulp, Paper, and Board Testing Committee (Finland, Norway and Sweden)
- TAPPI — Technical Association of the Pulp and Paper Industry, USA
- APPITA — Australian Pulp and Paper Industry Technical Association

ISO standards are used in association with international trade and are officially recognized around the world. As ISO standards become available, the corresponding SCAN-test methods are being withdrawn and replaced with the ISO standards.

10.1. Pulp testing

A lot of testing methods are in use to characterize pulps with respect to quality, processability, and suitability for various end uses. Many of these test procedures provide useful behavioral information, while some of the tests provide the means to predict behavior.

10.2. Pulp testing methods

- Laboratory sheet forming
- Drainability
- Beater evaluation
- Kappa number
- CED Viscosity
- Bauer McNett Classifier
- Sommerville screening
- Water Retention Value
- Zero-span tensile strength

10.2.1. Laboratory sheet forming

Many pulp properties are determined on hand-made laboratory sheets. A laboratory sheet former consists of an upper section, a wire screen on which the sheet is formed, and a lower section for the drained water. The pulp is diluted to a low concentration (<0.5 g/l), and a certain volume of the pulp slurry, sufficient to make one standard hand-sheet, is transferred to the upper section of the sheet former. The very low concentration of fibers results in a sheet with an exceptionally good formation with fibers uniformly distributed in the sheet. The wet sheets are pressed onto drying plates and dried in a conditioned atmosphere at 23ºC and 50% humidity. The sheets stick to the drying plate; shrinking is therefore prevented.

A number of different types of sheet-forming equipment for laboratory use exist. They differ from each other mainly in the concentration of the pulp slurry, sheet type (rectangular, square or circular) and sheet dimensions, type of wire screen etc. In general, sheets are made in an open white water system resulting in low retention of fines (ISO 5269-1:1998). The fibers are evenly and randomly distributed, resulting in a so-called isotropic sheet.

Comparatively, in industrial sheet forming, the fibers align themselves to some extent in the direction of the machine, and there is a closed white water system giving a good retention of fines. If a hand-sheet's retention is required to be similar to that of commercial sheets from paper machines, a Rapid Köthen laboratory sheet former could be useful. It is also well-suited for sheet forming of mechanical pulps. The Rapid Köthen laboratory sheet former simulates the moving web when the water is drained from the pulp stock and includes a closed white water system accumulating the fines and improving the retention (ISO 5269-2:1998).

In order to get a sheet with fibers oriented in a certain direction, i.e. an anisotropic sheet, a more complicated sheet former needs to be employed. For example, the French sheet former (Formette dynamique) where the pulp slurry is sprayed from a nozzle towards a cylindrical rotating wire, creating a sheet where the fibers are more or less aligned parallel to each other. There is also a standard for determination of physical properties on laboratory sheets (ISO 5270:1988).

10.2.2. Drainability

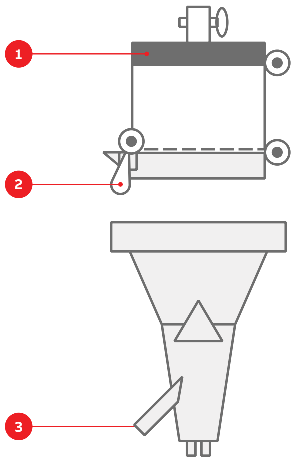
An important property with respect to pulp processing and papermaking is the resistance of fibers to the flow of water. The most common methods of determining drainability are the Canadian Standard Freeness (CSF) tester (ISO 5267-2:2001, TAPPI T227) and the Schopper-Riegler test (ISO5267-1:1999).

The freeness and Schopper-Riegler scales have an inverse relationship. CSF is defined as the number of milliliters of water collected from the side opening of the standard tester when pulp drains through a perforated plate at 0.30% consistency and 20ºC. Freeness measurements are widely used as an indication of quality for mechanical pulps and as a measure of the degree of refining for chemical pulps. The fines fraction is primarily responsible for changes in the drainage time. The removal of the fines fraction from beaten pulps can restore the original drainability, while the pulp retains its beaten strength properties. This is why there is criticism of the use of drainage measurements as an index of pulp quality.

The purpose of measuring freeness is to simulate the drainage rate on the wet end of the paper machine. During beating or refining, the proportion of fines in the pulp increases and the fibers become more flexible. This results in a lower drainage rate since the fibers are pressed more tightly together on the wire. The freeness value also gives an indication of how much the pulp can be beaten before it reaches the limit of the paper machine's drainage capacity. A lower freeness value through beating gives better bonding and more flexible fibers and a greater strength.

The standard freeness test starts with one liter of the pulp suspension (at a concentration of 0.3%) being poured into a drainage chamber (Figure 51:1). Thereafter, the bottom lid (Figure 51:2) is opened. The air valve on the drainage chamber is opened to start the drainage. The flow through the perforated plate decreases with increasing density of the fiber pad. The volume of the sample passing through the side discharge orifice (Figure 51:3) determines the freeness value of the sample.

There are a number of disadvantages in testing freeness manually. To obtain reliable values, the sample has to be handled in the same way every time a test is made. The advantage of using an automatic freeness analyzer is that the sample is handled the same way every time, both in the preparation stage and in all the tests.



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Schematic drawing of a standard freeness tester, for use in the laboratory.

10.2.3. Beater evaluation

Beating is a process to mechanically condition the fibers for papermaking. In general, laboratory beating methods have a more selective action than mill refiners and produce results that cannot usually be duplicated in the mill. A number of laboratory beating devices are in use around the world. One common device is the PFI mill (ISO 5264-2:2002). It utilizes a grooved roll that is off-center from a smooth trough. The roll and the bedplate rotate at a high speed but with different peripheral velocities. This induces friction, rubbing and crushing of the fibers to produce the beating effect. The device does not require any calibration, since there is no metal-to-metal contact and no edges to wear. Another advantage is that it only requires a small amount of pulp to carry out a complete evaluation. Another standardized laboratory beater is the Valley beater (ISO 5264-1:1979).

10.2.4. Kappa number

Roughly, the Kappa number is an indication of the lignin content, or bleachability of pulp. A Kappa number test is used in mill control work for two specific reasons:

1. To indicate the degree of delignification occurring during cooking
2. To indicate the chemical requirement for bleaching

The two objectives are never combined in the same test because of the large processing gap between cooking and bleaching.

Lignin is responsible for the yellowish-brown color of paper and is removed by bleaching. Bleaching, however, also reduces the mechanical strength of the fiber. Therefore, the lignin content must be well known, so that only a minimum amount of bleaching is used.

The standard laboratory test for kappa number (ISO 302:1981) is defined as follows: The number of milliliters of 0.02 mol/l potassium permanganate solution consumed under the specified conditions by 1 g of pulp (calculated on an oven dry basis). The results are corrected to a value corresponding to that obtained when 50% (mass/mass) of the permanganate is consumed in the test. Faster tests based on optical techniques are available for online control.

10.2.5. CED viscosity

An indication of degree of polymerization of the cellulose can be obtained by measuring the viscosity of a cellulose solution of known concentration. Cupriethylene diamine (CED) is universally used as a cellulose solvent because of its ability to rapidly dissolve cellulose and because of its chemical stability (ISO 5351-1:1981).

10.2.6. Bauer McNett Classifier

Fiber fractionation is a procedure that segregates a blend of pulp fibers into different streams based on some physical properties of the fibers (i.e. length or flexibility). The fibers of a particular type can then be directed to the most suitable process and product.

The Bauer McNett classifier (BMN) is the most widespread of the fiber fractionation laboratory devices, and it is used to assess the size distribution of fibers. The BMN operates by the selective passage of fibers through a screen mesh, and it separates the fibers mainly on the basis of length. The device consists of a series of chambers (four or five), each with an increasingly smaller screen mesh. Mesh is the number of threads/inch in a wire.

A predetermined amount of pulp is poured into the first chamber at the start of a test. A constant flow of water passes through this chamber and the series of chambers that follows. Smaller fibers are carried by the flow through the mesh and to the following chamber to the sewer. At the end of the test period, the flow stops and the chambers are drained. Thereafter, the mass in each chamber is measured. Pulp with smaller fibers will have more mass in the chambers with the smaller mesh sizes. BMN classification is considered to be repeatable within the same laboratory, but to have less reproducibility between different laboratories. Length fractions of fibers are successively fractionated out. Definitions of the classes are as following:

R16	is the fraction that remains on the 16-mesh wire (1190 µm)
R30	is the fraction that remains on the 30-mesh wire (595 µm), but passes through the 16-mesh wire
R50	is the fraction that remains on the 50-mesh wire (297 µm), but passes through the 30-mesh wire
R200	is the fraction that remains on the 200-mesh wire (74 µm), but passes through the 50-mesh wire
P200	is the fraction passing through the 200-mesh wire

Another definition is to use, in a similar way, the classes; R14, R28, R48, R100 and P200. Today, classification of fiber length is usually achieved with optical fiber analyzers (see chapter 9).

10.2.7. Sommerville screening

Laboratory screening of pulp can be done with the Sommerville method. The purpose of the method is to separate contaminants such as shives in mechanical pulp, and stickies, plastics, sand, metal pieces, and flakes in recycled fiber from pulp fibers for subsequent examination and quantification. Contaminants affect the paper machine negatively and downgrade the final product.

The method uses a screening device, and the separation is based on size difference between fibers and contaminants. The screening device consists of a rectangular screen box, a screen plate with 150 µm slots (mini shives screens use smaller slots), a diaphragm chamber with an attached weir box, and a stand. A diluted pulp sample (less than 1%) with known consistency is added together with water to the screen box. The sample is screened and the amount of oven-dry materials added to the device is calculated and reported.

10.2.8. Water Retention Value measurements

Water Retention Value (WRV) measurements are carried out according to ISO 23714:2019. According to the definition, WRV is the ratio of the mass of water retained after centrifugation under specified conditions by a wet pulp sample to the oven-dry mass of the same pulp sample.

The test pad of pulp fibers is formed in a Büchner funnel connected to a suction flask. The suction is stopped when the dry matter content of the test pad is between 5%–15%. The test pad is removed from the wire and placed in a former, and the complete holding unit with the test pad is placed in a centrifuge bucket and centrifuged at a force of 3000 g for 15 minutes.

Immediately after the centrifuge stops, the test pad is transferred to a pre-weighed bottle and weighed. The bottle is placed in a drying oven and dried to constant mass at a temperature of 105°C for at least fifteen hours. The weighing bottle is closed and allowed to cool in a desiccator (dry atmosphere) for at least one hour. The closed bottle is then weighed.

Water Retention Value (WRV) is calculated according to:

7.1

$$WRV = \frac{m_1}{m_2} - 1$$

where:
m_1 = mass of the centrifuged wet test pad
m_2 = mass of the dry test pad.

WRV measured by centrifugation is used mostly for chemical pulps, where it has a good reproducibility. The reproducibility for mechanical pulp is not so good. WRV is used as a measure of fiber swelling. Other principles are also possible in order to measure bound water, but centrifugation seems to be the proposed standard, recommended for chemical pulp.

For never dried pulp, typical values of retained water relative to the dry weight of the pad are:

- Sulphite pulp: 258%
- Sulphate pulp: 165%
- Refiner pulp: 148%
- Groundwood pulp: 128%

10.3. Paper testing

Since there are many different paper grades and many properties of paper, there is a need for a large variety of test methods. A number of properties are important for all grades, and tests used to measure these properties have a wide application. Test methods have also been developed specifically for specialty grades and have a more limited application.

Measurements of paper properties are dependent on the instrument or equipment used and on the details of the testing procedure. The fact that paper is both viscoelastic and hygroscopic makes testing more complicated. Given that paper has both plastic and elastic qualities, any test which leads to deformation or destruction of the sample will give results that are dependent on the rate of application of the force. Paper always seeks moisture equilibrium with the surrounding air (it is a hygroscopic material), and the properties of the paper are therefore highly dependent on the relative humidity and humidity history. Types of properties include:

1. Structural properties
2. Strength and stiffness properties
3. Surface properties
4. Optical properties
5. Absorption properties

10.3.1. Structural properties
Structural properties include:

- **Caliper (thickness)**
  For thickness measurements, a thickness gauge is used in which the paper or a pad of sheets is held under a given pressure between two parallel plates. The thickness determines how bulky or dense a paper is for a given grammage. Uniform caliper is important for reel building and subsequent printing. Variations in caliper can affect several basic properties, including strength, optical properties and reel quality. Thickness is important for printing papers, condenser paper, saturating papers etc. (TAPPI T411, ISO 534, ISO 3034).

- **Density**
  Density is the mass per unit volume of the paper or board calculated as the ratio between grammage and thickness of the material and is expressed as kg/m3. It is a very important parameter of paper, particularly for printing papers.Bulk is the inverse of density. Sheet bulk relates to a lot of different sheet properties, and a decrease in bulk makes the sheet smoother, glossier, less opaque, darker, lower in strength etc. High bulk is desirable in absorbent papers, while lower bulk is preferred for printing papers (ISO534:1998, TAPPI T500).

- **Moisture content**
  Almost all grades contain some percentage of moisture. Depending on the relative humidity, type of pulp, degree of refining, and chemicals, the moisture in paper varies between 2–12%.

  Most physical properties of paper undergo a change as a result of variation in moisture content. Water has a negative effect on the paper; it plasticizes the cellulose fiber, and relaxes and weakens the inter-fiber bonding. The amount of water present in a sheet of paper plays an important role in the calendering, printing and converting process. Determining the moisture content of paper simply involves weighing a sample of the paper before and after drying.

- **Grammage**
  The grammage (also called basis weight) is the mass per unit area of the paper and board expressed as g/m2. Determination includes weighing a piece of paper with a known area.

- **Formation**
  Formation is an indicator of how uniformly the fibers and fillers are distributed in the sheet. Most of the paper properties depend on good formation, since a paper is as strong as its weakest point. More weak, thin or thick spots are found in a poorly formed sheet. This will affect properties like caliper, opacity, strength etc., and it will also affect the coating capabilities and printing characteristics. The tendency to flocculate depends on the type of fiber. In general, longer softwood fibers have a greater tendency to flocculate than hardwood fibers. There is no standard measure or unit for formation.

- **Air permeance**
  In general, the air permeance is obtained by measuring the air flow through a defined area under a known pressure drop. The unit for air permeance is µm/Pa·s. This unit can be converted by calculation into other instrument-specific units e.g. Gurley seconds, Bendtsen (ml/min) and Sheffield units. Air permeance test methods are standardized in TAPPI T460, ISO 5636. The air permeance is influenced by e.g. beating, pulp additives, sheet forming, and pressing.

  By controlling the combination of these components, the desired air permeance level is obtained. The air permeance has a close relation to the porosity of the sheet, and thus the absorption of printing inks. In sheet-fed printing processes, the air permeance is crucial to the runnability. Heavyweight coated paper must have a certain air permeance level in order to leave a passage for moisture in heat-set printing processes. Air permeance that is too low can cause blistering in the coating layer.

10.3.2. Strength properties*

Strength properties include:

- **Tensile strength**
  Tensile strength is determined by measuring the force required to break a narrow strip of paper when both the length of the test strip, and the rate of loading are closely specified. It is determined according to a standardized test procedure. The tensile strength of a paper depends on the fiber properties (see chapter 12). The results are also affected by the testing conditions. An increase in moisture content of the paper will decrease the tensile strength, while increasing elongation. The tensile strength is highly dependent on the directionality of the paper. (ISO 1924-1, TAPPI T494, ISO 1924-2, TAPPI T404).

- **Zero-span tensile strength**
  Another measurement of tensile strength is obtained by testing with a span as close as possible to zero (or smallest distance possible between the two clamps holding the sample in place). By testing wet sheets, the effect of bonds is reduced. The test is primarily used for pulp testing to understand fiber strength. In practice, it is dependent on the deformation of the fibers.

* Source, private communication: Thomas Fürst (Oct. 2005).

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Tear/Tensile diagram

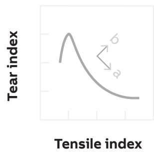
- **Compressive strength**
  Compression strength is defined as the maximum compression force per unit width that a test piece of paper or board can support until the onset of failure in a compression test. The actual test can be performed in several different ways. The most common tests are the Short-Span Compression Test (SCT) described in ISO 9895, TAPPI T825, and the Ring Crush Test (RCT) described in ISO 12192, TAPPI T818, T822. By measuring the compression strength of linerboard in cross direction, the stacking strength of a final corrugated box can be predicted.

- **Bursting strength**
  Bursting strength is the maximum pressure, which may be exerted perpendicularly to the surface of a paper, or board, before rupture occurs. (ISO 2758:1983, TAPPI T403).

- **Folding endurance**
  Folding endurance is the ability of a strip of paper to resist breaking when folded under a certain load. The folding strength is expressed directly as the number of double folds a paper can withstand. Folding endurance is the ten-based logarithm of the number of double folds. The folding strength value is very sensitive to local variations in the structure of a paper. Consequently, the test results are very sensitive to variations in testing conditions, i.e. variations in the relative humidity of the surrounding air. (ISO 5626, TAPPI T423, T511)

- **Z-directional strength**
  Z-directional strength represents papers' ability to resist tensile loading in a direction perpendicular to the plane of a paper (z-direction). When the Z-directional strength of the paper is exceeded, 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. There are two common methods for measuring strength in the z-direction; the Z-directional tensile method that measures the force needed to split a sample, and the Scott-Bond method that measures the energy needed to split a sample.

- **Tearing strength**
  Tearing strength is the force required to tear a sheet of paper, under specified conditions, continuing from an initial cut. The tearing strength is very dependent on the fiber orientation of the sheet. When a pulp is beaten (see Figure 52) the tensile index increases (a), whereas the tear index decreases, except for an initial increase. Differences in fiber quality may change the position of the curve in the diagram (b). Tear index is not considered to describe paper products very well, but it is still very commonly used in specifications. (ISO 1974, TAPPI T414)



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10.3.3. Surface properties

Surface properties include:

- **Surface strength**
  The ability to resist a force that strives to pull out fibers or fiber bundles from its surface is identified as the surface strength of paper. A low surface strength can cause linting and runnability problems. Methods for testing the surface strength usually use high viscosity, tacky oils, printing inks or adhesive tape. (TAPPI T459).

- **Roughness or smoothness**
  The purpose of a roughness or a smoothness measurement is to obtain a figure that describes the topography of the paper surface in a simple way. The generally applied method measures the ability of the paper surface to prevent an air stream from flowing between the paper surface and a surface or an edge (measuring head) pressed against it. The obtained result is an indicator of the paper's smoothness or roughness. Several test methods exist e.g., Bendtsen, PPS, Bekk, and Sheffield. The PPS-method is the most known worldwide, and it is used to determine surface roughness on most printing grades. (PPS method: ISO 8791-4, TAPPI T555; Bendtsen: ISO 8791-2, TAPPI T816; Sheffield: ISO 8791-3, TAPPI T538; Bekk; 5627).

- **Friction**
  The resisting force that occurs between two paper or board surfaces in contact, when the surfaces are brought to slide relative to each other, is called friction.

  Some methods of package handling rely on a certain amount of friction between cartons. It is therefore important for the printer/converter to control the amount of friction. The test to determine the friction coefficient is empirical. The quantity can be measured using an inclined plane test, and the result is then reported as the slide angle. It can also be measured on a horizontal bed tester. (TAPPI T815).

- **Softness**
  Softness is a subjective property, relating to how velvet-like the paper is and how easily it yields when crumbled. Softness relates to the feeling of softness when stroking the paper surface gently with the fingertips.

10.3.4. Stiffness properties

Stiffness relates to the elastic properties of a material, and it refers to the resistance given by the material to an applied force. Two types of stiffness are usually measured: tensile stiffness and bending stiffness.

- **Tensile stiffness** (ISO 1924-3) is a very important property of a printing paper to resist the stress of the tension during web printing in order to avoid off-set color (or maintain registers). A high tensile stiffness value in the liner layer is needed to obtain high bending stiffness in corrugated board.

- **Bending stiffness** represents the capability of paper and board to resist a bending force. (ISO 2493, TAPPI T489, T558, T566, ISO 5628, T543)

10.3.5. Optical properties

Optical properties include:

- **Brightness**
  Brightness is the intrinsic luminous reflectance factor (R∞) measured around wavelength 457 nm. The function of the term brightness is to be able to measure the effect of bleaching, and to measure the amount of colored substances in pulp. Drying of pulp increases brightness, and pressing decreases it. Brightness may not add much value to the “useful” properties of the paper, but it is the most important selling feature. (ISO 2470, TAPPI T452).

- **Light scattering**
  The borders between air and fibers provide surfaces for the light to be reflected from. A sheet made of stiff, tube-like fibers scatters more light than a sheet made of slender, collapsed fibers. Well-bound fibers provide fewer surfaces for light scattering than fibers with fewer bondings.

  The degree of cooking or bleaching of the pulp does not affect the ability of a sheet to scatter light, whereas beating, pressing or any procedure changing the physical structure of the fibers and sheet, greatly influences the scattering capacity. Both beating the pulp, and pressing a paper sheet, result in a higher degree of bonding and a denser sheet with less light scattering interfaces.

- **Opacity**
  Opacity is the ability of a material (i.e. paper) to prevent the passage of light. It is important that a paper has enough opacity, to prevent printed text from showing through on the reverse side of the paper. Opacity is important in printing papers, book papers, etc. The opacity of paper is influenced by thickness, amount and kind of filler, degree of bleaching and coating etc. (TAPPI T425)

- **Color**
  The color of paper, like that of other materials, depends in a complicated way on the characteristics of the observer and a number of physical factors, such as the spectral energy distribution of the illumination, the geometry of illumination and viewing, the nature and extent of the surrounding and the optical characteristics of the paper itself. (ISO 5631)

- **Gloss**
  Gloss is the property of a sheet surface that is responsible for its shiny or lustrous appearance. High gloss is desirable in high quality, prestigious printed images. The tone range of a glossy image is wider than that of a matte surface. It is possible to print with more saturated colors and deeper blacks on a paper with high gloss surface. Specular reflectance often worsens the readability of a text; therefore high gloss paper is undesirable in applications such as textbooks. (ISO 8254-1, TAPPI T480)

Table 11: Typical brightness values for different pulps

Pulp	ISO-brightness (%)
TMP	~ 60–70 %
Unbleached softwood kraft	~ 40 %
Bleached softwood kraft	90 %

10.3.6. Absorption properties

There are many methods available for testing the absorption properties, and an important requirement for all these tests is that the medium used for absorption into the paper should simulate as close as possible the end-use product. The media used can be water, oils of different composition and viscosities, or printing inks of different types.

Both absorption capacity and rate of absorption are key properties for fluff pulps and products, and for tissue products. Absorption properties include:

- **Water absorbency**
  The most frequently used water absorption test is the Cobb test, which measures the amount of water absorbed by the sample during a given time from an excess of water. This test is primarily used as an indicator of the degree of sizing, i.e. the water repellence of the paper. (ISO 535, TAPPI T441)

- **Oil absorbency**
  The absorbency of printing inks is often measured with a printability test. As an indicator of printability evaluation, the amount of ink transferred from the printing plate to the paper is used.

11. New technologies

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Traditional testing of pulp sheets, compared with alternative testing of fiber properties. (PLS-model, see chapter 13)

Traditional pulp testing is often characterized as time demanding, with several manual steps involved. The methods are not always representative of modern processes and products. New computer technology, electro-optical components, and modern signal processing have made new types of measurements possible.

