2. WOOD STRUCTURE AND FIBERS

Table of content

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Wood structure and growth

In pulping, it is crucial to understand the structure of a tree stem as well as the different types of wood and bark in the cross section of a wood trunk. Wood is not a homogenous material, and the properties of the wood material and fibers vary in the different parts of the tree stem.

Structure

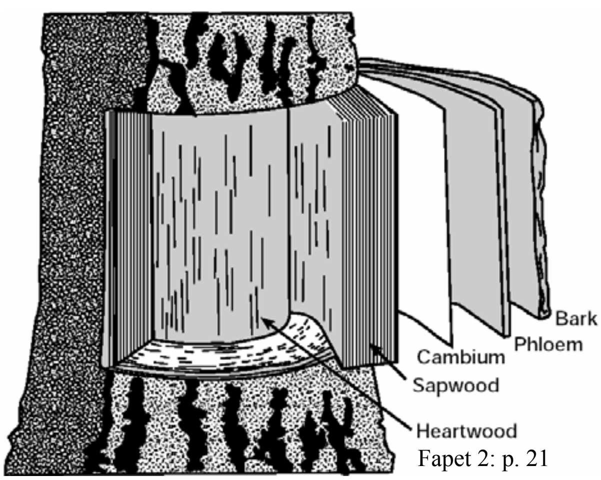
Picture 1 and Picture 2 show the structure of the stem of a tree and the different wood layers in the radial direction.

Heartwood is the inner, often darker colored section of the wood. It consists of dead cells that no longer have any function in transporting water or nutrients. Its main function is to provide support. Heartwood contains a higher amount of resins that are deposited in the cell walls and cavities as the cells die.

Sapwood is the outer, lightly colored section of the wood. It gives structural support to the tree crown, acts as a nutrient storage reservoir, and transports water from the roots to the tree crown. Some of the cells in the sapwood also transport sap.

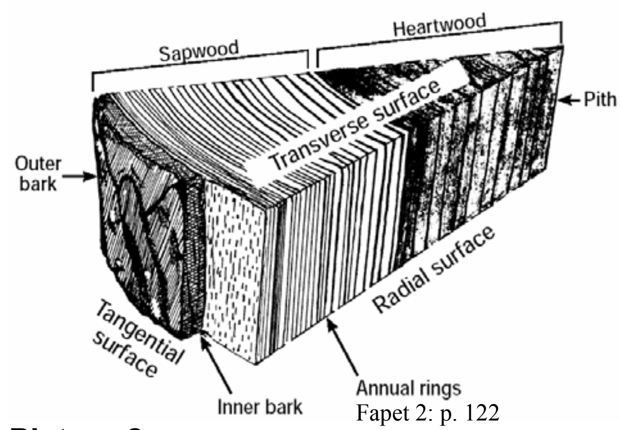
Cambium is the thin layer between the sapwood and bark where new wood cells are formed. It produces wood cells on the inside and bark on the outside. The rate of growth depends on the seasons. Early wood is produced during the first part of the growing season, while late-wood is produced during the latter part.

The bark consists of two layers; the inner bark (phloem) and the outer bark. The inner bark is a narrow layer of living cells through which the transport of sap takes place to provide the tree with energy. The outer bark consists of dead cells, which were once part of the inner bark. The outer bark contains a high fraction of extractives and its function is to protect the tree.