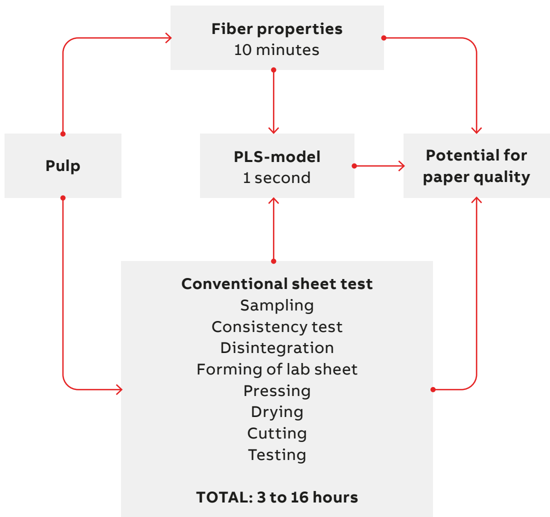
These techniques are suitable for automatic measurements, which lead to fast, more repeatable and operator-independent measuring methods.

Pulp testing is traditionally done by making laboratory sheets, which are later tested and evaluated, as indicated in Figure 53. The pulp is beaten in a defined way and with a given amount of specific energy, or for a given time, to one or several levels. Laboratory sheets are formed, pressed, dried and cut to suitable test strips and finally measured in sheet testing devices.

The time until a result is obtained can be from 3–16 hours. However, the pulp is made from fibers and the fiber properties define the pulp properties. Direct analysis of the fibers based on image analysis is the new way of assessing pulp properties. The advantage is that more detailed information is measured, which may explain the causes for deviations in pulp quality.

11.1. Optical technique

The optical technique is a fantastic tool. We can follow the moon passing the sun (solar eclipse) with the same principle that is used to study a small cellulose fiber in a light microscope, or for automatic classification online with L&W Fiber Online (Figure 54). The visible light covers only a limited part of the spectral range. Other parts of the spectral range that are used to analyze fiber quality will also be reviewed below.



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A large scale description of the measurement principle in Fibermaster. The moon (detected particle) is passing the sun (light source). The image represents the sensor signal.

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If the dotted line represents half the wavelength of the light, then the light scattering from particles with different sizes, which are hit by the light, will follow the curve in the figure

Particle size affects the light scattering; for example, smaller particles increase the scattering. One effect of this is that mechanical pulps scatter light better than chemical pulps. However, when the particle size is smaller than half the wavelength of the irradiating light, the light scattering starts to decrease, which means that scattering has a maximum at half the radiation wavelength. This is important for the selection of filler size. See Figure 55 for an illustration.

11.2. Polarized light

A phenomenon used in the early measurement of fiber length was the change in polarization of light when it passes through crystalline cellulose. This principle has also been used for consistency sensors, since the impact of air and filler could be avoided.

Fillers and air bubbles do not change the polarization. But drawbacks have been reported. If the polarization does not change at a compressed zone of the fiber (amorphous cellulose), the fiber may be detected as two fibers instead of one.

Polarized light does not allow the imaging system to see all the fines (ultrafine fibers), which means that this technique is not suitable for mechanical pulps since these pulps include a lot of fines. There can also be limitations when making measurements on synthetic and glass fibers.

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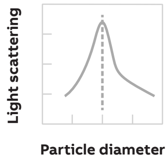

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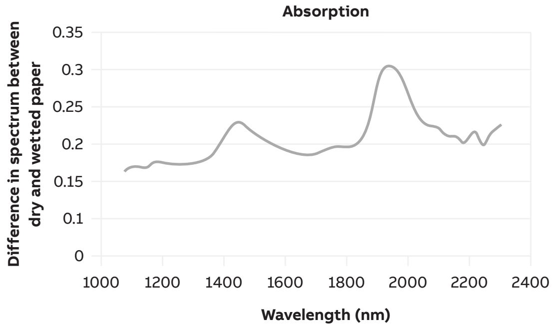
NIR spectra showing the effect from water. Measurement of water content is just one application.

11.3. Detailed analysis of fiber structures
Light microscopes are widely used in laboratories. Different techniques exist, for sample preparation, staining etc. This book does not include these methods in any detail. But the images in Chapter 6 are made with light microscopy, and most of them are made with an interference technique. Confocal techniques are used to study three-dimensional structures. They are still regarded as laboratory R&D instruments for studying details in well-prepared samples.
The scanning electron microscope (SEM) is widely used to measure fiber properties. A modern version, ESEM, can measure fibers without sample preparation and with different humidities.

In the NIR (near infrared) region, where the wavelength is longer than the wavelength of visible light, the alternating electromagnetic field starts to interact with the electric field around the molecules in the sample. The amplitude of the molecular movement increases and the energy of the NIR field is absorbed. The substance must have molecular groups which can stretch or vibrate in at least one resonating over tone in the actual NIR wavelength range i.e. C-H, O-H and N-H. The first tone lies in higher wavelengths intervals (MIR etc), and that requires a more complicated technique. In that case, a method using diffuse reflectance NIR is the best method to define yield, kappa number, lignin content, glucose, xylose and uronic acid during kraft digestion of birch. Multivariate data evaluation is used.

Using NIR for chemical information and combining it with image analysis for physical fiber properties has been suggested.
The technique for the development of a calibration model is described in Chapter 11.



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Validation of the models is an important part. Longer NIR wavelengths will not penetrate very deeply into water. Another effect on the propagation of radiation waves when they pass through materials containing small particles is the interaction with particle size. In the visible light area, a small particle size will change the intensity of the color. This wavelength interaction with particle size will also appear at other wavelengths than those of visible light.

11.4. Ultraviolet light
Ultraviolet light (UV) can be used for studying smaller dimensions than tracheids because it has a wavelength shorter than of visible light. UV is used to measure lignin content on fibers with an automated optical technique.

11.5. X-Ray technology uses very short wavelengths
With advanced laboratory tool for the radial determination of fiber properties in wood, such as density (x-ray absorption), fiber width (image analysis) and microfibril angle (x-ray diffractometry). Fiber wall thickness, coarseness and wood stiffness are calculated results.

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The electromagnetic spectrum

58
The Great Wall of China

Wave length (nm):

20 170 400 800 2500 5000 1000000

X-Ray	Vacuum UV	UV	Visible light	NIR	Mid IR	Far IR	Microwave
High protection energy	Inner shell electrons	Ionisation	Valence electrons	Overtones of molecular vibrations	Molecular bond vibrations stretch bend	Molecular bond rotation	Low proton energy

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11.6. Image analysis

The Great Wall of China was 5000 km long, and legend says it can be seen from the moon (Figure 58). But according to the astronauts Neil Armstrong, Jim Lovell and Jim Irwin, contrary to legend, it was not seen from the moon. Why? The ability to resolve an object is dependent not only on the length but, of course, also on the width of the object. The width compared to what can be resolved by the eye or a camera sets the limit. The thickness of the great wall of China was 4.5–9.0 m. In fiber analyzers, objects significantly narrower than the pixel size will not be detected. The problem when measuring fibers with image analysis is that fibers are much longer than they are wide (up to 100 times longer). The whole length of the fiber has to be in the viewing field and at the same time the width of the fiber has to be resolved. Detailed statistics can be calculated from images with modern image analysis. A special area of image analysis is blob analysis, which for example is used in L&W Fiber Tester Plus (current iteration of the STFI Fibermaster).

High processing capacity is necessary for image processing. The first Fibermaster system developed in 1992 used a pipeline processor for image analysis, or more specifically blob analysis. The image analysis functions were implemented in hardware modules. By connecting such modules in series, a number of image processing functions could be performed with high speed. The technique was used by the military for the detection and following of moving targets. In the first industrial version of Fibermaster, a new compact digital image sensor with built-in image processing capacity was used. The images could be transferred and processed in parallel.

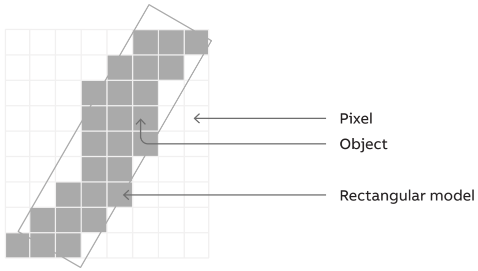
Today it is possible to use standard high resolution digital cameras and standard personal computer technology for online fiber analysis.

A strobe light catches an image (shadow) on the digital sensor. First the grey scale image is adjusted to compensate for the background. The background can be measured before each measurement with all moving objects excluded. The difference between the actual image and background removes the stationary background (anything that is stationary is filtered out). The next step is to set a greyscale threshold, where all pixels with low intensity are set to zero and all with high intensity are set to unity. We get black objects (blobs) on a white background. If the objects have holes, the holes must be detected and filled appropriately. Uneven contours can be evened out by expanding and eroding the object.

The skeleton can be found by thinning. A program can detect the contour of the object and the fiber ends. The area of the objects can be calculated. It is also possible to go back to the grey scale and calculate a grey value scale image. The grey scale of each pixel can be influenced by the greyscale of the surrounding pixels. Other special functions for fiber analysis are the detection of fiber-to-fiber crossings and the detection and handling of fibers crossing the border of the image.

Advanced filters like the fast fourier transform (FFT) can be used, but these types of image analysis take more time and are seldom used for fast systems. A digital image is built up of pixels. Objects which are significantly smaller than the size of one pixel cannot be detected. If the pixel size is 10×10 µm, a camera with 1000×1000 pixels covers 10×10 mm. A digitalized image of a detected object can look like the image in Figure 59.

If we want to model the object with two parameters, then a rectangle with a length and a width is a possible model. If the area and perimeter of the object are calculated, then the length and width can be calculated from these for the object and spatial filters applied on the grey primary parameters. An approximation is to set the length equal to half the perimeter and then calculate the width from the length and area. The result will be similar to that shown in the figure. Note that the resolution of length and width will be higher than the pixel size. A bigger object will give a better resolution since more pixels are involved in the calculation. An alternative to calculating the perimeter is to calculate a center line (skeleton) of the object for length.



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59
A digital image is built up of a number of pixels.

12. Measurements of fiber properties

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L&W Fiber Tester Plus

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Measurements of length and shape are shown with two-dimensional imaging technology. This is explained further in Table 12, on the next page.

If we measure the lengths of 20,000 fibers, and the average fiber length is 2.5 mm, then we have measured a total length of 50 m of fibers in a single analysis.

12.1. Measurement cell for image analysis of fibers

Different measurement cells have been used to analyze fibers in a suspension. A capillary tube with a circular cross-section orients the fibers in the flow direction and the fiber length is measured in this direction. With this technique it is natural to let all the fibers pass the capillary once and to measure all fibers in the sample. A drawback of this technique is that fiber deformations and fiber length cannot be measured independent of each other. The fiber length will in fact be a projected fiber length.

In a more modern fiber analyzer like L&W Fiber Tester Plus (Figure 60), the highly diluted suspension flows between two glass plates. The distance between the glass plates is very small when compared with other systems and limits the possibility for the fibers to move in one direction, but it allows the fibers to move freely in the other two directions.

Two-dimensional images allow us to measure fiber length and deformations separately, if the fibers are well aligned in a plane (Figure 61).

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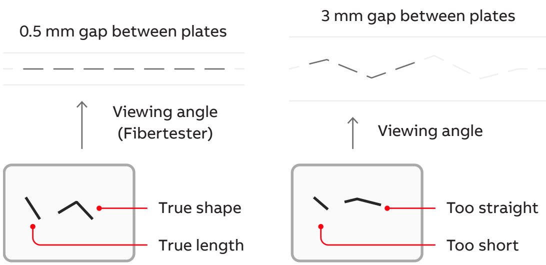

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An image from L&W Fiber Tester. Images can be stored during measurement and monitored afterwards

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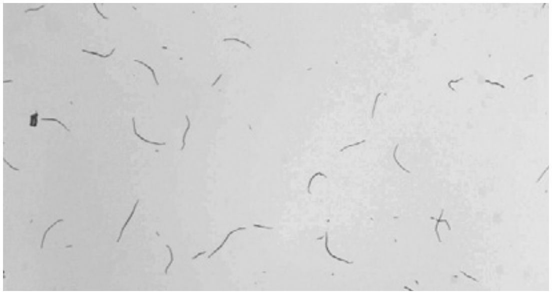
Table 12: Comparison between different principles for measurement cells. Glass plates with a short distance in between them combined with a two-dimensional camera, create a true projection of the fiber length and fiber deformations

Measurement cell	Comment
Capillary tube: Alignment of fibers only in one dimension (along the capillary axis)	Inaccurate projections
Glass plates with small gap (0.5–0.7 mm): Good alignment of the fiber in two dimensions in parallel with the glass plates	Two-dimensional measurements close to the truth (Fibermaster)
Glass plates with larger gaps (1–5 mm): Three dimensional movement allowed	Inaccurate projections

A three-dimensional appearance of the fibers and orientation across the image plane will cause an error (Table 12 shows comparisons).

If the distance between the glass plates is greater than the fiber length, this error will be greater. Low flow speed in the measurement cell gives a laminar flow pattern. For very high flow rates, the flow will become turbulent.

A problem with capillary cells and also with very narrow gaps is that fibers can become stuck there. Using a dynamic measurement gap solves this problem in L&W Fiber Tester Plus. The gap is 3 mm before measurement, decreases to 0.5 mm during measurement and increases again after measurement.



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A typical image of eucalyptus pulp fibers from bleached chemical pulp can be seen in Figure 62. Note that all the fibers in principle have a curvature, or are kinked. A single vessel cell is also seen in the image. The image is a greyscale image, before compensation for the background.

12.2. Fiber model

A fiber has a complicated structure, which varies with species, growing conditions, pulping technique and refining. In order to measure fiber properties, we have to define typical properties which are possible to measure. An obvious parameter is fiber length. However, fiber length is not simple to measure. One model can be to consider the fiber as a rectangle with a width and a length.

For example, in L&W Fiber Tester Plus, the area (A) and perimeter (P) are measured for each detected object (fiber).

63
Fiber length for CTMP, chemical birch, and chemical pine with fines (l<0.2 mm) excluded.

Length (L) and width (W) are calculated from the following equations:

A = L × W
P = (2 × L) + (2 × W)

Where:
A = measured area of detected object
P = measured perimeter of detected object
L = calculated length of detected object
W = calculated width of detected object

The length is about half the perimeter and the width is then calculated from this length and the area. All pixels in the image are used to calculate length and width averages for the object.

Another way of defining length is to measure the length of the center line along the fiber. Length, width and shape factor are measured for each fiber in Fiber Tester and can be stored in a raw data file. Round objects can be excluded.

Since length, width and shape factor are calculated for the same objects, it is possible to describe the statistics as, for example, two-dimensional length-to-width distributions or even three-dimensional length-width-shape distributions.The latter is more difficult to show in a diagram but two-dimensional distributions are a powerful tool.

12.3. High resolution in fiber width

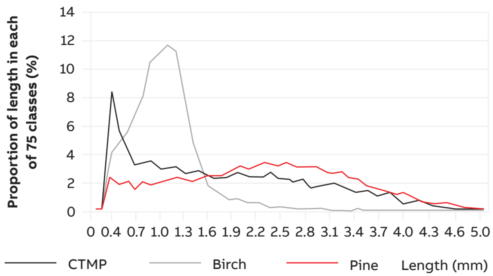
The fibre width is 20 µm and the length is 1000 µm. For an assumed pixel size of 10 × 10 µm, the area contains 200 pixels. If the area changes 1 pixel, the width will have a corresponding change, which means (although the fibre is only 2 pixels wide) the possibility to resolve, changes will be in the order of 0.5% of the width, i.e. 0.1µm.

12.4. Fiber length

Fiber length positively influences sheet strength, but it can also have a negative effect on sheet formation. Length is measured with a minimum impact of the degree of fiber deformation. This means that fiber length is measured compensated for fiber deformation. After reporting average length, the most common presentation of data is the length distribution, which can be seen in Figure 63. If the limit for fines is 0.2 mm, which is according to the standard, the curve starts at 0.2 mm.

The international standards for measurement of fiber length are ISO 16065-1 and ISO 16065-2. These two methods are similar; the main difference is that polarized light is used in version 1, and non-polarized light is used in version 2. In Figure 63 below, we can see length distributions for different kinds of fibers. Birch has very few fibers above 1.5 mm.

CTMP of spruce has fibers as long as those of chemical pulp of pine, but spruce CTMP also has a lot of fines and cut fibers. The surface area below each curve is the same. Each curve is built up of 75 fiber length classifications. The ordinate-scale (Y axis) shows the proportion of the fiber length (%) in each length class. Each length class is 0.1 mm wide.



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64
The width of the fiber varies along the fiber axis.

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Distribution of the fiber width for different pulps

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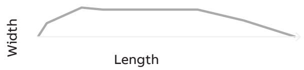
CTMP fibers are straighter than chemical fibers. 100% in shape factor means a completely straight fiber.



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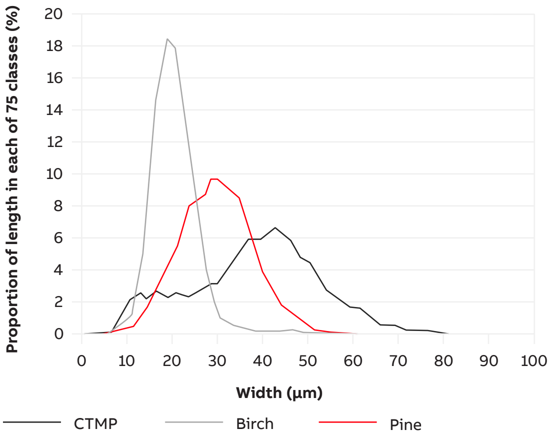

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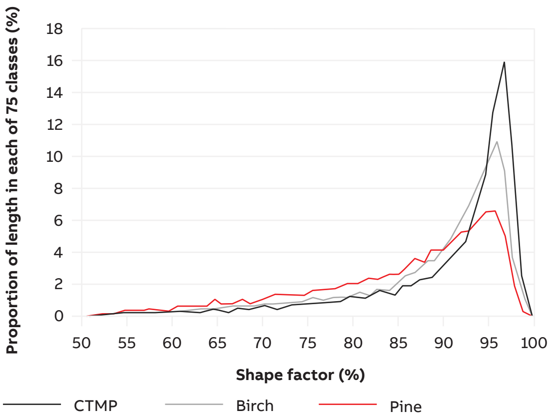

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12.6. Fiber deformations

A variation in shape factor between 81% and 85% can make a difference of 15 Nm/g in tensile index in unrefined samples from bleached Scandinavian softwood market pulp (see Chapter 14 for more details). This difference remains after refining with constant energy even though the tensile index level has increased due to fibrillation of the fiber surface.

12.7. Shape factor

The shape factor (also called form factor) is an important measure of pulp quality. Shape factor is defined as the ratio of the maximum extension length of the fiber (also called projected length, which is close to the distance between the fiber ends) to the true length of the fiber (along the fiber contour) and is often presented as a percentage.

$$S = 100 \times l / L$$

l = projected length; L = true length;
S = shape factor

A high shape factor means straight fibers and gives in most cases good mechanical properties in the sheet. It is well correlated with tensile strength and tensile stiffness. A gently treated laboratory pulp has straight fibers, whereas there are several process stages in a mill that are potential curlers of fibers, like presses, mixers etc.
Fibers with a shape factor below 50% are not

included in the statistics in L&W Fiber Tester Plus because very few fibers have such a low shape factor. CTMP fibers of softwood after latency treatment are straighter than softwood chemical fibers. Nevertheless, softwood chemical fibers give a better sheet strength due to better bonding, since they are more flexible and contain less lignin.

Curl is often used as an alternative to shape factor. Curl is defined as:

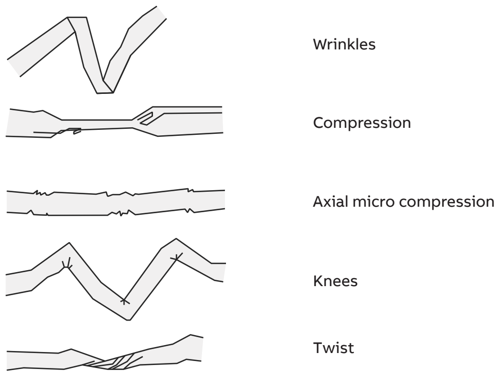
$$C = (L / l) - 1$$

12.8. Kink

Local deformations such as knees and wrinkles in the fibers are called kinks. They are detected as changes in the direction of the main axis of the fibers within a limited distance of the fiber. A direction on each side of a center point is calculated. If the angle is above 20°, a kink is recorded (Table 13 shows class by angle). Data from kink measurements are: kink/mm, kink/fiber, kink> 60° per fiber, mean segment length (average distances between the kinks), modified kink index (20°) [Kibblewhite] and mean kink angle. Detailed information about distributions and actual position of kinks on each individual fiber is available.

One way to detect the effects of hidden deformations is to treat the fibers chemically or mechanically and measure the result on the fibers. One such technique is to measure dislocations and other weak points in spruce pulp fibers involving hydrochloric-acid-induced cleavage of the fibers and an analysis of length-weighted fiber length distributions.

It is possible to save raw data to be able to look at individual fibers and the computed kink angles afterwards. Kink and shape factor are often correlated. All types of deformation are included in the shape factor. The number of local deformations of the fiber may, on average, be one per fiber, meaning that the fibers in general have weak points. These are probably important for the fiber strength.



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67
Different kinds of possible deformation of the fiber wall

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Table 13: Class weights for the kink index formula

Class (i)	Angle	Weight
1	10–20	1
2	20–50	2
3	50–90	3
4	90–180	4

$$\text{Kink index} = \sum_{i=1..4} \frac{\text{Weight}_i \times \text{Number of kinks}_i}{\text{Total fiber length}}$$

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A fiber with two detected kinks will result in three undamaged segments of the fiber

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69
Shape factor correlates well with the number of kinks per fiber, because all types of deformations are reflected in shape factor

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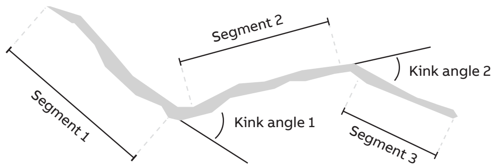
How different areas of fines are classified. By definition, no objects can be in the L>W area. At TAPPI settings of the fines measurement, the limit between fines and fibers are at 100um instead of 200um



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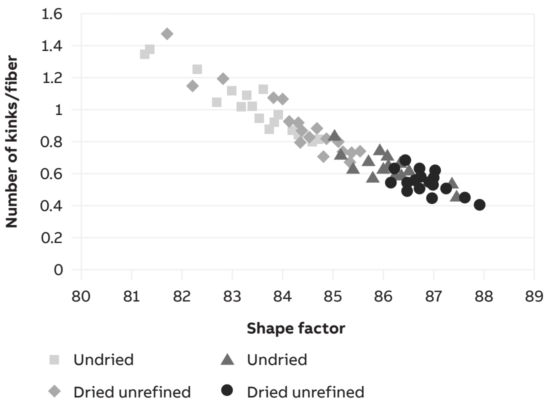

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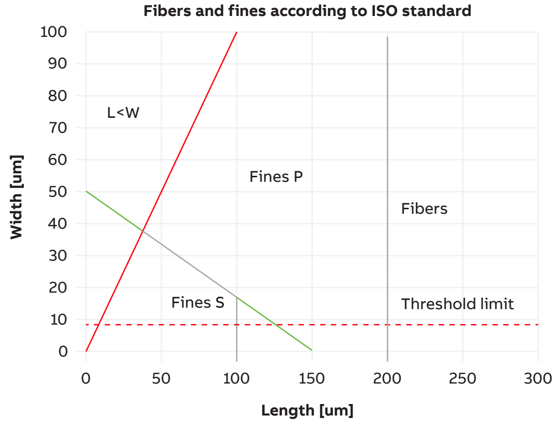
Particles that are bigger than 7 µm are detected in L&W Fiber Tester Plus (actual pixel resolution is 3.5 µm). A defined maximum length limit of 200 µm is commonly used as a definition of fines. Filler particles are smaller than 5 µm and are not detected with resolution limit set to 7 µm.



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12.9. Fines

Fines often have a different impact on processes and products than the fibers. Primary fines are available before beating and include ray cells. Primary fines have poor bonding properties. Secondary fines are created during beating and they improve the strength of the sheet (Figure 70 shows classification of the two).

Both types of fines have a negative impact on the dewatering capacity on the paper machine. While beating softwood, a large part of the produced secondary fines are shorter than 100 µm and thinner than 30 µm. When beating hardwood, the dimensions of the produced fines have a wider span in length (the variation in length of fines can be bigger compared to beating softwood fibers).

12.10. Fibrills

When beating the fibers, some thin parts of the fiber wall are partly loosened. Those fibrils are at the limit of what is possible to see in a measuring cell wide enough to let fibers flow through. By filtering the image is it possible to see larger fibrils (Figure 71). By measuring the fiber with and without this filter is it possible to get a value of the degree of fibrillation of each fiber. As a value, the fibrils part of the area or perimeter of the whole fiber is used. By getting the value for an individual fiber, it is possible to study how different fiber dimensions affect the fibrillation during the beating. When a mix of hardwood and softwood is beaten, we often see fibrillation on the long, wide softwood fibers but not on the thin, short hardwood fibers.

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A fibrillated softwood fiber

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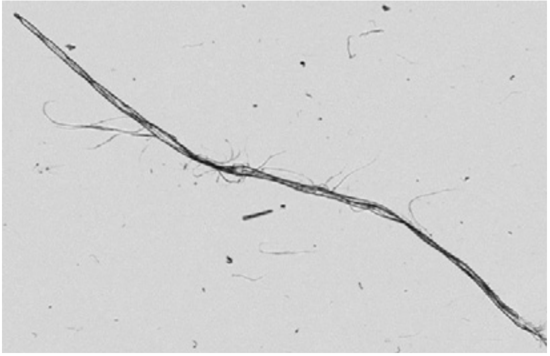
72
Fibrills contribute to fiber bonding and closely relate to strength properties in the dry paper.



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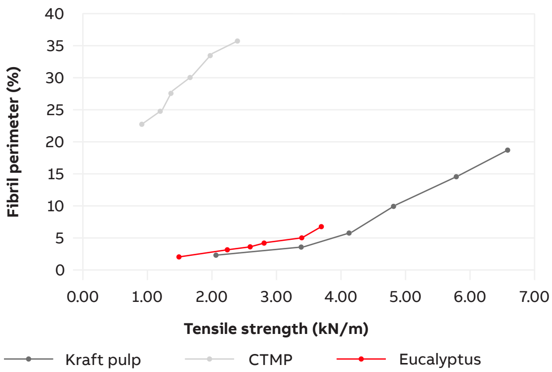

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12.11. Crill

In the pulp, there also is thinner fibrillar material, called crill. These particles can be a few 0.1 µm wide, and 100 µm long. Many of these particles cannot be seen with normal visible light. In the crill add-on feature within Fiber Tester Plus, the attenuation that is dependent on light scattering is measured at different wavelengths of the light.

The light scattering is dependent on the size of the particle or the structure that scatters and the difference in index of refraction compared with the medium around the particle.

Normally the scattering is highest when the size of the particle is in the same order as the wavelength of the scattered light. When choosing wavelengths, light absorption of different chemical groups needs to be taken in consideration. In this case, we have chosen 365 and 850 µm. The ratio of the attenuations at the two wavelengths is used as an indication on the number of particles with a size in the 0.3-0.4 µm region.

In the beating process, crill develops very similar to both secondary fines and fibrils, hence are also important for fiber bonding and strength properties in the dry paper.

13. Objects other than fiber

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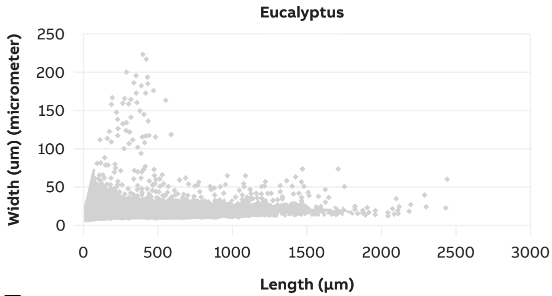
Each detected object in an eucalyptus pulp is marked with a dot. Objects narrower than 50 µm and longer than 0.2 mm are fibers. Shorter are fines, and wider objects are mainly vessel cells. Vessel cells eucalyptus (number vessel/100 000 fibers)

13.1. Vessels

A typical collapsed vessel cell of eucalyptus can be of the size 200×200×20 µm. A typical hardwood fiber can be 800×20×20 µm. In the case of hardwood pulps, vessel cells can cause printing problems, and this can limit the use of hardwood pulps for the production of certain paper grades. The amount of vessel cells relative to the amount of fibers, and the length/width distributions of the vessels are measured.



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The experience from L&W Fiber Tester Plus is that the ratio of detected vessel area to the detected fiber area in a sample is a good measure of percentage of vessels. Vessel cells are thin-walled and often collapsed, which makes their area interesting. The total volume of the fibers is a measure of the consistency. The ratio of number of vessels to number of fibers for the whole sample (0.1 g) is also monitored. The size distribution of the counts is shown in a length/width matrix, see example in Table 14. In this case, only fibers wider than 100 µm were measured. Another way of expressing the same thing is by the ratio of total vessel length to total fiber length. Note that these different ways of expressing the amount of vessel cells can give different results. It is not completely clear what is the best definition of vessel cells, and that is the reason why alternatives are used. In the samples used in Figure 73, the vessel cells were concentrated with hydrocyclones.

Fibers are defined as objects longer than 0.2 mm and never wider than 0.1 mm in the measurement. Vessel cells are defined as objects wider than a certain width, for example 0.1 mm. If a comparison is to be made between different instruments, it is important to define detection criteria in similar ways. When this is written, the detection criteria for vessel cell detection are rather simple, but they work well for virgin eucalyptus and acacia.

In more difficult applications, it is possible to use the L&W Fiber Tester Plus to collect images with vessel-cell-like objects and then manually check the nature of the objects. Since there are only a few vessel cells per thousand fibers, longer measurement times can be necessary in order to achieve good statistics for the measurement of vessel cells.

13.2. Shives

Detected particles with a width greater than 75 µm are measured as shives.

Shives have poor bonding ability to fibers and they cause quality problems in the paper and in the papermaking process. Short shives (< 1.5 mm) are considered to give linting problems. Large shives (Length > 1.5 mm and width > 150 mm) are considered to increase the risk for web breaks. If the sums of the corresponding channels in Table 15 are calculated, then signals for linting risk and web-break risk can be monitored.

Different averages are reported such as number of shives per number of fibers, and total length of shives in sample/total length of fibers in sample (length weighted), and number of shives/g if the weight is known (in laboratory samples). Total volume of shives in sample/total volume of fibers in sample is recommended to use in online applications.

If only a few shives are available in the sample, the statistics can be improved by measuring at somewhat higher consistency and by taking the average at several measurements. For an online system, it is recommended to use a sliding average or an exponential filter to even out the random noise.

Table 14: The table shows example of length/width distribution for vessel cells (acacia).

0.20 <W < 0.50	–	25 %	0 %
0.15 <W < 0.20	24 %	15 %	4 %
0.10 <W < 0.15	33 %	0 %	0 %
Width (mm) Length (mm	0.1 < L < 0.2	0.2 <L < 0.3	0.3 < L < 0.5

Table 15 : The table shows example of length/width distribution for shives (Red numbers = increased risk for linting. Grey numbers = increased risk for web break).

0.30 < W < 1.0	30	10	10
0.15 < W < 0.3	600	90	20
0.075 < W < 0.15	2250	355	100
Width (mm) Length (mm	0.5 < L < 1.5	1.5 < L < 3	3 < L < 7.5

14. Calculated properties

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The fiber illustrated as a cylinder for the calculation of wall thickness. A wall density has to be set.

14.1. Coarseness

Coarseness is defined as weight per unit fiber length. ABB's L&W Fiber Tester Plus calculates coarseness and reports coarseness on the standard laboratory report. Coarseness is calculated as a constant multiplied by the number of images included in the measurement and the dry fiber weight of the sample. This number is divided by the total fiber length for the measurement. The constant is the measurement volume for one image divided by the total volume for the whole internal circulation.

$C = \text{constant} \times Nb \times M / \Sigma L$

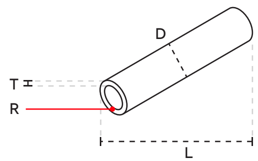
- Nb = number of images included in the measurement
- M = measured weight of "dry" fibers fed into the system
- ΣL = sum of fiber length for the measurement
- constant = the corresponding volume for one image per total volume in the circulation

Note: The constant is in practice defined by calibration.

Coarseness has commonly been used instead of fiber density for historical reasons. It had not been possible to measure fiber diameter in the past. An extension may be to calculate fiber density – a measure of weight per fiber volume!

14.2. Fiber-wall thickness

An average fiber-wall thickness can be calculated from L&W Fiber Tester data. The density of the fiber wall can differ between different species. For example, eucalyptus and pine do not necessarily have the same wall structure. It is possible to use different wall densities. The wall thickness influences the flexibility of the fibers. Thin-walled fibers are the more flexible and collapse more easily than a thick-walled fiber. More flexible fibers will give better bonding in the sheet (boiled macaroni theory). A thick-walled fiber needs more refining. The wall is only a few micrometers thick, which makes it difficult to measure using normal light microscopy.



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$T = D / 2 - \sqrt{D^2 / 4 - C / (\pi \times R)}$

Where:
- T = average wall thickness for the whole sample
- C = coarseness (weight per length unit)
- D = diameter (average fiber width)
- R = density of fiber wall (must be defined by calibration)
- C and D are measured in Fiber Tester.

14.3. Slenderness

Slenderness, defined as the ratio of length to width, can be calculated from raw data and weighted in the same way as other properties. Volume weight can be a good choice.

The ratio increases for long and narrow fibers. The amount of fibers in this corner of the length/width distribution is an interesting fraction. The length-to-width ratio for European beech is 37, for aspen 61 and for spruce 95.

15. Pulp properties

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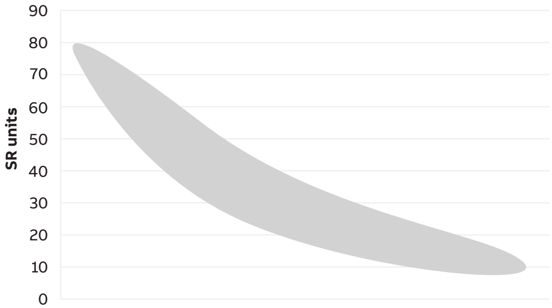
Regardless of the similarities between CSF and SR, the test results cannot generally be transformed between the test methods because of differences in the testing equipment. This is a summary from several measurements, as an indication (Source: TIP 0809-01).

15.1. Freeness

The Canadian standard freeness (CSF) method is widely used for mechanical pulps. The scale range is from 20 to 700 ml. High freeness means easily de-watered pulp, i.e. pure water gives a freeness value of 880–890 ml. For chemical pulps, the Schopper-Riegler method (SR) is more common. The scale is opposite to that of CSF, so that 1000 ml corresponds to 0 SR-units, and a volume of 0 ml corresponds to 100 SR-units. The SR-method is not suitable for well-beaten hardwood pulps because these fibers can pass through the wire without building up a sufficient fiber bed.

Conversion from CFS to SR



D = diameter (average fiber width)
R = density of fiber wall (must be defined by calibration)

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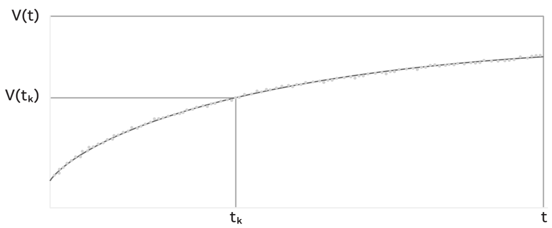
Both methods suffer from the fact that the drainage of the pulp does not simulate the drainage process in a modern paper machine. Nevertheless, these methods are standard methods and in all trading of pulp or discussion of refining these traditional units are used.

Automatic drainability testing systems, like the one in ABB's L&W Freeness Online, are calibrated against CSF or SR, where freeness is calculated from the dewatering of the pulp as a function of time.

The drawbacks of manual freeness tests, such as time-consuming sampling and consistency determination, combined with the very critical handling of the entire test procedure, make the laboratory testing of freeness one of the most expensive and troublesome methods. It is quite common that only a few measurements per sample point can be done per day, and this makes laboratory-determined freeness unsuitable for process control. All these drawbacks are easily overcome in an online, automatic test system like the one in L&W Freeness Online.

The volume of the water is measured as a function of time. The flow during the formation of the fiber pad is integrated; the volume flow can be calculated. The volume signal is sampled into the computer and is then adapted to a mathematical function. The noise is reduced in this way, which is important when the signal in the next step is to be differentiated.



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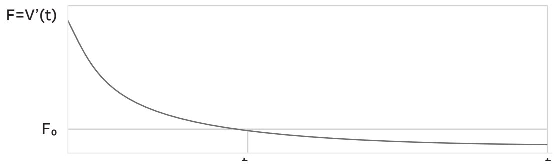
Dewatering curve measured from the balance

15.1.1. Calculation of freeness

- Volume of sample (water+fiber) draining through the screen is measured as a function of time (V(t)) .
- A mathematical function is adapted to V(t) to obtain the filtering effect of the weight signal. (see Figure 76)
- The drained water as a function of time is recalculated (V(t) is differentiated) to a flow rate curve (F) as a function of time (see Figure 77).
- The time when the flow F0 is reached is read from the flow curve F(t). This flow corresponds to the flow that passes through the lower part of a manual freeness instrument (see Figure 78).
- The volume that, in a manual freeness sensor, would have flowed through the bottom pipe is subtracted from the total volume V(tk). The volume in the tank of the freeness module when the measurement starts (Vk) is also subtracted. The freeness value is calculated as follows:

Freeness = V(t) - F × t - V



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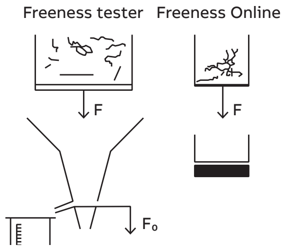
The flow from the wire calculated from the drainage curve.



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The funnel in the freeness sensor is in practice a flow sensor. In Freeness Online the integrated flow is measured by the draining of measurement tank as a function of time.

15.2. Near infrared (NIR)

The NIR spectra are used for strength predictions in combination with fiber distributions. Water is always present in a paper sheet. It affects the spectrum close to 950–980 nm and 1920–1940 nm (OH).

Table 16: Path length in water for NIR

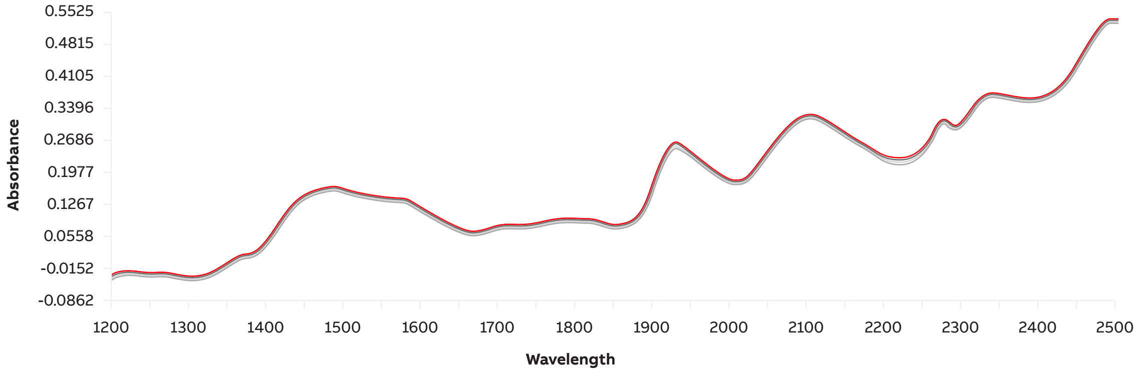
Wavelength (nm)	Path length(nm)
1190	19.9
1450	0.9
1940	0.2

Cellulose affects the spectrum at 1490, 2102, and 1818 nm; hemi cellulose affects the spectrum at 1982 nm; and lignin at several wavelengths for example 1680 nm.

As described in chapter 8, the NIR spectrum depends a lot on water. Measurement on a dry sheet makes the method more independent of the water. The formation of the sheet is critical. The thickness of the sheet is also important.

15.3. Optical properties

The optical measurements performed early in the process can be used to predict the same properties of the final product. Then, the necessary actions can be taken immediately upon deviations observed in the pulp line. The time delay in the papermaking process is avoided and the paper manufactured is always less likely to be off specification in terms of optical properties. The pulp furnish is optimized regarding bleaching, optical brighteners and color dyes. The savings connected are obvious.



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79
A typical NIR spectrum for a paper (wavelength in nm).

80
Part of the spectrum included in the measurement of brightness with an effective wavelength of 457 nm.

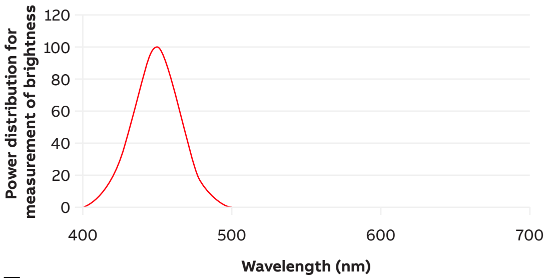
81
Color matching functions.

82
CIE L * a * b color space.

15.3.1. Brightness

The brightness parameter is used to monitor the bleaching process. Brightness together with fluorescence is used to supervise the dosage of OBA (optical brighteners). Brightness is the most commonly used parameter in the sales specification of paper and paperboard products. See Figure 80.

The same parameters are used in the pulping process to supervise the possible dosage of dyes used to maintain the desired shade, whether white or colored. The recycled pulp requires particular supervision in this respect as the incoming recycled pulp may vary in terms of color. Then the representative information collected early in the process is of great value.



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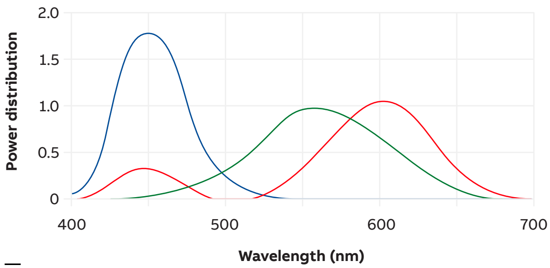

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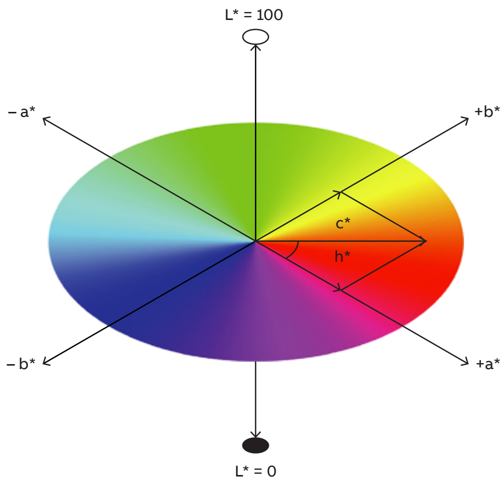
15.3.2. Color

The colorimetric response of the human eye can be described by means of the color matching functions according to Figure 81.

In case of a spectrophotometer, the tristimulus values X, Y, Z are calculated by spectral addition of the product of the color matching function, the illuminant function, and the reflectance factor obtained by the measurement. All other colorimetric parameters are then calculated from the tristimulus values.

The colorimetric parameters commonly used are L*a*b* at specified illumination. The L*a*b* parameters constitute a color space with a grey-scale axis (L), a red-green axis (a), and a yellow-blue axis (b) in a three-dimensional color system (Figure 82). These parameters are used to specify the color of the final paper product.



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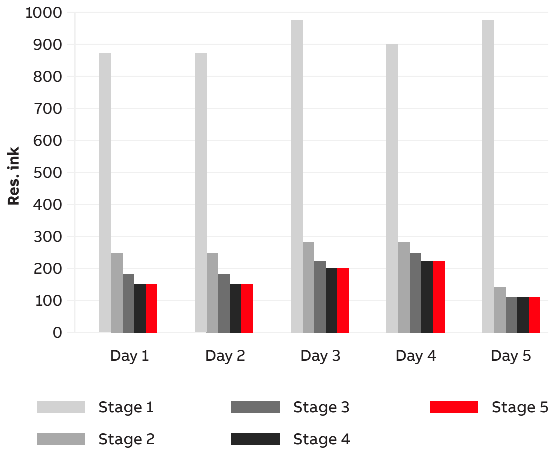
83
Development of residual ink content at different process stages in a DIP plant.

15.3.3. Whiteness

The parameter whiteness is used to describe the perceived whiteness of a finished sheet. Whiteness is, for example, influenced by bleaching, coloring and OBA. Though whiteness may be considered as the most understandable of the optical parameters, it is a fairly new parameter in paper product specification and is rapidly gaining more and more interest. It is used particularly for the OBA- containing paper grades.



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15.3.4. Residual ink

One task in the flotation of recycled pulp is to detach the black ink particles remaining from the dissolved, printed sheet.

The black ink absorbs light to a much greater extent than the cellulose fiber. This absorption occurs in particular in the range between 900–1000 nm. Thus, by measuring this absorption at different flotation stages, the performance of the flotation process can be supervised. When necessary, the recycled pulp can be additionally bleached.

Measurement of residual ink is standardized and the parameter measured is referred to as L&W Elrepho ERIC (estimated residual ink content). The method is based on the Kubelka-Munk theory, which means that the scattering coefficient and the grammage must be measured. The absorption coefficient and the ERIC 950 value can then be calculated. A simplified method is suggested for online applications, where the scattering coefficient is kept fixed at e.g. 55. Then the absorption coefficient follows from a reflectance measurement on the dry pulp sample. This simplified method should work well for process control purposes.

As an example, the residual ink was measured over five days at a plant for newsprint. Figure 83 shows how the amount of residual ink varies in the incoming pulp. There is a steady increase of residual ink in stage 2 for four days. However on the fifth day the process was adjusted and the removal of residual ink was significantly improved.