Fapet 2: p. 21

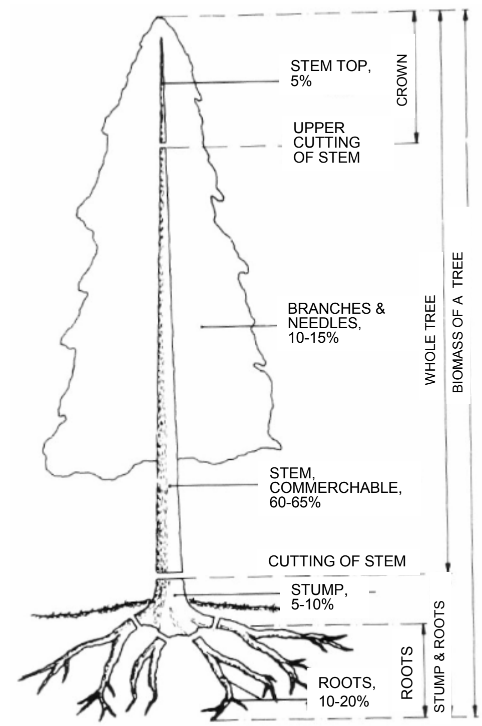
Picture 1. Main structure of the wood stem of trees in the boreal and temperate zones



Fapet 2: p. 122

Picture 2. The three primary planes of wood

That proportion of the tree which can be used in industry varies but can be in the range of 60%-65% of the total biomass of the tree. The rest of the biomass of a tree is often left in the forest or used as fuel wood.



Picture 3. The different parts of a tree PV, Modified by KH

In Table 1 are given some typical values for the wood raw material of the major wood species growing in Finland.

Table 1. Properties of Finnish pulpwoods

Wood species	Pine	Spruce	Birch
Wood density [1) kg/m^3	400	380	480
Bark density [2) kg/m^3	300	370	515
1m^3 of unbarked wood contains:			
wood m^3	0.88	0.87	0.86
dry wood kg	350	330	410
bark m^3	0.12	0.13	0.14
dry bark kg	36	48	72
dry wood chips kg/loose m^3 [1)	150	140	180
debarked chips loose m^3/m^3 of unbarked wood[3)	2.3	2.3	2.3
dry sawdust kg d.s./loose m^3 [1)3)	140	130	170

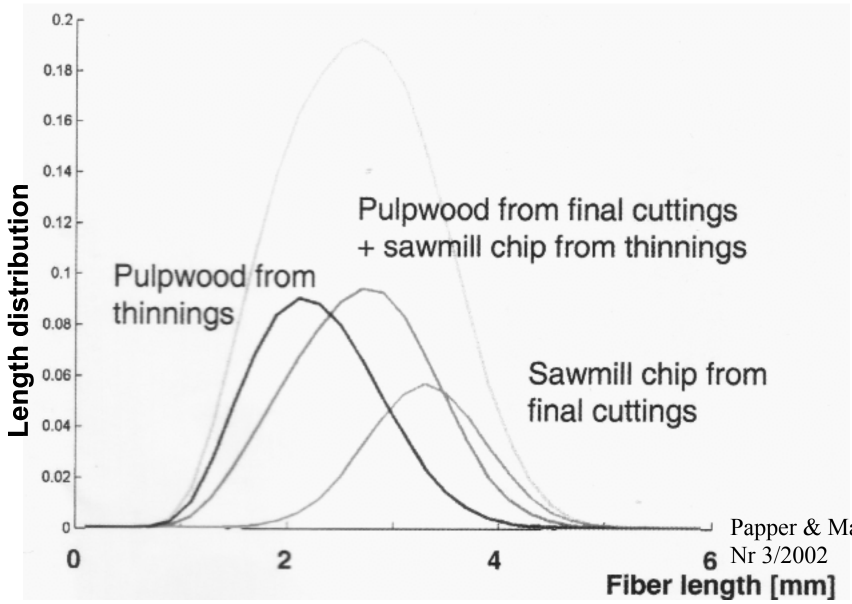
1) Density of dry wood.
2) Density of dry bark. Bark volume as measured from the diameter difference of stem with and without bark.
3) Important parameters for the dimensioning of digesters. PV, Modified by KH

Growth

The tree grows in the longitudinal direction at the top of the tree and at the ends of the branches. Here, juvenile wood that consists of small and short wood cells is formed. In the cambium part of the wood, wood cells or fibers are formed, and the wood grows in the thickness direction. Here, mature wood that consists of longer cells is formed.