16. Statistics and reports

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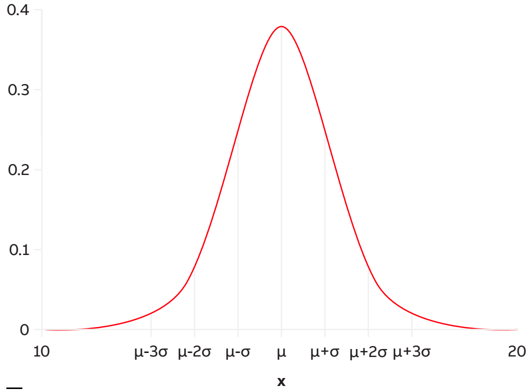
Normal distribution;
σ = standard deviation,
μ = mean value.

16.1. Gaussian density function

The normal distribution, called the Gaussian density function, is the most important distribution function in mathematical statistics (see below). It is widely used to describe variations in signals. It describes random errors in repeated similar measurements of the same object. The probability for a result from a measurement to fall within certain limits can be described.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \times e^{\frac{(x-\mu)^2}{2\sigma^2}}$$



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Confidence intervals:

- 68% of the observations are within +/-1 standard deviation (σ) from the mean value
- 95% of the observations are within 2 standard deviations from the mean value
- 99.7% of the observations are within 3 standard deviations from the mean value

Arithmetic mean value

$$x = \frac{\sum_i x_i}{n}$$

- n = number of values
- x = arithmetic mean

Example:
Calculate the average value for 5, 9, 7, 7, 4
x = (5+9+7+7+4) / 5 = 6.4

Limitations:

- Does not predict uniformity of product very well
- Extreme values have large influence

Standard deviation

$$\sigma = \sqrt{\Sigma\ (x_i - x)^2/(n-1)}$$

Example:

Value	(xi - x)	$(xi - x)^2$
6	-1	1
4	-3	9
8	1	1
12	5	25
	-5	25

- x = arithmetic mean = (6+4+8+12+2+10) / 6 = 42 / 6 = 7
- Σ (xi - x)2 = 70 (n-1) = 5 σ=+/-3.7

16.2. Confidence interval

When a trial series is carried out and the value of a certain property is estimated, it may be necessary to indicate the uncertainty of the estimation. This is usually done by indicating the limits within which the true estimated property would be with a certain indicated probability.

$$x \pm t_p \times \sigma / \sqrt{n}$$

Where the coefficient t_p is derived from a reference table. The standard deviation σ_p, of the mean representing 68% probability for the calculated mean value based on n observations, where the standard deviation of the measured property itself is σ, is given by:

$$\sigma_p = \sigma / \sqrt{n}$$

16.3. Poisson distribution

Detection of shive elements or vessel cells in fiber images can be regarded as single rare events. The detections are random and independent of each other. These types of events are regarded as Poisson distributed. If μ = mean value for detection, and σ^2 = the variance, then the standard deviation for the average is:

$$\sigma = \sqrt{\mu}$$

If 625 shives are found, then the standard deviation will be 25.

16.4. How many fibers have to be measured for statistical significance?

For the calculation of length, the number depends on the length distribution. If we say that the length distribution for softwood has a normal distribution (which is not completely true but is an acceptable approximation) and has an average L= 2 mm and σ = 1 mm, then σ_p for the calculated average will be $\sigma / \sqrt{n}$, where n is the number of counted fibers. If we count 10000 fibers, then $\sigma_p = \sigma / 100$. In our example, this is equal to 0.01 mm.

We need the statistics to achieve accuracy in the average values. If we test 625 fibers 'a high count for manual testing (microscope)' then σ will be 0.04 mm. Accordingly, it is difficult to reach the same repeatability manually with a microscope that can be reached with an automatic optical analyzer. In the optical device, we can easily increase the count to 40000 fibers and decrease the statistical scatter (σ) to 0.005 mm. When the distribution is divided into classes, the scatter in each class will, of course, be higher than that of the average, depending on the number of counts in each specific class.

There is a limitation for how many fibers are recommended to count. At some point, other sources of error, such as sample handling, will set the limit for variations in the sample.

16.5. Weighting of data

In the following we will describe how certain weighting functions can be used. Each measured value is multiplied by a weighting factor before the sum of the different values is calculated.

There are large differences in size between fiber objects. Fines are very different from fibers, and the manner in which fine objects affect the average of certain properties depends a lot on the technique used for weighting the data. We often define fines as elements shorter than 0.2 mm and exclude them from calculations of fibers with a length above 0.2 mm. But you will also find a lot of small objects above this limit.

Following weightings are used:

- 1, which is equal to arithmetic weighting by number
- Length-weighted, weighted with respect to length
- Length× length-weighted, sometimes called mass weighted (which is misleading, since optical methods cannot measure mass but are based on the fact that fiber length often correlates to wall thickness of the fibers), weighted with respect to length^2
- Area-weighted, weighted with respect to length × width
- Volume-weighted, weighted with respect to length × width^2

Weighting that is more in favor of large objects will increase the average or increase the influence of higher parts of the distribution.

Mass weighting is often a reference, when comparing with screened fractions and this is one reason for using weights. Another reason is that if we want good statistics for the fibers with less impact of fines, weighting is a way for improvement.

Weighting is a non-linear operation. If you use multivariate data analysis, it can be recommended to test different weighting functions to improve the models, since the mathematics in MVDA are linear and do not cover non-linear operations.

Example A

We shall calculate statistics for the synthetic fiber distribution shown in figure 85. Data are presented as mean values and distributions. Length-weighted data are more commonly used. If the data for fiber properties are to be used to estimate some sheet properties at a certain sheet grammage, then mass-weighted data should be better. The closest you can come to mass with an optical system is to use area or volume as weightings. If you think wall thickness is proportional to fiber length, then length × width × length might be a good weighting.

Weighting of data means to study how much of a certain property is carried by certain fibers.

In the simplest case, the weighting is the number of particles. We then have a length distribution where the value of each class is the number of particles in this class, or is expressed as the share of the particles by number in that class. The average will be:

Formula A $$\bar{l} = \frac{\sum_{i=1}^{n} l_i}{n} = \frac{\sum_i 1 \times l_i}{\sum_i 1}$$

which is the arithmetic mean value. This value can also be calculated approximately from data classified in a distribution:

Formula B
l = Σ(class value$_i$ × class center$_i$)/ Σ class value

Suppose that we wish to describe the result of a fractionation where the reference is the true weighted classes representing the distribution. This means that the value for each class should be how much absolute mass then is in each class. For simplicity, assume the particles to be massive with given constant density.

If so, we can use volume weighting of the data. The volume-weighted mean fiber length will be:

$$\bar{l} = \frac{\sum_i^n v_i \times l_i}{\sum_i v_i}$$

Length has been used as a standard weighting partly because it is a better approximation to mass than an arithmetic value and partly for historical reasons. It was not possible to measure width with the early instruments for length measurement.

This is the same expression as in [Formula A] but the weighting factor 1 is substituted with the volume of each particle. The volume is calculated in the conventional way from length and width.

The corresponding calculation based on the distribution is identical with [Formula B] but the class- value is now the sum of the volumes instead of the number of particles in the class.

Data can be weighted with any property in the same way, but the results should have a physical meaning so that they can be interpreted.

Data from L&W Fiber Tester Plus are often presented as length-weighted (x_l) or arithmetic averages (x_a) of length, width and shape factor.

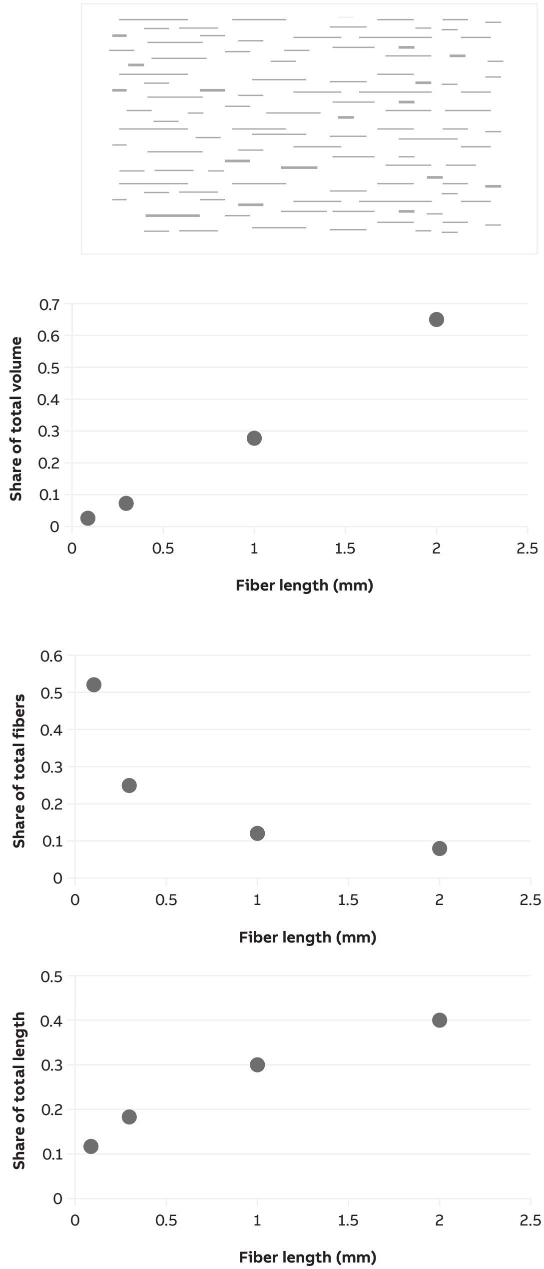
[14.10] $$\overline{x_l} = \frac{\sum_i l_i \times x_i}{\sum_i l_i}$$

[14.11] $$\overline{x_a} = \frac{\sum_i x_i}{n}$$

Data used in the example (Figure 85) were:

Number of objects	Length (mm)	Width (mm)
10	2	0.2
15	1	0.15
30	0.3	0.1
60	0.1	0.05

• Arithmetic mean length = 0.43 mm
• Length weighted mean length = 1.17 mm
• Volume weighted mean length = 1.58 mm



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85
Example of weighting of results. All distributions describe the same sample (above). Different weightings highlight different regions of the data.

Example B

A mixture of CTMP, chemical birch and chemical pine fibers was analyzed in the L&W Fiber Tester. Values in Table 17 were reported. The first column represents an arithmetic mean value, which means that the weighting factor is 1.

Table 17: Class weights for the kink index formula

Weighting factor	1	L	L×W	V	L×L
Mean length	0.999	1.555	1.772	1.924	2.259
Mean width	23.9	26.9	31.8	37.0	30.6
Mean shape factor	91.3	90.0	89.6	89.5	88.4

The other columns represent different weighting factors; length, area, volume and the square of the length. Length- weighted is traditionally used.

Volume is used in the L&W Fiber Tester, when it is important to get close to the mass. L × L are used by older devices on the market to get close to the mass because measurements of width did not exist or were not very reliable. For calculations of blends in the L&W Fiber Tester, volume is often used. Volume-weighted proportions of fiber species can be translated to mass-weighted proportions.

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86
Fiber length distributed into 5 length classes with 5 different weightings.

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87
Volume weighted distributions of fiber width.

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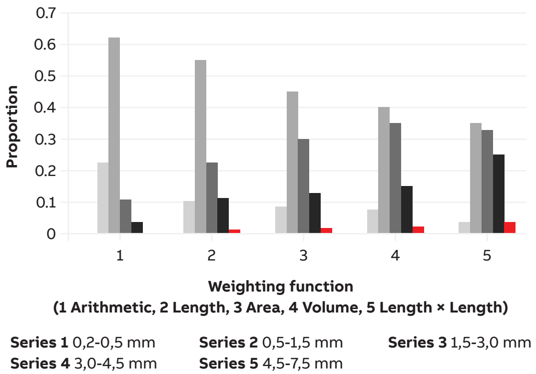
88
Data from Fiber Tester divided into 15 length classes and 15 width classes. Two-dimensional presentations give an extra dimension to the data analysis. Shape factor depends on the fiber length. Observe the red colored area for bendability. For the shape and bendability figures, the color indicates the value, and the lines show the proportion of the volumes.

The length distributions with 5 length classes for the actual mix of fibers (CTMP, HW and SW) are shown in Figure 86 with different weightings. As was exemplified in the synthetic example A, the same pattern is shown here based on data from Fiber Tester. Different parts of the distribution are highlighted with different weightings.

Figure 87 shows volume-weighted width distributions of SW, HW and CTMP. CTMP is well separated from SW with volume-weightings. The lignin still remains in CTMP fibers and thus the fibers are clearly wider than chemical fibers.

Since length, width and shape factor are measured on the same objects, it is possible to study multi- dimensional distributions. The easiest is to monitor two components with the third as a color-coded surface falling into different classes of the other two.

As can be seen by how the proportion of volume (Figure 88) is distributed depending on length and width, it is clear that length and width do not correlate. If we look at shape factor, we can see that it depends on length but not on width.



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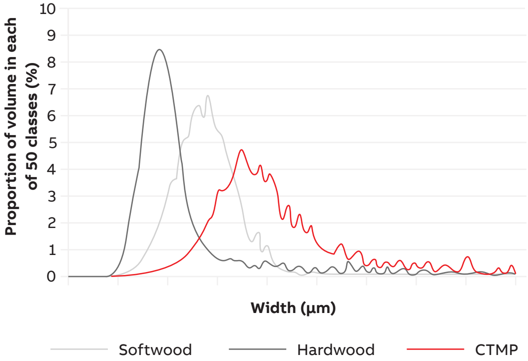

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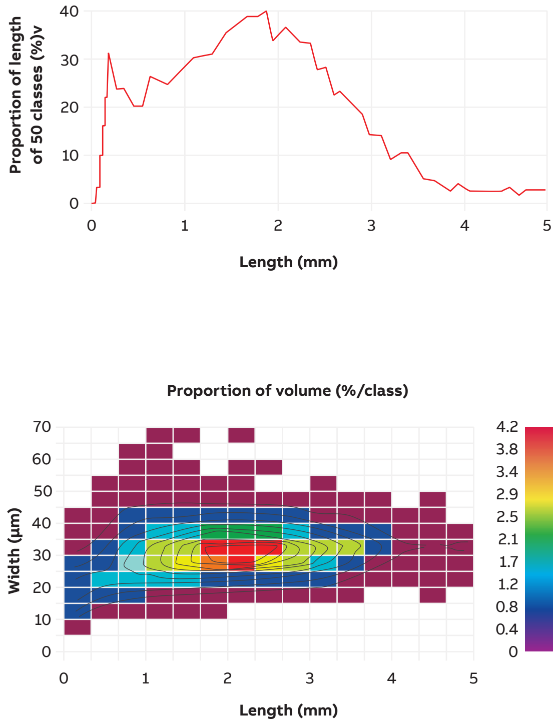

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Shape factor depends on fiber length; chemical pulp.

16.6. Decoupling of impact of length on other fiber properties

By looking at different fiber properties in separate length classes, the impact of length on these properties can be minimized. The following classes are often used (Table 18).

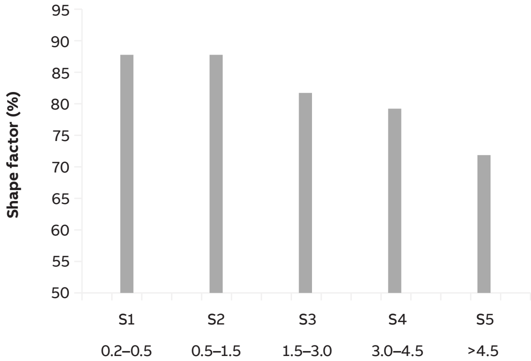
Shape factor, as it is defined, is correlated with fiber length. In order to separate changes in shape factor from changes in length, it is recommended to study the shape factor in different length intervals. Typical intervals used can be seen in Table 18.

Table 18: Division into basic length classes

Length (mm)	Proportion	Width	Shape
0.2–0.5	P1	W1	S1
0.5–1.5	P2	W2	S2
1.5–3.0	P3	W3	S3
3.0–4.5	P4	W4	S4
>4.5	P5	W5	

For hardwoods, the 0.5–1.5 mm interval is a representative interval. For softwoods, the 1.5–3.0 mm interval is representative and often used.

Deformations can also be measured as local deformations of the fibers. In this case, the dependence on length is a minor problem. In the case of chemical pulps, temperature and pH have small effects on shape factor within reasonable limits. The flow speed in the measurement cell is selected to have a minor effect on shape factor. The width of the fiber seems to have a very small impact on the shape factor (Figure 89).



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17. Sampling

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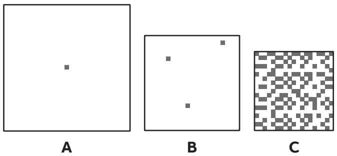
In this illustration, A represents one sample per 3,000 ton pulp, B represents three samples per 1,500 tons, and C represents 100 samples per 1,000 tons.

17.1. Representative samples to check production delivered to customers
One company introduced on-line measurements of pulp quality for frequent checks of the production of market pulp. Manual laboratory hand-sheet testing is time-consuming. In the example in Figure 90 (A), the standard sheet-testing procedure with sampling, beating, sheet forming and standard tests was applied every second day. The large square represents two days production of 3,000 tons of pulp. The dot represents one sample taken from the production.

An automated laboratory analyzer is easier to operate. Measurements from such an analyzer were taken once every shift. With six measurements on the same production volume, we get more representative measurements as shown in Figure 90 (B). With automatic sampling from an online fiber analyzer, such as ABB's L&W Fiber Online, quality can be measured once every 5-10 minutes, which is 100-200 measurements per 1,000 tons, as shown in Figure 90 (C).



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17.2. Sampling theorem
For correct sampling of an analog time-varying signal to a discrete signal, certain conditions of the signal have to be fulfilled. It should be possible to recreate the analog signal without false frequencies popping up. If the analog signal includes time variations faster than half the sampling frequency, false frequencies will occur (Nyqvist theorem). The way to handle this potential problem is to filter the analog signal before sampling. The low pass filter should be designed to cut away frequencies greater than half of the sampling frequency.

In the pulp and paper industry, the processes are often slow because of the number and capacity of the mixing chests. Automatic measurements for fiber quality control with a 5–15 minute cycle time are often enough, but there are examples where the fastest possible measurements are required.

Figure 91 illustrates how to select sampling frequency. The same signal is sampled five and three times respectively. With five samples, the frequency is sufficient to describe the actual signal (process) reasonably well. This is not the case with the other example with three samples. Here the curve is not well represented by the sampling. It is not possible to recover a signal which is similar to the initial curve.

17.3. Master sample

One user of the L&W Fiber Tester noticed large variations (scatter) in the data for samples of waste paper from the yard (waste stock). However, there was a large variation between the waste paper reels.

In order to obtain a representative average, the user had to take a lot of different manual samples from different reels. He then mixed all the samples, disintegrated and mixed well and a representative sample was taken from this mix to the L&W Fiber Tester.

In this case, this was a necessary step to obtain reliable data from the L&W Fiber Tester. These averaged values could then be correlated with the runnability of the paper machine. Representative samples are needed in all steps of the analysis.

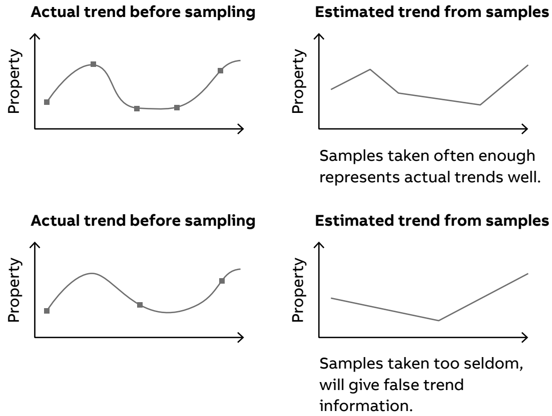

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Illustration of the problem of sampling and the risk of information loss. It is important to have many samples to be able to follow and understand the process. More samples per unit time will always give a better representation of the reality.

17.4. Manual preparation of samples for fiber measurement

Most fiber analyzers are accurate and have good repeatability. However, a critical requirement is the correct preparation of the samples. You can easily introduce variations by a few percent when you take a smaller part out of a larger sample. Since laboratory fiber analyzers use small volumes, it can be practical to prepare large volumes and then take new representative samples from these. Stirring immediately before sampling is very important, since fibers have different sedimentation speeds. Here are some guidelines on how to prepare samples before you analyze in the L&W Fiber Tester:

Wet samples to the fiber analyzer:

- Measure the consistency of the sample
- Take out an amount that corresponds to 2 g of dry fibers, and disintegrate it in 2 liters of water in a standard disintegrator (10 minutes or 30,000 revolutions)
- Transfer a volume that corresponds to 0.1 g dry fibers into a bottle, and fill it up to 200 ml with water

Dry samples:

Alt 1:

- Pre-soak 2 g of the sample in water for at least 4 hours
- Disintegrate (re-slush) the sample in 2 liters of water, at 30,000 revolutions, in a standard disintegrator
- Transfer 100 ml of this volume, corresponding to 0.1 g dry fibers, to a bottle and fill up to 200 ml with water

Alt 2:

- Take out 0.1 g by weighing, and then dilute with water to about 100 ml
- Disintegrate the sample in a mixer, and fill it up to 200 ml with water

Alt 3:

- Take out 1 g dry sample by weighing, and then dilute to about 300 ml
- Disintegrate the sample with a hand mixer (avoid sharp edges in the mixer)
- Dilute to 1 liter. Transfer 100 ml, corresponding to 0.1 g dry fibers, to a bottle and fill it up to 200 ml

The way in which samples should be prepared depends on the purpose of the analysis. However, no matter what sample preparation method is used, care must be taken to avoid altering the fundamental properties of the fibers to ensure that false or erroneous results are not recorded. In general terms, it is desirable to achieve a stable state for the suspension. The sample should not change properties during the analysis. ABB's L&W Fiber Tester usually makes double tests. If the sample is not stable, the double test will detect a deviation and signs of an impending deviation will also be monitored. For mechanical pulps, the shape factor or latency will change with temperature. To stabilize a sample before a freeness test, hot disintegration is sometimes used, but if the deformations of the fibers are to be investigated, the sample preparation should of course avoid changing the property to be studied. It has been observed that fiber deformations can also change with time in chemical pulps. For example, the time between refining and measurement of the deformations can play a role. This will also have an impact on how pulps are stored in the process before the paper machine.

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Sampling from the process, the principle operation of the L&W Pulp Sampler.

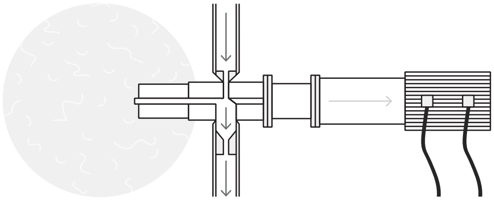
17.5. On-line samplers

Online samplers are available for low consistency pulps and medium consistency pulps. It is possible also to develop samplers for high consistency pulp. In mechanical pulping, individual samplers for high consistency refiners would make it possible to automatically follow and optimize each refiner separately. Samplers should take a representative sample from the process. The analyzer must be able to handle different distances to the sampling points and account for transportation time of sample to the analyzer. It is important to capture the sample from a pipe where pulp is transported upwards to ensure that there is enough pulp in the pipe. Sampling of processes is a difficult issue, especially when small amounts of samples are used. See Figure 92.

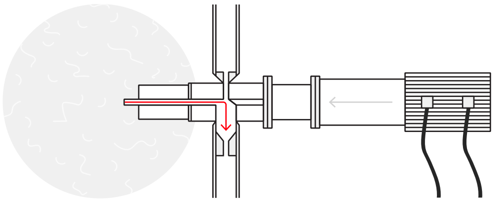
If particles are left in the sampling chamber, they will be taken back into the process. At 2, the fresh water supply is switched off and the sampling chamber is filled with the fiber suspension. At 3, the sampling chamber is pulled out, and the sample is isolated from the process pipe. Finally, the fresh water supply is switched on again, and the fibers pass into the sampling line to Fiber Online. The fresh water enters the sampling chamber as a water jet through a small hole placed at the sample outlet. When the sample has passed into the sampling line, it is already diluted and it can therefore be flushed with pressurized water, thus allowing for long distances between the sampler and instrument.

If the consistency or the pressure in the process pipe is low, several strokes of the sampler are required in order to get the appropriate amount of fibers to the analyzer for reliable results.

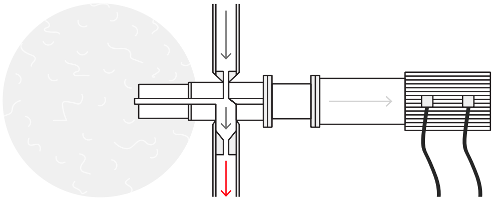
After the sample has reached the analyzer, the tubing is flushed with clean water to be prepared for the next sample extraction from the process.



1. Flushing (cleaning) the sampler with water



2. Taking a sample



3. Pushing the sample with water

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L&W Fiber Online with 4 positions for the input of samples from the process.

17.6. An online fiber quality / pulp analyzer
L&W Fiber Online measures fiber properties online via a sampling device placed in the manufacturing chain (an installation on a pipe for the production of bleached chemical pulp is shown in Figure 93).

Up to eight samplers can be used for automatic sampling of the process. The instrument is also equipped with an input for manual samples. The online system and the laboratory analyzer are built with the exact same components for capturing images of the fibers. This makes it easy for the laboratory to follow up calibration.

The measurement technology with its special sampling system enables totally automated and frequent analysis of pulp quality throughout the manufacturing process.

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18. Impact of fibers on products

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From tree to end product

Paper can be described as a stratified structure composed of fibers and fines. Each gram of paper contains many millions of fibers. In addition to the fibrous material, many paper grades also contain large amounts of fillers. The fibers' flexibility and the presence of fines increase the bonding surface and improve the bonding ability between the fibers. Length, fiber deformations, cross-sectional properties, fiber surface and chemical composition are all important for paper quality.

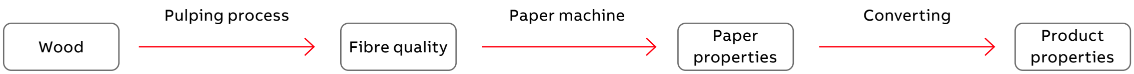
Paper properties are dependent on the fiber species used, on the pulp manufacturing process and on the paper machine. The final paper properties can be established by controlling the fibers in the pulp, i.e. by making sure that they have the right quality. A paper with desired properties can be obtained by choosing the raw material and the treatment of the fibers.

The quality of the end product is determined early in the process chain. How can quality be communicated through the chain of processes? It is possible to analyze the fiber quality in a product by disintegration of the paper and also by disintegration of the end product.

It is thus possible to measure some properties at the end of the chain together with specific properties of the product.

This may help to develop an understanding of what is needed from the fibers. Measurement of fiber properties makes it possible to connect the fiber properties directly to the end-use. Measurements online early in the process chain are made in order to control and optimize the fiber properties.

All paper products have their own specifications and special tests to verify whether the product fulfills the requirements. An important thing to know is which fiber properties are the most suitable in each case. Since these may be difficult to define, tests on laboratory-made sheets are used to test pulp properties. A lot of knowledge is available regarding the properties of hand sheets. Therefore, it is of interest to relate fiber properties to hand sheet properties as one step. It is also an advantage if we can describe pulp quality with a few basic fiber parameters. Information about sheet properties described in following sections of chapter 18.



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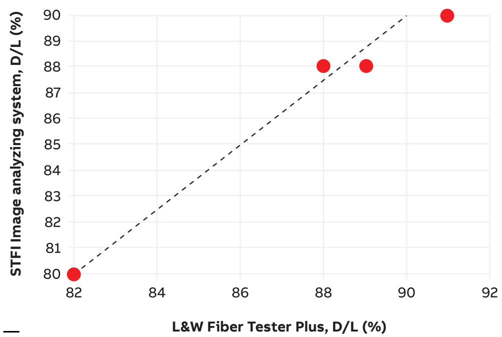
Let's examine the principal effects of fiber properties on traditional properties of hand sheets.

18.1 Reinforcement

Fiber length is an important property of pulp, and longer fibers generally improve the strength properties up to a certain point. Limited bonding of the fiber in the network will limit the possibility for the fiber to carry a load at the ends of the fibers. With longer fibers, the bonding will be less critical. Very long fibers are more easily entangled with each other, giving an uneven fiber distribution in the sheet, i.e. the sheet will have a poor formation.

18.1.2. Shape factor in suspensions and in the sheet

A comparison was made between the mean fiber shape factor in four pulps, and the mean fiber shape factor measured on laboratory sheets made from these pulps, using an image analysis system. To make the laboratory sheets, a CTMP from a laboratory refiner was used. The pulp had a high latency (highly deformed fibers) and was divided into four separate categories. Each category was treated at different temperatures (20, 55, 65 and 85°C) during the disintegration according to SCAN-M 10:76.



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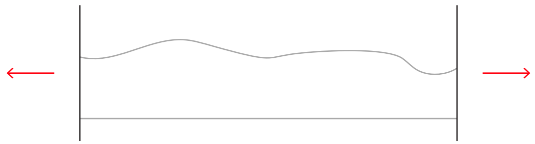
By using different temperatures, the pulps were given dissimilar degrees of fiber deformations and thereby different fiber shapes.

About 0.5% of the fibers in the suspension were dyed with black ink to enable the shape in the sheet to be studied with an image analysis system. The fiber shape obtained from L&W Fiber Tester Plus was roughly the same as the shape factor in the sheet. The main work was to show theoretically by FEM-simulation of fiber networks that curled fibers lowered the tensile stiffness of the sheet.

18.1.3. Stretched and free segments

A stretched fiber segment between two bonding points will carry load in the sheet. A non-stretched segment will carry load first when the sheet has been sufficiently stretched (figure 96).

Since the fiber is bonded in a network (figure 97), only parts of the fibers are free segments. Some kinds of paper are very dense, while others have an open structure (like tissue). Pulp for tissue is often not beaten very much, and this leads to the open structure. In this structure, fiber flexibility is more important for strength since fewer fines are available for bonding.



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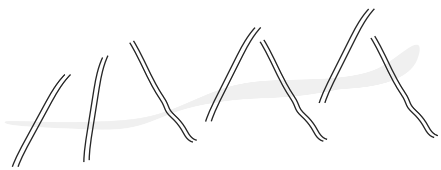

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18.1.4. Individual fiber strength
Wet zero-span test makes it possible to measure the fiber strength separated from other effects. The zero-span tensile strength value is intended to be an indicator of the average strength of individual fibers. However, it is dependent on fiber deformations. It is also suggested that the deformations themselves are more important than the fiber strength in a non- deformed fiber. The local deformations of fibers may be potential weak points of the fibers.

18.1.5. Fiber width
For certain pulps made from wood from a single species fiber, width does not correlate with fiber length and wall thickness. However, in a mix of different pulps, it may correlate. A low fiber width will give a sheet a more even surface and better formation.

18.1.6. Fibrillation
During the beating, a thin part of the fiber wall partly becomes loose. This is part of the secondary fines that still are still connected to fibers. The function in the sheet is the same as for the secondary fines mentioned below.

18.1.7. Primary Fines
Primary fines give low strength because of their low bonding potential. Opacity and bulk are affected. Drainage is affected negatively. Ray cells are primary fines.

18.1.8. Secondary Fines
Secondary fines are produced during beating and give strength to the sheet. Modification of the fiber wall leads to an increased uptake of water by the wall and also to a more flexible wall. Measurements like Canadian Standard Freeness (CSF), Schopper-Riegler (SR), and Water Retention Value (WRV) correlate with both these effects and with bonding.

18.1.9. Coarseness
It is believed that high fiber wall thickness gives high fiber strength, which will provide a high tear index. To calculate fiber wall thickness, coarseness can be measured if we have input of the fiber weight. Coarseness is defined as weight per unit fiber length, and it seems reasonable that the diameter of the fiber will also play a role. Sometimes it can be of value to calculate an overall fiber density, and this is done by dividing the total mass of the measured fibers by the total volume of the measured fibers instead of dividing by the total fiber length. This can be extended to calculate an average fiber wall thickness as well. If an average wall thickness is to be calculated, a fiber wall density has to be set.

This fiber wall density may be different between different species. A thin fiber wall increases paper strength for a certain grammage, and a thick fiber wall gives bulk to the sheet.

18.1.10. Bonding strength

The strength with which fibers adhere to each other, together with fiber strength, contributes to the pulp strength. Both the bonded area and the specific bonding strength between fibers affects the bonding strength. More flexible fibers and more secondary fines both increase the bonding area. The sheet density and the light scattering ability of a sheet may thus be used to predict the bonded area. The fibers are more densely packed in the sheet, when there are a lot of contact points between the fibers. Increased density and decreased light scattering ability denote more bonded area. The bonding strength can be defined as the strength in the z-direction. Bonding is increased by beating. Hemi cellulose is important for bonding.

18.1.11. Freeness

Beating increases bonding and decreases drainability at the same time. Freeness sensors are also sensitive to small particles that reduce drainability, but do not necessarily increase strength. WRV is another measure of how well water is bound to the fiber. It is intended to simulate the water content after the press section in a paper machine. WRV is often said to correlate better with strength than standard drainage measurements (CSF etc). However, freeness measurements are the most widely used measurements in stock preparation testing.

18.1.12. Flexibility

Flexible fibers are believed to give stronger sheets and increase the surface available for bonding.

18.1.13. Vessel cells

Vessel cells cause linting problems in the printing press. Bad bonding properties of the pulp increase the risk of linting. Bad bonding between fibers and vessel cells can also cause linting problems in the paper machine.

18.1.14. Kink

Local deformations of the fibers are called kinks. A kink can be a weak point of the fiber, since the strength of the fiber is obviously unevenly distributed along the fiber axis. Kink correlates well with shape factor in most cases, since local deformations are included in shape factor. Deformed fibers give a more elastic paper (a good property when manufacturing sack paper) if the paper is freely dried.

18.1.15. Shives

Shives lead to paper weaknesses, as they cause web breaks.

18.2. Tensile stiffness and tensile strength

Pulps collected from different positions in different mills were analyzed with respect to shape factor in the L&W Fiber Tester; tests were also performed on handsheets. Tensile index depends a lot on the deformation of the fibers. The samples with the highest tensile index were laboratory-made samples. Note that these fibers were very straight from the beginning and strong already without beating.

Tensile strength is used in pulp testing as a general characteristic for the capability of bonding between fibers.

98
Shape factor measured on never-dried pulp in non-integrated pulp mill correlates very well with the Tensile Stiffness Index [RISE].

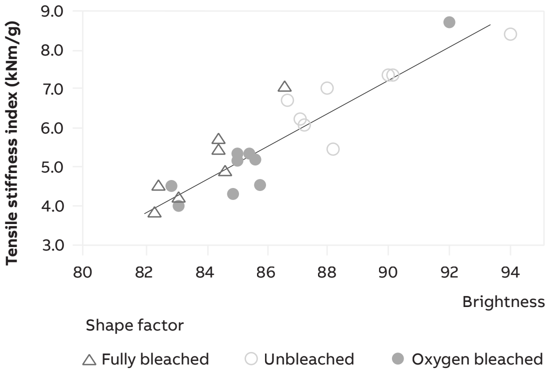

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Table 19: Light scattering ability for different types of species

	Pine	Birch	Eucalyptus
Length (mm)	3.0	1.1	0.9
Width (µm)	30	18–22	12–16
Wall thickness (µm)	8	3	2–3
Number of fibers/mg	2000	8000	16000
S (m2/g) at tensile index 50 kNm/kg	29	34	41

18.2.1. Light scattering

For slender and thin-walled fibers, the surface area/ weight ratio is greater than that for broad and thick fibers. This provides a larger surface area, both for bonding and for light scattering. Increased beating lowers the light scattering in the case of chemical pulp and increases the tensile index. Eucalyptus gives the highest light scattering at a given tensile index (Table 19).

18.2.2. Tear strength

The tear strength depends on fiber length, fiber strength, cross-section properties, degree of bonding between fibers, and degree of orientation of the fibers in the paper. Longer and stronger fibers have higher tear strength. The tear index increases in the early phase of beating but then decreases with beating.

Table 20: Effect on the paper sheet of fiber properties with all other parameters kept constant

Fiber property	Tensile	Tear	Bust	Formation
Increase in fiber length	+	+	+	-
Decrease in shape factor	-	+	-	+/-
Increase in % fines	+	-	+	+
Decrease in coarseness	+	-	+	+

18.3. Single layer products

18.3.1. Printing papers

Newsprint furnishes and magazine papers for printed media belong to the category of wood-containing paper where the life cycle of the printed product is quite limited. As a result, it is important to have a high pulp yield. Newsprint furnish consists of a mixture of mechanical pulp–groundwood or TMP (usually spruce) and lightly refined chemical pulp. Sometimes a small amount of filler is added. The mechanical pulp adds valuable properties to the newsprint, all of which are related to printability, bulk, compressibility, opacity and formation. Sometimes, the strength properties of mechanical pulps are insufficient to produce a sheet that runs well on the printing press, and the pulp is therefore reinforced with chemical pulp.

The need for reinforcement pulp has decreased with the development of paper machines and the properties of mechanical pulps. It is more and more common to use recovered paper in a newsprint furnish and the waste paper then also includes a certain amount of chemical fibers. The grammage of newsprint papers is 40–45 g/m2. Important properties for printing papers are listed below with an explanation of why they are important.

Surface strength – low surface strength will result in fibers being torn from the web surface, and this may lead to dusting. Linting can also occur if the fibers are ripped off and stick to the printing press surface. Linting reduces the availability of the printing machine, since it has to be shut down and cleaned.

Fracture toughness – fracture strength is important for the runnability of the printing press. High fracture toughness gives the paper web the ability to resist fracture from a crack in the web.

Opacity – it is not desirable to read the print on the opposite side of the paper.

Smoothness – a smooth surface is a necessity for good printing. A rough surface will lead to linting, dusting and uneven print quality.

18.3.2. Fine paper

Fine papers are white, uncoated printing and writing grades that contain less than 25% mechanical pulp in the furnish. The grammage ranges from 50 to 100 g/m2. A large item is A4 copy paper. Fine papers are made from a mixture of fully bleached softwood pulp, hardwood pulp and fillers. Good sheet formation and a well-filled surface are necessary attributes for fine paper grades, while strength is not a limiting factor. Therefore, sulphite, hardwood, and chemical sawdust pulps are preferred over long-fibered kraft as furnish. The pulp furnish for fine paper is usually given a light to moderate refining, and 10–15% filler is added. Important properties for fine papers are listed below with an explanation of why they are important.

Surface strength – low surface strength will result in fibers being torn off the web surface, and these may stick to surfaces within the copying machine, causing machine failure.

Dimensional stability – a paper should not curl when toner is applied in a copying machine.

Bending stiffness – the paper should not be like a cloth and bend; it has to stay flat when held.

Smoothness – a smooth surface is a necessity for good printing. A rough surface will lead to linting, dusting and uneven print quality.

Picking

A problem with some hardwood species is vessel picking. The phenomenon is illustrated in figure 101. Large vessel cells tend to fasten on the printing plate. The problem is worse on fast machines with a high-tack ink. A sheet with good bonding potential may be one way for improvement.

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99
Surface of newsprint Environmental Scanning Electron Microsope (ESEM) image (150× magnification). A lot of fines are seen between the fibers.

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100
The surface structure of fine paper made in ESEM, (150× magnification). The wide bands are vessel elements probably from birch.

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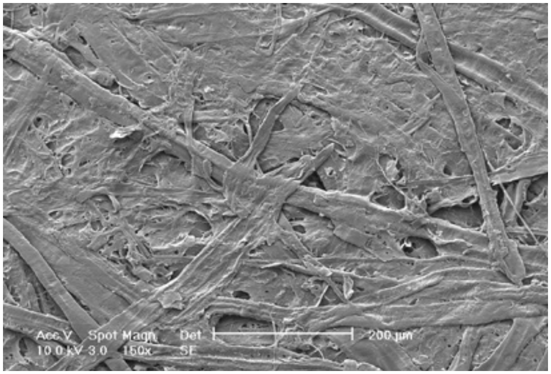
101
Picking - A vessel cell on the surface of the paper is poorly bonded to the sheet and loosens during printing.



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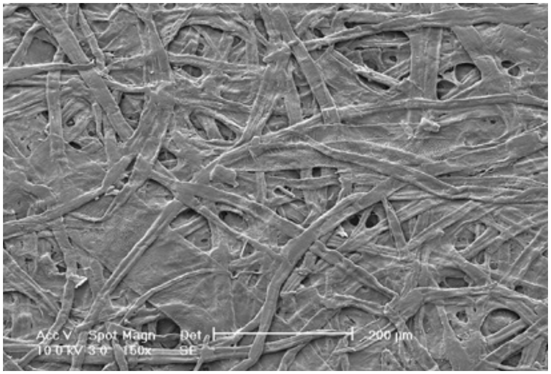

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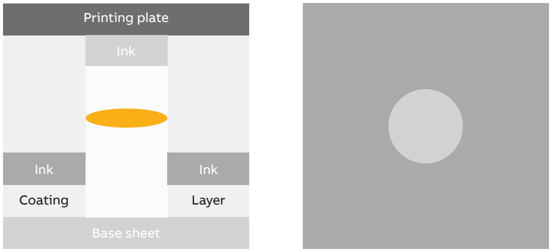
18.3.4. Lightweight Coated (LWC)

Lightweight coated (LWC) is a grade of mechanical printing paper of low grammage, primarily used as a publication paper where surface quality and weight are important.

LWC-papers must have good runnability and good printability. Stable quality is regarded as important. LWC-papers consist of groundwood pulp or thermomechanical pulp, even though they are quite different mechanical pulps. Groundwood pulp is rich in fines, which gives good printability to papers, but low strength.

The consequence is that a large amount of chemical pulp has to be added to the furnish. The long-fibered TMP is stronger and less chemical pulp needs to be added to the furnish. However, TMP gives poorer printability and has a higher specific energy consumption.



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18.3.5. Corrugating medium

Corrugating medium is a lightweight board used for the fluted inner plies of corrugated box stock. It is principally made from semi-chemical pulp and recycled fiber. High bending stiffness is required for corrugated box construction, and the fluted layer provides much of it by keeping the two liner layers apart from each other. Mechanical strength properties such as tensile, burst and tear are unimportant except in certain limited applications. Sheet finish and appearance can also often be ignored. The ideal furnish for corrugating medium is semi- chemical pulp because of its high crush resistance, although these pulps are notably weak with respect to the more common strength criteria.

18.3.6. Sack grades

Sack grades are usually manufactured from well-refined, unbleached softwood kraft pulp to meet the strength requirements. The pulp is refined in high consistency refining in order to introduce microcompressions and crimps. Rosin sizing and/or starch is added to the furnish to provide additional internal strength. The grammage is between 60 g/m2 and 150 g/m2. Good sheet formation is extremely important for uniform strength, which is why these machines are operated with very low consistency in the forming section. For this grade, free drying is preferable, to allow the sheet to shrink during drying. This provides good tensile energy absorption (TEA) through good stretch.

An explanation of important properties for sack papers are listed below.

TEA and Fracture Toughness – sack paper needs to withstand applied forces of large magnitude by having a good stretching ability. Curled fibers with microcompressions are more stretchable.

Air permeance – efficient sack filling requires that the product entering the sack displace the air captured in the sack. Extreme permeance will result in dusting during filling, product wastage and dirty sacks. Insufficient permeance will result in stress to the sack during filling, and improper sack sizing.

Tear and Burst strength are also important for sack paper to prevent rupture in the paper bag or sack when it is containing heavy objects.

18.4. Stratified products

18.4.1. Tissue

The term tissue covers a wide range of extremely low-weight sheets. Sanitary tissue includes facial and bathroom tissues, paper towels, and paper napkins. Industrial tissues include condenser, carbonizing, and wrapping grades. The grammage for tissue paper is in the range of 15–25 g/m2. Tissue cannot be produced on a conventional paper machine because of the low grammage of some products and the loose structures of others. The raw material used can be TMP, recycled paper or bleached kraft pulp. CTMP in the form of fluff pulp is used for diapers and sanitary napkins.

Important properties for tissue grades are listed below with an explanation of why they are important.

Softness – the paper should be velvet-like.

Smoothness – a rough surface with fibers sticking up, giving the surface an uneven appearance, would feel rough against the human skin. The surface must be smooth.

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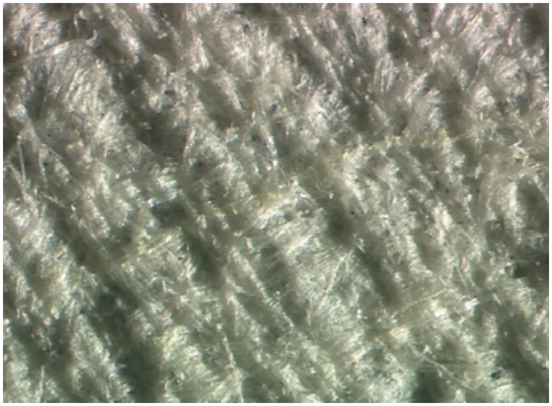
102
The surface structure of tissue from microscope, (30x magnification). Notice an open sheet structure compared with the figures 99 and 100 shown earlier

Ability to absorb water – tissue paper is most commonly used for wiping up liquid media of some sort, usually water, and the capability to absorb a relatively large volume is probably its most important property.

Wet strength – the intention of tissue is to be wetted; therefore it has to have sufficient wet strength not to fall apart immediately after becoming moist.

Dry strength – a certain dry strength is necessary in the converting process.



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18.5. Linerboard
Linerboard, the facing of corrugated fiberboard, is a relatively lightweight board. Linerboard consists of different layers; a rather dark and coarse high-yield, unbleached kraft base sheet (bottom liner), and a lighter, cleaner, better quality layer (top liner) with a good printing surface. The grammage is between 100 g/m2 and 400 g/m2. When the raw material is recycled corrugated fiberboard, the paper grade is called "testliner".

The main requirements of linerboard are a high compression strength and a high burst resistance. The fibers are strongly oriented in the machine direction, since stiffness in the cross direction comes from the corrugating medium in the final product. Important properties for linerboard are listed below with an explanation of why they are important.

Burst strength – is often measured for liner. If the liner has low burst strength, the box will be weak, easy to penetrate and/or lose its structural integrity.

Compression strength – boxes and cartons made of kraft liner are often piled on each other and are thereby subjected to compression forces.

Good appearance and printability on one surface are also important. Using high-yield kraft pulp in the bottom liner, and a lower yield, well-refined kraft on the top liner can satisfy these requirements.

18.6. Paperboard
Technically, all sheets with a thickness greater than 0.3 mm are classed as paperboard, but there is no clear definition of paperboard in precise terms. Boards can have a single-ply or multi-ply structure with a grammage of 250 g/m² or higher. A partial listing of paperboard grades is given on next page (table 21). Bleached or unbleached kraft pulp is used as well as mechanical pulps and recirculated fibers. An explanation of important properties for paperboard are listed below.