The wood cells are also called fibers, and they are the fibers needed for the production of paper and board. The fibers formed in the outer annual rings are larger and longer than the wood fibers in the center of the wood. The wood fibers in the outer layers of softwoods can be 2%-300% longer than the wood fibers in the center of the softwood. For hardwood, the length difference can be 100%-150%. In Scandinavia, the softwood fibers reach their full length in annual rings 10-20 years old or older. In fast growing areas, the difference between juvenile and mature wood is smaller, and the fibers reach their full length earlier.

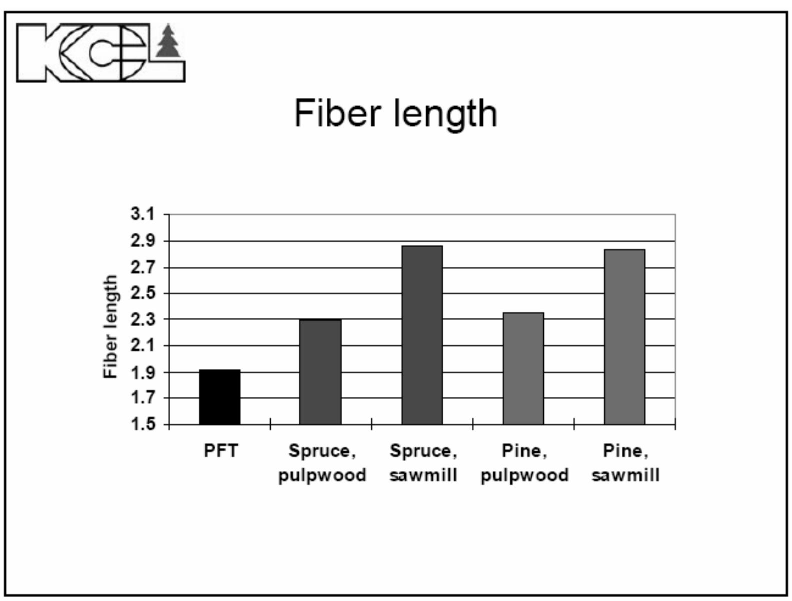
As a result of the way a tree grows, pulpwood obtained from thinning will have shorter fibers than pulpwood from sawmill chips or final cuttings as can be seen in Picture 4. The selection of the wood raw material is an efficient way to control the fiber properties of softwood pulp in particular.



Papper & Massa
Nr 3/2002

Picture 4. Fiber length distribution in Scandinavian softwoods

Juvenil wood from softwood, the first 5-25 years of annual rings, has lower density, wider annual rings and shorter fibers than normal pine and spruce. The fiber lengths of PFT, pine first thinning, is shorter than for pulp wood and sawmill chips. Wood from young wood will give shorter fibers with reduced paper strength properties. Chemical pulp from young softwoods is, however, suitable for some paper grades.