Bending stiffness – packages have to be rigid and not crumble when stresses are applied.

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103
A SEM-image from a cross section of paperboard. Note the open structure in the middle of the sheet, the black coating layer and the tight bonded sheet at the surface close to the coating.

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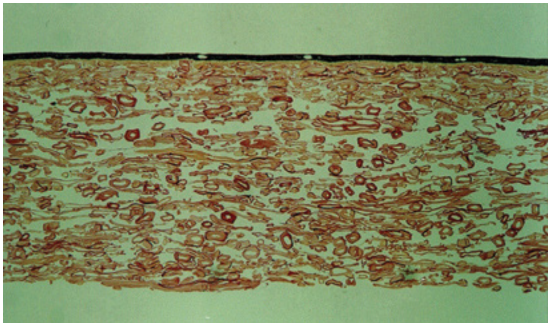
It is possible to build up sheets with advanced structures to optimize quality.

Smoothness – a smooth surface is necessary for good printing. The top layers of paperboard boxes are often used to print information regarding the box contents, etc.

Other properties, such as opacity and bulk, are more dependent on the area of use. The main advantage of multi-ply forming is the ability to utilize bulky low-grade waste materials (mostly news) in the inner plies of the board, where low strength and extraneous materials (ink, coatings, etc.) have little effect on the properties of the sheet. Since several furnishes may be used on a single multi-ply machine, the stock preparation system is generally more complex than that utilized in papermaking. The top liner, the under liner, the filler plies, and the bottom liner may all require individual systems.

In a sheet construction like that in figure 104, the surface layer of hardwood ensures an even surface. The next strong layer is made of chemical softwood with good bonding properties. Hardwood and softwood are often mixed in the surface layer. Bulk in the middle layer is achieved by using chemical-mechanical pulp with wider and stiffer fibers. A bonding layer is in this case applied outside the middle layer in order to keep the layers together.



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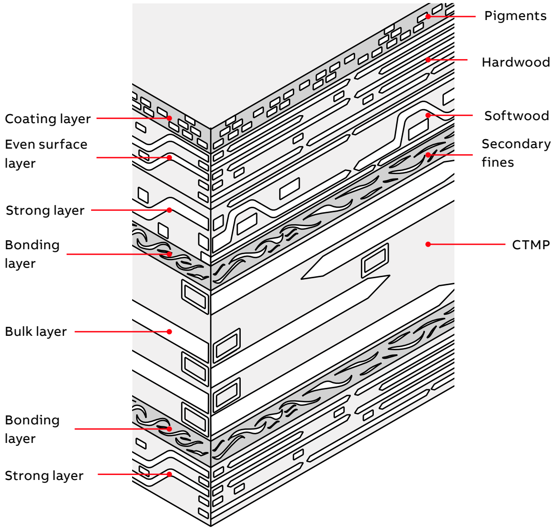

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Table 21: A partial listing of paper boards

Liquidboard	A board with high demand on bending stiffness. Must be very neutral with regard to taste and smell. Made of virgin pulp. Different species used in different layers to meet different demands on surface and mid-layers. Usually coated top layer.
Linerboard	A board having at least two plies, the top layer being of relatively better quality; usually 100% virgin pulp furnish. Testliner uses 100 % recycled paper.
Foodboard	A board used for food packaging with single-ply or multiply construction, usually with 100% bleached virgin pulp furnish.
Folding box board (carton board)	A multiply board used to make folding boxes with virgin pulp used for the top ply (liner); the remainder of the plies are made from secondary fiber (recycled waste).
Chipboard	A multiply board made from 100% low-grade secondary fiber.
Baseboard	A board that will ultimately be coated or converted.
Gypsumboard	A multiply board made from 100% low-grade secondary fiber that is used for the outer surfaces of plasterboard.

19. Models

It is desirable to be able to make measurements and to supervise fiber quality parameters online in the process. However, in some cases it is preferable to know how the fiber properties will affect laboratory sheet characteristics.

Available knowledge often relates to laboratory sheets, which show the potential paper properties of the pulp. In the laboratory procedure, a laboratory beater is often used, but the result is different from that achieved in an industrial beater. It is difficult to make realistic trials to model the actual paper properties from pulp properties since the papermaking process involves a lot of complicated parameters.

A sheet from a paper machine is of course affected by the set-up parameters in the machine. A laboratory sheet former does not produce a sheet with the same properties as a paper machine.

For these reasons, one technique for the development of models relates to laboratory sheets, although with the mentioned limitations. The other technique is to develop models directly from process data and the testing of the machine made paper.

19.1. Mathematical and physical models

Linear models have limitations; the world is not linear, but it can be regarded as linear within certain limits, and we have good tools to handle linear models. Non-linear models are much more difficult to handle. One way of solving this problem is to introduce known or estimated non-linear functions before using the linear modelling tools. When statistical data from fiber distributions are used for linear modelling it can be an advantage to know that the weighting functions used are often non-linear operations. Different statistics to represent the fiber properties will give different results. Tests using different types of weighting functions may be one way of improving the models.

The stability of the models will increase if knowledge about the process/relationships can be included in some way in the models. A formula based on an understanding of concrete physical relations is always better than a purely mathematical correlation. I would classify the method to calculate the amount of fiber components in blends described in this chapter as being of this latter type.

A limitation of all models is that they are valid only within a limited range.

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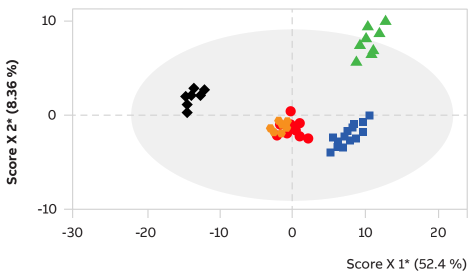
PCA model. Black is recycled pulp. Green is unbeaten virgin pulp. Blue is beaten virgin pulp. Red is the mix and orange is broke.

19.2. Multivariate data analysis (MVDA)
Multivariate data analysis is an efficient tool for the development of linear models. The theory of multivariate calibration does not differ from that of univariate calibration except that many variables are used to describe the predictor space. Modern instruments collect a large set of data when performing an analysis, but the interpretation and evaluation of these large amounts of data is tedious and difficult. Multivariate analysis can be applied on large data matrices, e.g. PCA (principal component analysis) and PLS (partial least square, or projections to latent structures).

PCA Model Kraftliner



Distributions of fibre properties were used as input variables.
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PCA is used to obtain an overview and a good approximation of the main variance in the data. All the K-variables (number of variables) and N-variables (number of observations) form a K-dimensional space in which each sample is represented as a point. By PCA, all samples in the original K-space are reduced to a new low dimensional (usually 2–4 dimensions or principal components, PC) plane, onto which the samples are projected. The contributions of the K-variables to the sample-oriented projection are visualized by a variable-related projection (loadings).

PLS modelling solves problems with correlated variables by using a few orthogonal latent variables or principal components describing the X and Y block to perform regressions and find a correlation between the descriptor (X) and responses (Y). In other words, principal components are calculated for the X-matrix in the same way as PCA, except that PLS finds relations between the structures in the X- and Y-matrices.

From an experimental set of data, half the data is often used to calculate of a model. The other half of the data is then used to test the predictive capacity of the model.

Results from a joint project many years ago between what was then STFI and Fibertracker with Södra Cell and Vinnova (Swedish agency for innovation systems that provided financial support) are shown in figure 106. Tests to build linear models of traditional sheet properties showed good possibilities by combining the standard Fibermaster properties with some other measurements. The most important data from Fibermaster were the shape factor values. The fiber properties were measured on never- dried pulp and were used to predict sheet properties on paper made of dried pulp. In the figure below (figure 106) one result is shown.

Pulp samples are collected from the process during a certain time, with representative variations. Laboratory sheets are made and tested with standard sheet testing equipment. It is critical that the standard testing equipment works well with small variations and is well calibrated. If the reference is not correct, the developed models will not work. The fiber properties of the same samples are then determined.

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106
An input of Fibermaster data, water retention value and specific beating energy could predict tensile index quite well.

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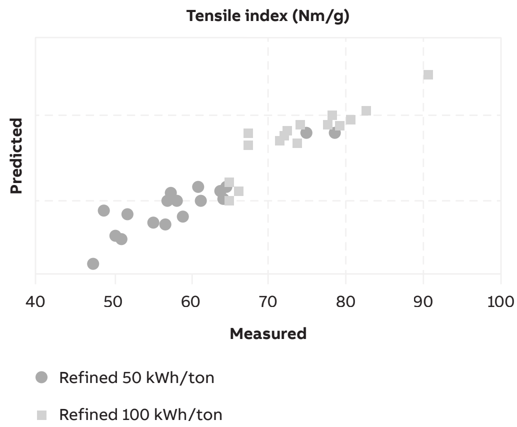
107
An illustration of how a model is developed offline and then used online for real time predictions.



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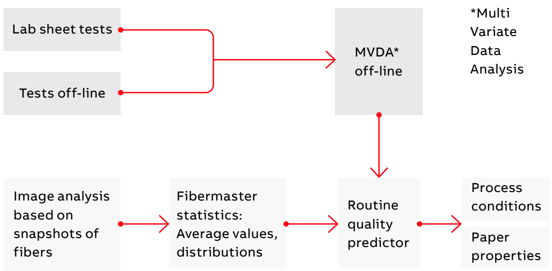

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107

The models are then developed from these data sets using, for example, the multivariate modelling technique. The developed model consists of a number of factors which can then be used to for example predict strength properties direct from measured Fiber Tester data.
This type of prediction (PLS) has been described by one user.

The single distributions from length, width and shape factor from Fibermaster were used and were combined with NIR spectra from paper sheets made of the same samples, beaten at 1000 revolutions in a PFI beater, in order to predict tensile index. Reference samples were about 30 fully bleached pulp sheets taken after the dryer from a chemical sulphate pulp mill. Conventional pulp sheet testing was performed. The data included natural variations in strength including noise. The samples were divided into two data sets and the degree of explanation and the prediction capability was calculated; the results are shown in the following tables (22 and 23). The first unit using this technology was installed in a non-integrated pulp mill in Sweden.

The samples were divided into two data sets and the degree of explanation (R2Y) and the prediction capability (Q2) was calculated; the results are shown in the following tables.

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Table 22: Model result for the calculation of Tensile Index at 1000- PFI revolutions.

	R2Y	Q2
NIR	0.76	0.33
Fibermaster	0.69	0.5
NIR + Fibermaster	0.85	0.56

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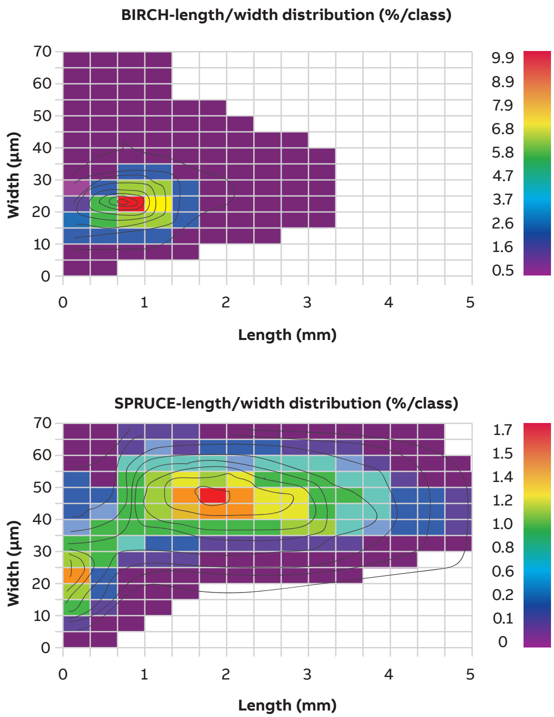
Table 23: Model results for the calculation of specific energy needed to reach a Tensile Index of 70 Nm/g.

	R2Y	Q2
NIR	0.79	0.41
Fibermaster	0.70	0.54
NIR + Fibermaster	0.96	0.68

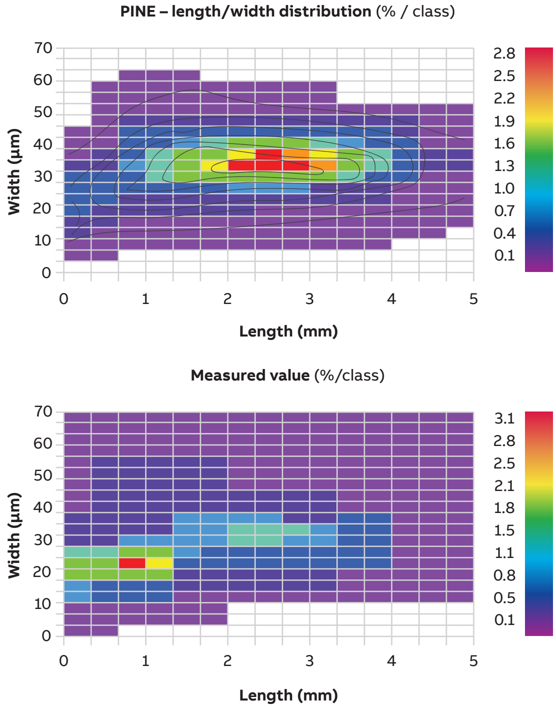
19.3. Distributions and prediction of fiber blends

Volume-weighted 2-dimensional distributions from L&W Fiber Tester Plus are used to calculate fiber mixes in recycled pulp. Mixing of up to four different pulps can be predicted. Averages and distributions are available for the fiber properties, weighted in different ways in L&W Fiber Tester Plus. Both length-weighted and volume- weighted “surface data” are stored in the following classes; proportion of length and volume respectively in 2-dimensional length/ width matrixes in 15×15 classes. Figure 108 (below) and 109 show examples of three pulps used in production of paperboard.



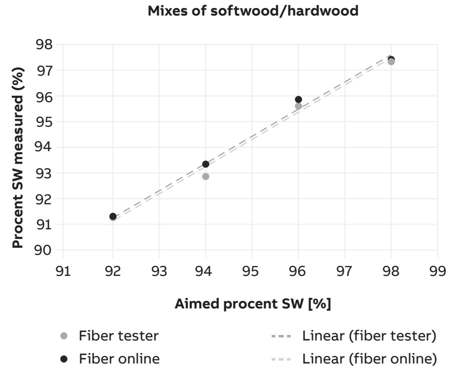
108

108
Upper; length/ width distribution of chemical birch fibers. Lower; length/width distribution of CTMP made from spruce. The distribution is volume weighted.



109

109
Upper; length/ width distribution of chemical pine. Lower; measurements for a mix of all three pulps. The distribution is volume weighted.



110

110
Chemical pine and CTMP of softwood pulps were weighted separately and mixed together. The composition of the mix was calculated.

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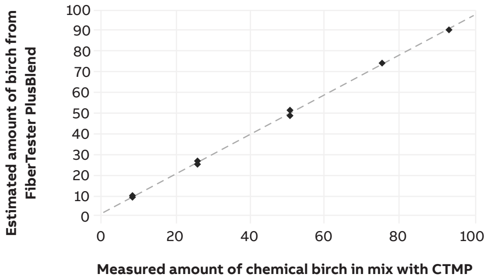
111
Chemical birch and CTMP softwood pulps were weighted separately and mixed together. The composition of the mix was calculated with the L&W Fiber Tester Plus Blend package.



Prop. Birch	Prop. CTMP
90	89.43
90	88.98
75	74.75
75	74.33
50	49.45
50	51.31
25	26.52
25	25.56
10	10.17
10	10.66

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111

Three fiber components were used in a board mill. Chemical fibers of Nordic birch and pine were used together with CTMP made from softwood. The three distributions are very different. Birch has a narrow distribution with respect to both length and width and the average values are low for both. The other two have a wide distribution with respect to length. CTMP made from softwood has a wider distribution and the results were compensated with the fiber density measured in Fiber Tester for each reference in order to predict weight relations. Finally, a mix of all three pulps was made with in width and also a higher average.

The maximum in width is above 40 µm for CTMP. For chemical pine the maximum is clearly below 40 µm. CTMP also has significantly more fines. These differences make it possible to use these distributions to calculate data for mixes of these pulps. Calculated and measured amounts are compared in figures 108 and 109 on the previous page.

Volume-weighted L/W-distributions were used one third by weight of each component. The same references were used and the same densities. The result is shown in Table 24.

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Table 24: Calculation of mix three components

	Birch	Pine	Spruce(CTMP)
Blended mix (% of weight)	33.3	33.3	33.3
Calculated mix (% of weight)	34.4	31.3	34.4

19.4. Separation of spruce and pine

Since the distribution functions of spruce and pine are similar, the separation possibilities with Fiber Tester are limited.

19.5. Bauer McNett model

Length distributions presented by optical analyzers give results which differ from a conventional Bauer McNett (BMN) classification, based on screening and weighting. This can be a drawback when introducing the new technology. One way to show the potential of the new technology is to model BMN fractions with the optical technique. How can this be done? This way of doing this has been suggested: Fiber intervals corresponding to the BMN fractions are defined, and a weight factor is defined for each interval.

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112
Tensile index (refined market pulp) vs. shape factor from never-dried pulp based on bleached softwood market pulp from four Scandinavian mills.

By using actual fiber length data, a set of fiber classes and a set of weight factors, the BMN classes (R14, R28, R48, R100 and P200) can be estimated with good precision.

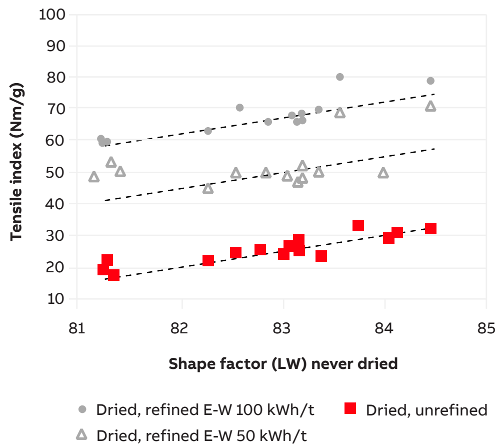
The methods can probably be improved by defining each length class in terms of a non-rectangular filter, which conforms to the analyzed BMN fractions. The weights could also be developed to be divided into more classes than the number of BMN classes. Volume-weighted data could also be used. The only limitation will be if different species with different fiber wall dimensions are used.

The blend module in ABB's L&W Fiber Tester Plus can estimate the composition in a mix of four components, and can be used by defining four BMN fractions, and use each fraction as a reference (cf. fig. 108 and 109).

19.6. Strength predictions from fiber properties
The shape (form) factor was measured with Fiber-Tester on wet pulp samples from different mills on different occasions, and the tensile index was determined on refined (with an industry-like refiner) market pulp from the same samples. A very strong correlation could be seen (figure 111). It is interesting that the same slope seems to be valid for different refining levels (constant specific energy).

Without considering all other variations such as fiber length etc., we can see that, with the help of the shape factor and the specific refining energy, tensile index can be predicted quite well (figure 112).

But it was also shown that quite good models based on fiber parameters from the wet pulp could predict tensile index after drying, refining with constant specific energy, laboratory sheet forming and standard sheet testing. The results verify that shape factor (form factor) measured by Fiber Tester in itself is a key fiber property for the prediction of strength properties. It is also measured online in many pulp mills in Scandinavia.



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19.7. Modeling of fiber networks
The ultimate model to relate fiber properties to paper sheet properties would simulate a sheet built- up from fibers. This would be a physical model. By feeding the fiber statistics into a three-dimensional model of the sheet built up by fiber models and by using FEM (finite element method) to calculate the properties of the sheet, all paper properties could be estimated.

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113
Simulated fiber network with curled fibers.

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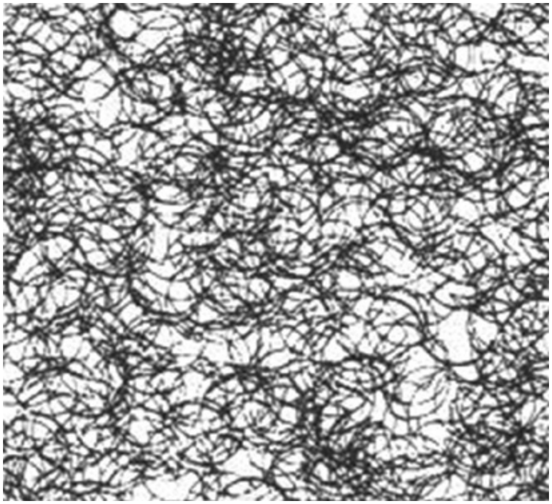
114
Number of kinks increases with decreasing viscosity.

Small steps have already been taken in this futuristic direction. It has been shown with very simple models of fibers and sheets (figure 113) combined with FEM calculations how deformed fibers with different distributions influence the tensile stiffness of a two-dimensional sheet. However, very simple models have been used so far.



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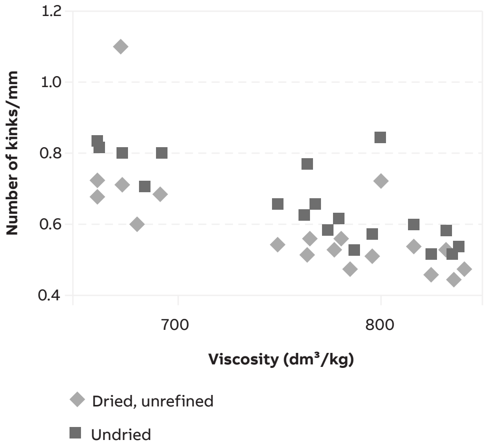
19.8. Viscosity

Results from RISE indicate that the number of kinks per mm of fiber increases with decreasing viscosity. Accordingly, shape factor will decrease at lower viscosities. A direct correlation is always a better model than a more complicated model with many variables.



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19.9. Mental models

A reflection is that we all actually use mental models. We make up our own mental images of processes, and from those images or mental models we try to analyze a certain situation. An example, regarding the beating of fibers, is cooked and uncooked spaghetti. Raw spaghetti (unbeaten pulp) consists of stiff ribbons unwilling to form sheets.

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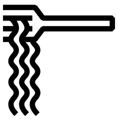
115
The spaghetti test
– a mental model

Cooked spaghetti (“beaten” fibers) is flexible, and the pieces follow each other’s shapes and easily form tight structures. The surface of the spaghetti is also modified during cooking.

One way to test whether spaghetti is ready to eat is to throw it against the ceiling and see if it sticks there. If it stays, the spaghetti is ready. It is difficult to get rid of this mental model describing the development of fiber properties.



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19.10. Reconciliation of data
In systems with large amounts of data, it might be possible to describe all the variations with a few independent variables. All parameters could then be predicted on the basis of these limited variables. This can also be used to reduce noise in signals.

20. Applications of online fiber analysis

20.1. Delivery check and control of HW- and SW-chemical pulp for the market
A main goal for quality improvement is to test and verify final pulp quality more frequently. It is also of interest to improve the pulp quality and to decrease the variations. By measuring at the fiber level instead of relying on laboratory paper testing, deviations can more easily be detected earlier in the process. Certain quality variations are present already in the wood supply, while others are generated in the process. For example, deviations in fiber dimensions (length, width) can often be due to the raw material. Different types of wood, for example roundwood and saw mill chips, have different fiber properties. Deviations in fiber strength and shape factor are more related to the process. A faster detection of different types of deviations will shorten the action time for correction. Management of grade changes. If a certain grade requires a mix of fiber types, one application is to use ABB's L&W Fiber Online to accurately control the mix.

20.2. Communication of pulp quality properties
Traditional laboratory tests seldom predict paper quality well, and more frequent tests of fiber properties are now becoming more and more common. Experience suggests that fiber properties give more stable signals (less noise) than sheet properties. The purpose of a quality control project is to deliver a pulp that works well for the customers.

The most important quality properties of the fibers to work with in the pulp mills are:
- Fiber length
- Fiber width
- Fiber shape
- Coarseness
- Fiber strength
- Fiber surface

Measurements of the first three parameters is fully automated and installed online in mills producing bleached chemical pulp; this is well established in the mills today. The measurement of other parameters is partly automated but is not used online so far. Fiber surface, which is correlated to drainage properties, is widely used. Some optical properties are also widely used.

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116
Input of fiber data predicts refining energy in the paper mill.

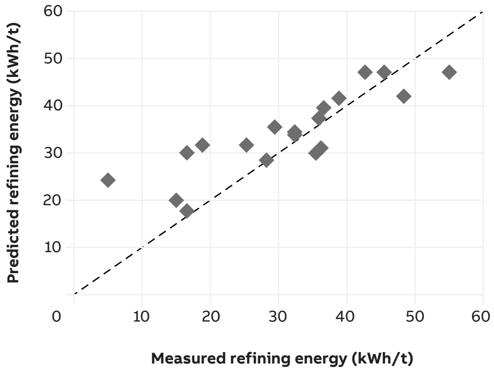
20.3. Linking data between pulp and paper mills

The usage of fiber data in quality control also makes it possible to tighten the alignment between pulp and paper manufacturers. The influence of fiber quality in the customer's end product can be studied by linking the fiber data to the paper production.

Results from a study of the relation between fiber characteristics and paper production in a paper mill are shown in figure 116. A multivariate model was developed with fiber data as X-variables and refining energy as Y-variables. The study shows that the monitoring of fiber data can predict the refining energy needed in the paper mill to maintain constant paper quality.

20.4. Uniformity

In deliveries of market pulp, uniformity between shipments is of great importance. The installation of the same equipment for online fiber analysis in all the mills of one company, followed by calibration of the systems to deliver comparable numbers, has given unique possibilities for process and quality control. Process development using a comparison of fiber properties among the mills is one of the most studied areas. Quality comparisons aiming for uniformity and exchangeability of products between the mills are also made easier by the installation of accurate and frequent quality measurements. The possibility of achieving stability in the quality increases with frequent control, and it will also result in a faster feedback to the production staff and better possibilities of avoiding deliveries out of specification. This will pay off in confidence between supplier and customer.



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20.5. Process control – Action limits

Fiber deformation measured as shape factor is a property that is to a great extent created in the pulp mill. Since it is created in the pulp mill, it should also be possible to control it there. One example described here is to follow shape factor frequently online. One user has, based on experience, defined action limits. When the signals pass an action limit, something unexpected has happened and the operators should follow up what has happened and take corrective action.

In the example in figure 117, the mill uses action limits for fiber properties. The example shown is from a period before the active use of action limits. In this case, the shape factor dropped below the action limit over two days. If the operator had reacted immediately to the online measured change, two days of costly downgrading of the pulp could have been avoided. The reason for the quality change was a drop out of certain fiber-protective chemicals in the bleaching process. In this case, the action was first taken after the offline testing two days later. Similar situations happen from time to time.

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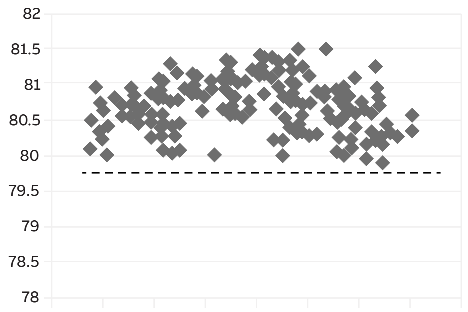
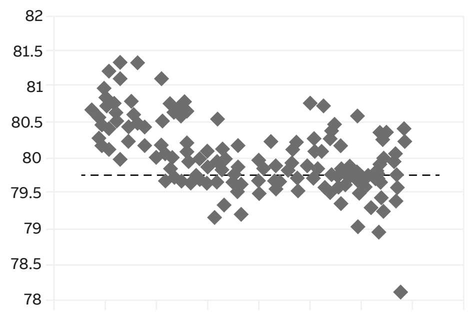
117
Shape factor is one of the most important fiber properties for paper strength. Higher shape factor means higher strength. The shape factor decreased in the pulping process, which was monitored by L&W Fiber Online.



Normal production over action limit



B-grade production under action limit

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117

20.6. Fractionation of pulps

Different qualities of pulp can be achieved through the screening or fractionation of pulp from one production line into two separate streams. This technique is often used in a part of the production to produce reinforcement pulp. This process is monitored by using length and width data from Fiber Online. Also, the sampling frequency is of great importance. Figure 117 shows length measurements from one of the mills, in a transition stage from non-screening to screening and separation into two different pulp qualities.

20.7. Control of production flow during grade changes in the pulping line

Pulp mills alternating between hardwood and softwood use Fiber Online to control the transition. It takes up to eight hours for the pulp to pass through the pulp mill, so it is important to detect when the change comes to the headbox of the drying machine. But the transition from one fiber type to another can also be fast or slow. It is important to know when the old quality goes out of range and when the new quality is reached. The intermediate time can vary from one to seven hours. During this time, a lot of pulp is produced. Some mills use the standard data from Fiber Online. An alternative is L&W Fiber Online Blend software that calculates the mix based on two-dimensional length/width distributions and monitors the calculated mix.

When the initial part of the grade change reaches the final buffer, the mixed pulp is stored in a separate buffer. When the final phase of the change is detected, the new grade can start. The pulp stored during the grade change can then be mixed into the new grade controlled from fiber measurements and can be sold at full price with the fiber length variations always within the specified limits. The cycle time for measurement with L&W Fiber Online during transition is 5-6 minutes.

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118
The screening process is monitored well, by using L&W Fiber Online data.

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119
Fiber length during campaigns with HW and SW. Many samples (dots) during the transitions mean that the grade change has taken a longer time.

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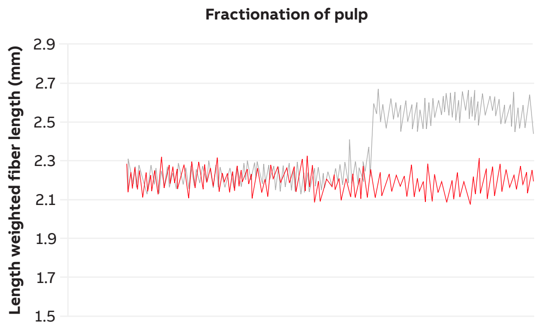
120
The HW line suddenly includes some SW pulp, which causes the final blend to drop from 80% HW to 60% HW.



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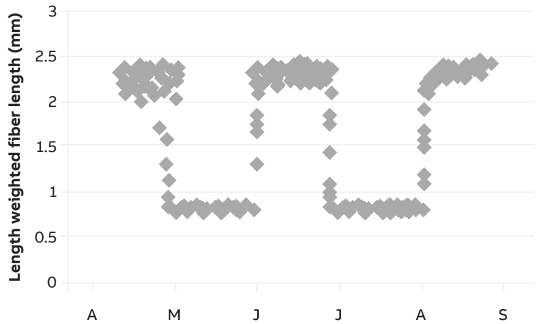

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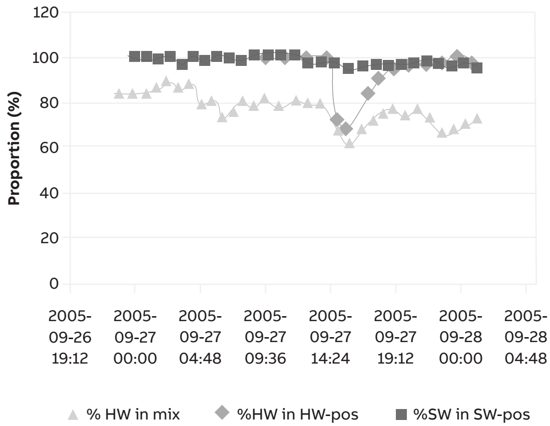
20.8. Broke fine paper

The process described in figure 31 on page 40 is common for an integrated fine paper mill. Separate hardwood (HW) and softwood (SW) lines come into the stock preparation. When a grade change occurs, long fibers may be mixed into the HW line (figure 120). This causes a drop in the amount of hardwood after mixing and changes the formation of the paper on the paper machine. This knowledge can be used to avoid such a situation by changing the production strategy. One possibility is to control the mix directly from the measurement.

Even if the SW and HW lines are completely “clean”, a mix of broke creates an uncertainty in the mix after the blend chest. The same reasoning can be applied for broke: Use of online measurements can improve the production strategy and better control the final mix of HW and SW.

An example of a grade change on a fine paper machine is shown in figure 121. The HW/SW mix is changed at the time of the grade change. This mean that the HW/SW mix in the broke will also change, although this latter change will be somewhat delayed. In the example in the figure, the change in broke came back to the machine six hours later. After which, the changed mix in the broke led to a new disturbance on the machine.

Without online measurement of the mix, as in this case, the machine tender has no knowledge of this effect. It is not possible to calculate it. It has to be measured.



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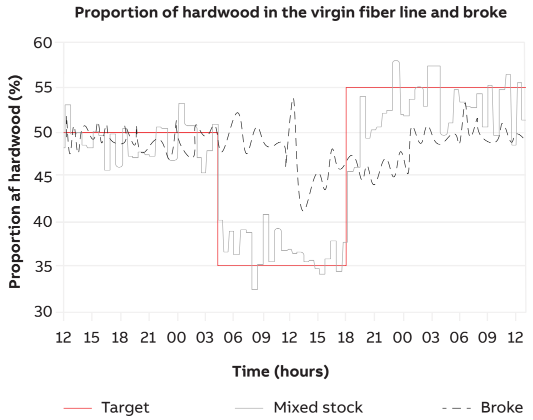
121
The effect of the broke from a grade change in this case came 6 hours after the actual grade change.

20.9. Other experiences

In one mill, it was found that during a cook the softwood suffered a significant reduction in normal expected length. Because the fiber properties were being monitored with a fiber property analyzer, it was addressed quickly without any problems arising. Normally, a situation such as this would not have been found until the pulp got to the paper machine and possible breaks occurred or some other type of upset occurred due to the abnormal softwood fiber length.

Another example from the same mill was a pulp "swing" in the pulp mill during a transition from SW to HW. Formation of the paper dropped without "any apparent reason" – i.e. no changes were intentionally made at the wet end or to the furnish.

It was found that the average fiber length of the HW increased significantly. This caused the average length to the stuff-box to increase as well and resulted in a poor formation. With an online unit, it is believed that the sample frequency and reaction time of the machine crews would be improved to the point that they would be able to react to the increase in HW fiber length and compensate for it by a reduction in SW addition.



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20.10. Optimization of beating

For one mill, the main objective was to decrease costs by reducing softwood without sacrificing machine runnability or sheet strength properties. An online fiber analysis system allows operators to make decisions based on data that are very precise, repeatable and only minutes old instead of being several hours old. Mills cannot afford to add testing manpower to quickly get the amount and accuracy of data that an online system can provide and still attain the goal of cost reduction of materials. They would simply be adding costs in one area to reduce those in another. There is nevertheless the initial cost of equipment and yearly maintenance.

There are “sweet spots” for fiber length, fibrillation, shape factor and WRV (freeness). Online monitoring of these parameters, with a system that can measure accurately and often, allows the papermaker to maintain these critical targets to avoid upsets on the paper machine and produce consistent sheet strength, while at the same time optimizing BSKP. The optimal refiner settings:

- Maintain desired fiber length average, do not cut fibers
  - Track fibrillation
- Track freeness to move around desired target (this can also be done online)
- Optimize shape factor to the desired level
- The straightening effect on shape factor has a time effect. If the beaten pulp is stored too long (several hours) before being used for paper making, the shape factor may drop again!

Online sampling locations (figure 31 on page 40):

- At the output of the softwood refiner(s)
- At the output of the hardwood refiner(s)
- At the machine chest (by monitoring the soft-wood and hardwood line, the difference would be the broke)

20.11. Security paper

In the production of security paper, good formation is a necessity for good watermarks and superior printing. Formation is strongly dependent on fiber length. Many of these mills have successfully installed online systems for fiber length measurement. Long cotton fibers are cut to suitable and constant average fiber length to obtain a uniform formation.

20.12. Sack kraft

The fiber analyzer shows how variations in the raw material and pulp mill affect the paper machine. This has resulted in improvements of the wood handling and improved strategies for refining.

At one mill, there was a problem with the tear index for a certain grade. Experience from tests with Fiber Online, and comparison with strength data from the reel combined with PCA (see page 106) showed that the problem could be solved with another refining strategy for that grade.

20.13. Coated printing grades

A non-integrated paper mill tried to minimize costs by using different fiber grades on the market. Pure market pulp and rejected reels from other mills were used. Using ABB’s L&W Fiber Online, they found that the fines content could vary a lot between different suppliers. Certain incoming pulps had high fines levels, which caused trouble on the paper machine. Certain suppliers could be avoided. The same mill also uses measurements of fines and fiber length to optimize refining. This mill has also detected problems with vessel cells on the coating blade of the on-machine coater from one pulp and they also use an integrated shives analyzer in their fiber analysis system.

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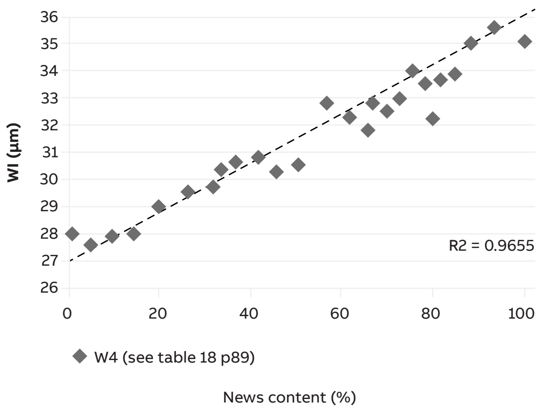
122
Fiber width is important for newsprint based on recycled fiber.

20.14. Prediction of fiber mix for recycled fibers

A good correlation between some of the variables achieved from the Fiber Online and the paper composition expressed as news and magazine content was found in one case. However, the control potential was limited in this specific case. The evaluation showed that fiber width was the most important single fiber parameter in predicting news content, especially class W4 (which means average width for length class 3–4.5 mm). W3 (which includes length class 1.5–3 mm) showed similar results. The mix could also be described with a model based on reference volume-weighted -dimensional length/width distributions of BSKP, BHKP, TMP and SGW. See figure 122.



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20.15. Vessel cells in DIP

Recently it has been discovered that recycled pulp has a larger proportion of hardwood fiber species containing vessel cells. Fiber debris, ink, and shives must be recognized in relation to vessel cells. These cells are well suited for identification in image analysis systems for fibers.

20.16. Other measurements in a deinked pulp (DIP) plant

Spectrometers for VIS- and UV-measurement on dry sheets can be used for the automatic control of brightness and estimated residual ink content (ERIC 950 nm). It is also possible to use the VIS spectrometer for the measurement of color (L*a*b*) in the DIP plant.

20.17. Control of mechanical pulps

TMP refiners have to be controlled at two levels. First, the process has to be stabilized and controlled with respect to consistency and production rate. This is a fast control.
On the next level, the specific energy level has to be controlled. This is normally done by automatic sampling systems. Freeness measured as CSF seems to be well accepted in mechanical pulping for this purpose. This has led some suppliers to try to copy the old manual CSF unit in their automatic systems, even though the method is not very modern. CSF is operator-dependent, but it is reported that it should be possible with the same operator and routines to reach a 95% confidence interval of +/-4 ml (in practice this interval is probably wider).

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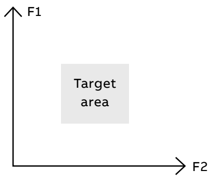
123
One approach for control of the refining of mechanical fibers is to use two parameters to describe quality. F1 (reinforcement; mainly fiber length) and F2 (bonding; mainly freeness).

It has been shown in a case study that modern closed loop control of a TMP plant can reduce the variance in freeness by 80%. The closed loop control used weighted mean fiber length sampled every 7.5 minutes. The second stage refiners and the reject refiner were run in the same way. The first stage was consistency controlled based on a mathematical model including thermodynamics; mass flow balance and water balance. The disc clearance for each refiner was optimized on the basis of manual sampling and the offline measurement of mean fiber length for each machine. A possible control strategy for screen-rooms in order to separate the control of shives from the control of freeness has been investigated with good results. However, screen rooms are seldom designed for automatic control. The active control element is the reject refiner. Another control parameter is the fillings in the refiner. Plates get worn out and have to be replaced or the pattern can be optimized. This can be measured as a balance between fiber length (F1) and freeness (F2) (see figure 123). Specific energy control tries to keep the process within a certain target area according to the figure. This can be used to obtain information about when it is time to change the plates.



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Shives are detrimental objects in mechanical pulp. Today, screening systems are quite effective in reducing shives. Narrow slots (150–200 µm) remove most of the shives, which are then treated in the reject handling (reject refiner). Nevertheless, it seems that there is still a need for the measurement of shives in all production of mechanical pulps. Reject refiners often tend to cut fibers. It is a balance to kill shives but keep the fiber length. In mechanical pulping, the refiners work at a high consistency (HC), but low consistency refining (LC) is used in some processes today. One effect is a reduction of shives.

It is important to measure fiber length in order to prevent or minimize fiber cutting. Treatment of the fibers in refiners results in a reduction in the shives content and also deformed fibers. These properties should also be of interest as a mean of monitoring refiner operation, but much is not reported. Shape factor and width are relatively new measurements with good accuracy. By combining length and width for fibers it is possible to work with volume-weighted averages and distributions in fiber analysis, and this seems to be an advantage for mechanical pulps. In fact, shape factor is a direct measurement of latency. In order to measure latency, the sample has to be taken before the latency-removal chest, which means it has to be taken in the blow line from each refiner. This would also allow optimization of each refiner.

A BCTMP mill with many grade changes needs online measurements of freeness, shives, fiber length and brightness to measure final pulp quality frequently. It is critical for profitability to quickly arrive within the specifications of the new grade. For process control purposes, earlier positions in the production line are of course of great interest.

20.18. Impact from raw material

In one case study, a mill trial with a supply of different wood is described. The wood used at the mill during the time period of the study was spruce from seven geographical locations; five from Sweden, one from the United Kingdom and one from Russia. The amount of each chipped wood category was tallied and recorded each day. Pulp samples were gathered every second hour from the disc filter chest for full hand sheet quality testing. This was done for two mills. The trial was evaluated using factor analysis.

Note: The study showed that 40% of the variations in tear index were attributed to variations in raw material.

The raw material is obviously a source of variation in quality.

21. Cost of raw material and return on investment

* Source, private communication: Johan Persson, Per Malmquist, Johan Lundvik, Hans Göte Andersson, Bo Fredriksson (Oct. 2020).

21.1. Prices on the different market pulps*
The annual production of pulp worldwide is estimated to 475 million tonnes (Mt). This production can be divided into two major segments of which 275 Mt are recycled fiber and 200 Mt are virgin fiber. The majority of the virgin fiber, approx. 155 Mt, is used in integrated mills, and approx. 45 Mt is sold as market pulp. The prices of these different market pulps are described in this chapter.

BCKP: Approximately 40 Mt, or 90% of all kraft market pulp that is sold on the global market is manufactured according to the BCKP-process (bleached chemical kraft pulp). The pulp is divided in two segments; NBSK (northern bleached softwood kraft pulp) and BHKP (bleached hardwood kraft pulp). In Europe, the prices are set from PIX (price index), which is taken from the web site www.foex.fi. This homepage is working like a stock exchange for these pulps. When a pulp deal is to be made, the pulp producer uses the PIX pulp index from www.foex.fi for that day as a price guideline. Special deals for certain customers or specific discounts are calculated from that PIX pulp index. Another marketplace for pulp trading is NYBOT (New York Board of Trade).

The prices follow the marketing forces of supply and demand. If there is a lot of pulp in stock at the mills, or a lot in storage in harbors, the prices tend to decline. In contrast, the prices increase if the stocks are small.

Another parameter that usually has an impact on the pulp price is the dollar rate. If the dollar tends to be expensive, the whole world except for the North American market does not buy as much pulp and this causes a drop in the pulp price. This is due to the fact that the pulp is purchased in US-dollar (USD) and sold in local currency. Yet another factor that influences the pulp price is the price of recycled fiber (DIP). When the price of DIP increases, the price of the BCKP pulps increases about six week later, and when the price of DIP drops, the price of BCKP drops immediately.

CTMP: It is the second largest kraft pulp segment. The amount of CTMP is about 9–13 Mt. The prices follow the movement of the BCKP market and the prices are about 75% of the price of NBSK.

SGW, PSGW, NSSC, and TMP: These pulps follow the normal rules for the market with regard to supply and demand. The prices are negotiated between customer and supplier without any index from outside.

DIP: This pulp also follows the supply and demand rules. The prices have recently been high because of the large demand from the Chinese market. The prices of DIP are also dependent on political decisions such as how countries decide to collect paper or changing laws in different directions. DIP-pulps are not dependent on the dollar rate, since they are purchased in local currencies.

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124
Pulp price differences in Europe. % difference compared with NBSK 1976–1996 by quarter.*

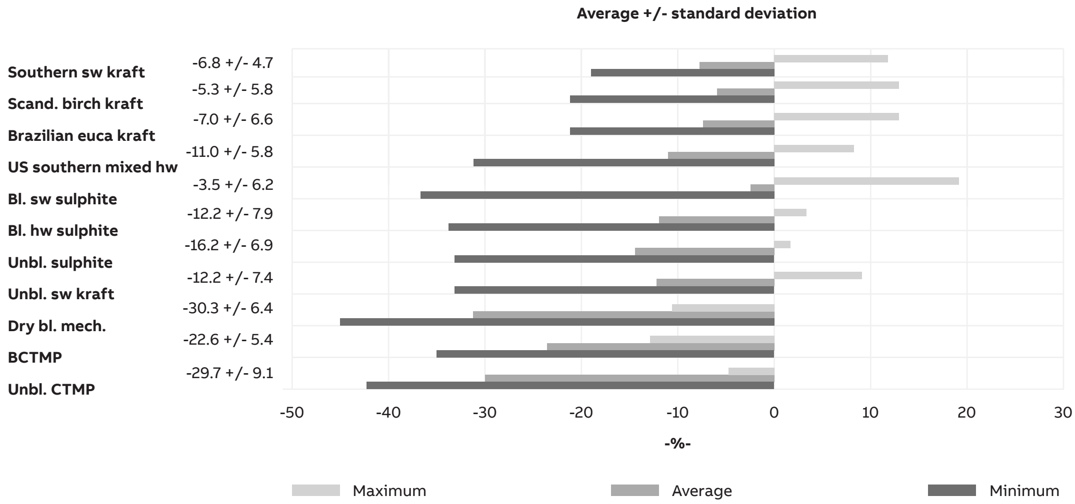
21.2. Operational costs

Figure 124 shows the price differences on the European market for different pulps compared with the highest valued pulp, NBSK.

Operating costs for NBSK are shown in figure 124 for a hypothetical case with a new pulp mill with a capacity of 500, 000 t/yr. The operating costs are divided into wood, other variable costs (such as energy and chemicals), personnel, other fixed costs, and distribution costs (to western Europe).

A return on investment (ROI) of 20% is also included in the diagram. The operating costs for a typical mill in Sweden and Finland may be around 400 USD/t of pulp. The dotted line at 650* USD/t of pulp is shown as the long-term trend price for NBSK. Finally, table 25 presents some price information for pulp and paper products in western Europe.

* Source RISI and Moody estimate 2020



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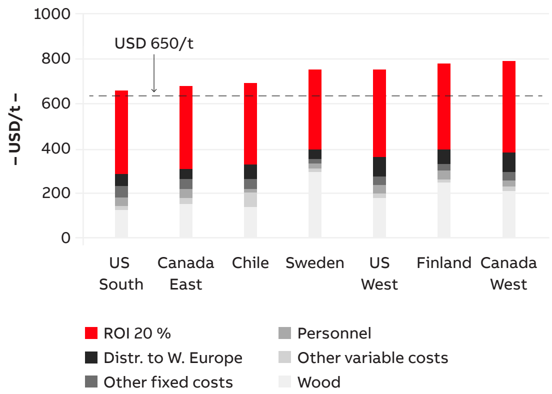
Sales price requirements for new hypothetical pulp mills (NBSK) with a capacity of 500 000 t/yr

Table 25: Price levels of pulp and paper products (CIF) in Western Europe, quarter II. $ are translated to € by a factor of 0.9.*

Grade	Price (€)
BSKP	426–480
BSKP, Southern Pine	444–462
BHKP, Eucalyptus	373
BHKP, Birch	373–408
RCP, Mixed grades	10
RCP, ONP	62
RCP, OCC	42
RCP, CPO	185
RCP, White woodfree shavings	140
Newsprint, 48.8 g/m2	485–500
SC Paper, 60 g/m2	605–650
LWC Paper, 60 g/m2	740–765
Uncoated woodfree, 80 g/m2, sheets	700–800
Unbleached kraftliner, 175 g/m2	420–470
	409–435
SC Fluting	330–360
Testliner	275–310

* Source: Jaako Pöyry (1998).



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It follows from the table on previous page , that the main pulp and paper products are sold at price levels of€650 - €1100 (CIF western Europe)*. As a guideline, the operating costs may be around 65–75% of this price and the variable costs may be 40–60% of the sales price, of course with large variations.

The economic return from the use of the fiber analyzer instrument may be related to one or more of the following factors:

- Lower operating costs
- Higher product price due to improved (higher) product quality
- A more saleable product due to a higher or a more uniform product quality

Assuming that the return is based on an investment cost of €200000 and that the payback time should be two years or less, a payback of about €100000 per year corresponding to the sales of 131–268 tonnes of product per year is required, see table 26 below.

* Source: Fastmarket RISI and Moody's estimates (2020).

Table 26 Payback requirement of 100 000 € for different levels of product price.

	A. Product price 1100 €/t	B. Product price 650 €/t
Number of tonnes for a sales of 100 000 €	288	131
Number of tonnes for operating costs of 100 000 €	348	170
Number of tonnes for variable costs of 100 000 €	532	362

When considering the payback, different analyses will have to be made for three different situations:

1. For a mill producing about 350000 t/yr, the operating costs must be reduced by about 0.33 €/ton.
2. For a mill producing about 350000 t/yr, an increase in product price of 0.33 €/t would yield the required payback. However, this figure is too small to be considered in price negotiations and it is more probable that the higher quality makes the product more saleable (higher sales volume) as in alternative 3.
3. For a product in the upper price range, the pay- back would be satisfactory for additional sales of about 300 t/yr, whereas for the products in the lower price range, additional sales of about 600 t/yr would be required.

These payback levels are only 0.1% of the overall figures for a mill.

However more specific calculations are asked for in each application. Thus, improved flexibility, higher and/or more uniform quality, new strategies for stock preparation (fiber mix and/or broke handling) and paper machine operation (fractionation and multi- layered formation, and higher production thanks to fewer web breaks) will have to be considered more in terms of their inherent benefits in different respects when evaluating online applications.

If the quality of the raw material (fibers) or the paper quality and/or production rate could be improved by using the fiber analyzer, the cost of the instrument would easily be balanced by these positive factors.

21.3. Example from a 350 000 t/yr market pulp mill

The mill specifies a minimum average fiber length. If the fiber length is below this value, the pulp will be downgraded and sold at a lower price to a less demanding customer. If such downgrading can be avoided by using an online fiber analyzer for control actions/control strategies, the payback can be calculated as follows. The control action can be to use a buffer for the temporary buffering of out- of-specifications production and later in-mixing. A strategy can be purely technical, but it can also be a bonus system to avoid bad situations (process upsets, etc.). The important thing is to measure the result frequently.

21.4. Using fiber analyzer data instead of strength indexes

Production of 20 t/h means 480 t/day. A price of 480 €/t means 230 400 €/day. Downgrading may be in the range of 3–9%. A 6% reduction of the price leads to losses of 13824 €/day.

A conservative estimation of 20 days downgrading gives losses of approx. 245769 €.

Larger savings per year are possible in the long run with other quality profiles than are made today. If the tear index of a pulp is not as important as previously stated, and instead a specification of shape factor will be better for the customer's product, then the ability to change yield and chemical dosage in the process may provide savings of another order of magnitude than the investment cost for a fiber quality analyzer!

21.5. Investment calculations
In an R&D environment, you can invest in new equipment if it will help to generate new knowledge. In industrial production, the generation of knowledge about your process, quality and problems is of course just as important. However, for investment in new equipment in the mill, it is usually not sufficient to merely have the opinion that a new system will help. You are required to show a return on the investment within a certain time. For measurement equipment, this time may be from six months to two years—corresponding to an "interest rate" of 50–200%!

One way to do this is to list possible improvements and then estimate how these improvements will affect the costs. In practice, cost reduction seems to be easier to calculate or at least to communicate than expanding business.

21.6. How can these savings be achieved?
Let us take one example – more uniform pulp. Causes for non-uniform pulp or stock can be:
- Variations in broke handling from grade changes or web breaks
- A temporary unknown fiber mix
- Fiber mix partly out of control
- Process upsets in the pulp mill
- Process upsets in the stock preparations
- Process breakdown in the pulp mill
- Process breakdown in the wood handling
- Variations in incoming raw material

21.7. What can we do about these causes?
Early detection of the problem will reduce the negative effect.
- We can avoid unnecessary long production stops
- We can avoid running out of specification longer than necessary

If we increase our knowledge about the causes of these problems we can make improvements by changing operating strategy.

21.8. How does this lead to cost reductions?
- A non-uniform pulp/stock has more weak points or periods than a uniform pulp/stock. If a defect occurs in the web, the probability of a web break is occasionally greater in a non-uniform sheet. If the uniformity increases, one risk factor for web breaks is reduced. Estimate a percentage of how much you think this can reduce the frequency of the web breaks.
- The risk for out-of-specification product will decrease. Set a percentage of how much you think you can reduce culled paper.
- Variation in pulp quality may be the reason for adding chemicals for compensation. Cost of chemicals may be reduced with fewer incoming variations.
- Customer claims because of out-of-specification product: What is the economic value if you avoid only one customer claim? It can mean that you can reduce the risk of losing a customer.

21.9. Other examples

- Increased demands from the paper mills for frequent quality check on pulp production.
- The shape factor affects tensile index up to 15 units. To increase tensile, you have to add fibers, which will increase your costs.
- Better selection of wood. Cost for raw material is up to 50% for a pulp mill
- Smaller losses due to grade changes and broke handling
- Loss of customers due to the delivery of poor quality (out of specification)
- Quality monitoring of a given pulp
- Replacement of one commercial pulp by another
- Positioning a competitor's pulp
- Early prediction of physical paper properties allow actions to be taken in time
- Control of fractionation
- Refiner control
- Control of screening

The following possibilities for reductions are often used in calculations:

			SAVINGS (€/t)
	Optimistic	**Realistic**	**Pessimistic**
Reduction in customer claims			
Reduction in machine breaks			
Reduction in culled paper			
Tighter basis weight limits			
Reduction in additives usage			
Fiber substitution			
Refiner energy savings			
Total savings			

22. Reference testing

22.1. Resolution
The resolution of an instrument determines the smallest change in an observed property that can be sensed by the instrument. For ABB's L&W Tester Plus, the resolution sometimes is even higher than the pixel size, which has been explained in earlier chapters.

22.2. Measurement range
The measurement range can be defined as the range in which the instrument can measure within specified maximum errors. It can also be defined as within which range the instrument has sensitivity. For your stereo, you usually have the –3dB points defined for the spectral range of an amplifier or loudspeakers. This represents the point where the signal is 50% of what it is in the middle of the spectral range.

22.3. Repeatability
This is defined as the consensus of results from tests from the same samples, on the same instrument, and with same operator involved, if the method is operator dependent. In process control applications, repeatability is most important. Repeatability tests are often defined for acceptance tests of sensors. For example, define standard deviation for 20 equal samples tested on the equipment (see also chapter 10, about statistics).

22.4. Reproducibility
This is defined as the consensus of results from tests from the same samples, on different instruments, and at different times. This is often called accuracy. The example that is most often used is firing guns against a target. If the hits are well placed together, then the repeatability is good. If the hits are gathered around the middle of the target, then the accuracy is good.

22.5. Reference instrument
If a better method or instrument is available, this can be used as a reference. However, regarding new fiber analyzers, the situation is that no better method exists. Stable operation over time is often followed up by tests of stable reference material. For fiber analyzers, synthetic fibers (rayon) are used. Round robin tests are also organized to compare different instruments.

RISE sends out samples every quarter to users of L&W Fiber Tester Plus as a subscription service. They send rayon fibers to be used for weekly tests by users and also bleached hardwood and softwood fiber samples for more accurate tests. Statistics are distributed and the users can see if their instrument is different from the others. Periodic tests are always necessary to follow up if calibration has to be done.

One user of L&W Fiber Online uses all three reference samples mentioned. They check fiber length, fiber width and shape factor. For each property they have set both a warning limit (WL) and an action limit (AL). Actions that need to be taken are:

Results within WL	OK
Results outside WL	Check next sample!
Results outside WL at next sample	Run an extra test!
Results still outside WL	Contact responsible for instruments
Results outside AL	Run a second sample
1. Still outside AL	Contact responsible for instruments
2. Outside WG	Run a second sample
Still outside WG	Contact responsible for instruments

Warning limits and action limits are set by experience for each property or by recommendation from the supplier.

23. Bibliography

Ander, P. & Daniel, G. Characterization and Comparison of Industrial and Laboratory Pulp Fibers using HCl, Cellulase and FiberMaster Analyses. Nordic Pulp and Paper Research Journal Vol. 20 No. 1/2005.

Björk, E., Granlöf, L. & Mohlin, U-B. Pulp quality with STFI Fibermaster. PUB 8, RISE, 2002.

Bådenlid, R. et al. Sätt vid framställning av massa samt produkt av sättet. Patent application No. SE 0001419-1, Stora Enso R&D, Karlstad, Sweden.

Dillner, B. Fiber Property Development – Tailoring Softwood Pulps for Different Products. SPCI, 2002, Stockholm.
Fellers, C. & Norman, B. Pappersteknik. KTH, 1998.
Forgacs, O.L., Robertsson, A.A. & Mason, S.G. The Hydrodynamic Behaviour of Paper-Making Fibers. Pulp and Paper Mag. Can. 59(5), 117 (1958).

Fralic, G., Mozaraffi, S., Flynn, G. Mill-wide Advanced Quality Control for the Production of Newsprint. Strand W.C., IMPC 2001.

Fransson, P-I. et al. Mätningar med STFI FiberMaster i ett kartongbruk. RISE, TF 74, 1997.

Granlöf, L. et al. Vessel elements in hardwood pulps – appearance and measurements. RISE report, PUB 14, 2003.

Hagedorn, A. et al. Optimizing Machine Efficiency Through Fiber Quality Management. TAPPI 2006, Papermakers and Coating and Graphics Arts Conference.

Hallgren, H. & Fredlund, M. Formningsstudier på FEX; Effekt av formningsprincip, retentionsmedelsatsning och massaval på pappersegenskaper vid finpapperstillverkning. RISE C 175. 1989.

Hill, J. Process understanding profits from sensor and control developments. Int. Mechanical Pulping Conference, Oslo, 1993.

Hill, J., Karlsson, H. & Ostman T. Process design and control of screen-rooms. Pulp & Paper Can. 83(5), T125–T129, May 1982. Horn, R.A. & Setterholm, V.C. Fiber morphology and new crops. 1990

Jangmalm, A. Network modelling of the elastic properties of paper. Licentiate Thesis no 52, Department of Solid Mechanics, KTH, Stockholm, Sweden,1996.

Johnson, R.A. & Wichern, D.W. Applied multivariate statistical analysis (third edition). Prentice Hall, ISBN 0-13-041773-4, 1992.

Joris, G. & Roux, J.C. High yield computerised refiner machine. Current and future technologies of refining, Vol. 2, 1991.

Joutsimo, O. et al. The influence of fiber ultrastructureal damage on pulp and paper properties. APPITA 2006, Melbourne, Australia.

Karlsson, H. Improvements with L&W STFI Fibermaster. PAPTAC 2004, Montreal, Canada.

Karlsson, H. New techniques for measurements of fiber properties including vessel cells and mix of fiber species. APPITA 2006, Melbourne, Australia.

Karlsson, H., Fransson, P-I. & Mohlin U-B. STFI Fibermaster. SPCI 1999, Stockholm, Sweden.

Karlsson, H. & Fransson, P-I. FiberMaster ger pappersmakaren nya muskler. Sv. Papperstidning, 97:10, 26 (1994).

Karlsson, H. & Fransson, P-I. Method and apparatus for producing and testing a fiber bed. Patent; US 6, 884, 320 B2, 2005.

Karlsson, H. & Fransson P-I. Filtering device. Patent; US 6, 520, 343, 2003.

Karlsson, H., Fransson, P-I. & Kastre L. Method and apparatus for measuring fiber flexibility. Patent US 5, 331, 405, 1994.

Karlsson, H., Johansson, B-L. & Jung, E. Experiences with computer control, based on optical sensors for pulp quality, of a two stage TMP-plant. Control Systems Conference, Halifax, 1980.

Karlsson, H.I. & Pettersson, J.G.T. Method and apparatus for determination of refiner mechanical pulp properties. Patent; US 5491340, 1994.Karlsson, H. et al.

Image Analysis for Quality Monitoring of Recycled Fibers. Control Systems, Stockholm, Sweden, 2002.

Karlsson, T. Utveckling och systemintegrering av mjukvara för detekt- ering och klassificering i realtid av lokala defekter hos långsmala objekt från bildsensor. TRITA-NA-E03120, Nada, KTH, 2003.
Kibblewhite, R.P. & Brookes, D. Factors which influence the wet web strength of commercial pulps. Appita 28(4), January 1975.

Krantz, T. Landvinningar under 20 års mät- och styrteknisk utveckling vid RISE. Sv. Papperstidning/nordisk Cellullosa nr 3, 1995 (99), pp. 36-38.

Lindblad, L. & Fürst, T. The Ultrasonic Measuring Technology on Paper and Board. AB Lorentzen-wettre (2001).

Lindström, J. & Karlsson, H. Optimizing the fiber process by using new on-line analyzer and experiences from pulp mill.
Tappi Japan, October 13–15, 2004, Hokkai-do, JAPAN.

Lundqvist, S-O. & Evans, R. Illustration of wood and fiber measurements with Silviscan. RISE Report, ART 15, 2004.

Markström, H. Testing Methods and Instruments for Corrugated Board. AB Lorentzen-Wettre (2005).

Mohlin, U-B., Dahlbom, J., Hornatowska, J. Fiber deformation and sheet strength. Tappi Journal, Vol. 79, No. 6, June 1996.

Mohlin, U-B. & Miller, J. Industrial refining – effects of refining conditions on fiber properties. Proceedings Refining 95, paper 04, PIRA, Atlanta, March 1995.

Mohlin U-B. Market SBK and refining response. Refining and Mechanical Pulping, Pira, Barcelona, Spain, March 2005.

Mohlin, U-B. & Olofsson, K. Formfaktor och böjlighet hos barrvedssulfatmassa – inverkan av vårvedsandel, HC-behandling och kappatal. RISE, TF 97, 1997.

Mohlin, U-B. Pulp evaluation for modern papermaking.
6th International Conference on New Available Technologies, June, 1999, Stockholm.

Mortens, H. & Naes T. Multivariate calibration. Wiley, New York, 1989. Paavilainen, L. The possibility of fractionating softwood sulfate pulp according to cell wall thickness. Appita 45(1992):5, 319-326.

Page, D.H. The beating of chemical pulps – the action and the effects. 9th Fundamental Research Symposium, Fundamentals of Papermaking, Cambridge, Mech. Eng. Publ. Ltd, London.

Page, D.H.et al. Curl, crimps, kinks and microcompressions in pulp fibers – their origin, measurement and significance. Papermaking raw material conference, 1985, pp. 183.

Paper and paper making. CEPATEC AB, Markaryd-binder (2005). Pauler, N. Paper Optics. AB Lorentzen-Wettre (2002).Pettersson, T. & Karlsson, H. Method for determining the average radius and/or the average length of particles carried by a flow medium. Patent; US 4529309, 1985.

Pöhler, T. & Heikkurinen, A. Amount and character of splits in fiber wall caused by disc refining. KCL, Espoo, Finland.

Olofsson, K. Mätmetoder för fiberrs fibrilleringsgrad. RISE, TF 56, 1997.

Olsson, R.J. et al. Multivariate characterization of chemical and physical descriptors in pulp using NIRR. Tappi Journal, October 1995.

Ring, G.J.F. & Bacon, A.J. Multiple component analysis of fiber length distributions. University of Wisconsin, SP Department of Paper Science, USA.

Scotch, M. Optimizing Bleached Softwood Kraft usage on a Paper Machine by using properties obtained through online fiber analysis. TAPPI Conference, Milwaukee, WI, May, 2005.

SIMCA-P Manual. Umetrics, Umeå, Sweden, 1995. Smook, G.A. Handbook for pulp and paper technologists. (1982). Storebråten, S. Karakterisering av massa och fiberr. Sv. Papperstidning No. 6, p. 125–130, 1999.

Strand, B.C. Analyzing the effects of raw material variation on mechanical pulp properties using integrated factor networks. Pacific Simulation, Moscow, Idaho, USA.Turunen, M. et al. Comparison of fiber morphology analyzers. Appita Annual Conference, 2003, Melbourne, Australia.

Tremainis, A. Advanced traditional methods of analysis of fiber surface layers. La Chimica e l'Industria, No. 2, March, 2006.

Yan, H. et al. Fiber length effect on fiber suspension flocculation and sheet forming. Nordic Pulp and Paper Research Journal, Vol. 21, No. 1/2006.

24. Index

N

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P

R

S

25. Abbreviations

A	Acid (symbol for bleaching stage)
ADt	Air dry ton of pulp; ton of pulp at 90% dryness
APPITA	Australian pulp and paper industry technical association
BCKP	Bleached chemical kraft pulp
BCMP	Bleached chemical mechanical pulp
BCTMP	Bleached chemical thermo-mechanical pulp
BHKP	Bleached hardwood kraft pulp
BMN	Bauer McNett, fractionation equipment for laboratories
BSKP	Bleached softwood kraft pulp
C	Chlorine (symbol for bleaching stage)
CCD	Charge coupled cevice
CED	Cupriethylene diamine
CIF	Cost, insurance and freight (trade term requiring the seller to arrange for the carriage of goods by sea to a port of destination, and provide the buyer with the documents necessary to obtain the goods from the carrier)
CMP	Chemical mechanical pulp
CPO	Computer print-outs; grade of RCP
CSF	Canadian standard freeness
CTMP	Chemical thermo mechanical pulp
D	Chlorine dioxide (symbol for bleaching stage)
DIP	Deinked pulp (from recycled fiber, RCF)
E	Alkaline extraction (symbol for bleaching stage)
EU	European union
FEM	Finite element method
FEX	Experimental paper machine installed in the 1980s at RISE, Stockholm, Sweden
FFT	Fast fourier transform
H	Hypochlorite (symbol for bleaching stage)
HC	High consistency
HW	Hardwood

IR	Infrared light. Longer wavelengths than VIS
ISO	International standardisation organisation
LC	Low consistency
LWC	Light weight coated paper (mechanical grade)
MC	Medium consistency; 5–15% consistency of pulp
Mt	Million tonnes
MVDA	Multivariate data analysis
NBSK	Northern bleached softwood kraft pulp
NIR	Near infrared light. Longer wavelengths than VIS and IR
NSSC	Neutral sulphite semi-chemical
NYBOT	New York board of trade
O	Oxygen (symbol for bleaching stage)
OBA	Optical brighteners
OCC	Old corrugated containers; grade of RCP
OMG	Old magazines, a recovered paper assortment
ONP	Old newspapers, a recovered paper assortment
OW	Office waste; grade of RCP
P	Hydrogen peroxide (symbol for bleaching stage)
PAPTAC	Pulp and paper technical association of Canada
PCA	Principal component analysis
PFI	Papir- og fiberinstituttet AS (Paper and fiber research institute, Norway)
PGW	Pressurized groundwood
PIX	Price index
PLS	Partial least square, or projections to latent structures
PM	Paper machine
PQM	Pulp-quality-monitor instrument
Q	Chelating stage (symbol for bleaching stage)
Q2	Prediction capacity of models
R2Y	Explanation capacity of models
R&D	Research and development

RCF	Recycled fiber, i.e. pulp made from recovered paper
RCP	Recovered paper, raw material for recycled fiber
RMP	Refiner mechanical pulp
RoEU	Rest of EU, the European Union (apart from Denmark, Finalnd and Sweden and Scandinavia).
ROI	Return on investment
S1	Secondary wall-layer 1
S2	Secondary wall-layer 2
S3	Secondary wall-layer 3
SC	Super calendered paper or semi-chemical pulp
SCA	Svenska Cellulosa AB (pulp and paper company with headquarters in Sweden)
SCAN	Scandinavian pulp, paper and board testing committee (Finland, Norway and Sweden)
SEK	Swedish krona; Swedish currency
SEM	Scanning electron microscope
SGW	Stone groundwood pulp; a type of mechanical pulp
SR	Schopper-Riegler. See CSF. SR normally used in papermills using chemical pulps
STFI	Pulp & paper research institute of Sweden, nowadays RISE (Research in Sweden Softwood)
T	Peracetic stage (symbol for bleaching stage)
t	Tonne; 1000 kg
TAPPI	Technical association of the pulp and paper industry, USA
TEA	Tensile energy absorption
TMP	Thermo-mechanical pulp; a type of mechanical pulp
US	United States (of America
USD	US Dollar; US currency
UV	Ultraviolet light. Shorter light wavelength than VIS
W	Water (symbol for bleaching stage)

RCF	Recycled fiber, i.e. pulp made from recovered paper
WRV	Water retention value
WFC	Wood-free coated (paper); coated fine paper
VIS	Visible light
X	Enzyme stage (symbol for bleaching stage)
Y	Dithionite (symbol for bleaching stage)
yr	Year
Z	Ozone (symbol for bleaching stage)

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