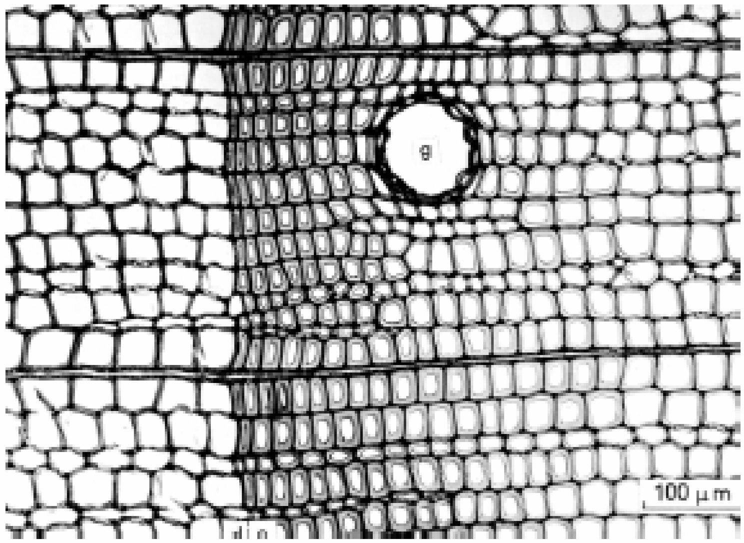


PWF, Robertsen

Picture 5. Fiber length of Scandinavian spruce and pine

Early wood and latewood

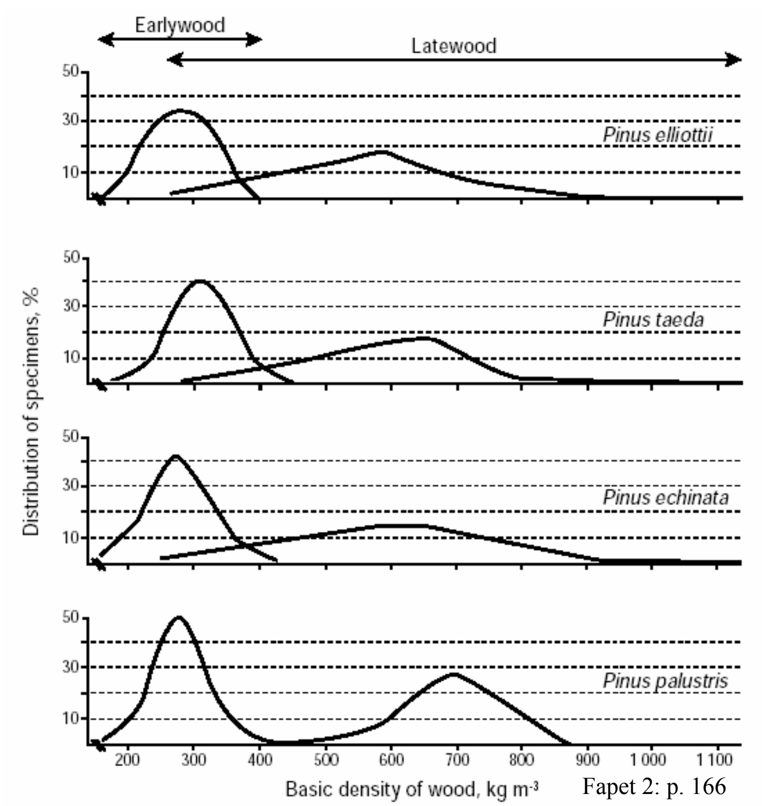
The early wood fibers formed in the spring are thin-walled and somewhat shorter than the latewood fibers. The seasonal growth of a tree is clearly seen as annual rings in the cross-section of a cut stem. The annual rings of the trees are due to the difference between early wood and latewood fibers. Picture 6 shows the cross section of spruce wood and the difference between early wood and latewood fiber wall thicknesses and fiber width. Early wood is lighter in appearance than latewood.



Fapet 6A: p. A22

Picture 6. Cross-section of a spruce (Picea abies) sample showing an annual growth ring boundary

The difference in fiber wall thickness leads to differences in wood densities between early wood and latewood. The density differences can be seen in Picture 7.



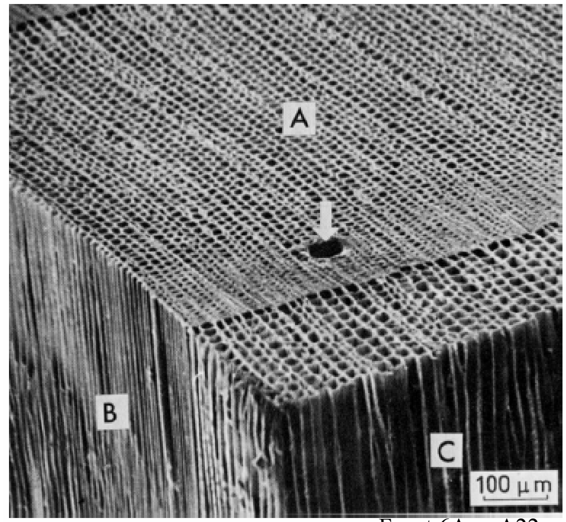
Fapet 2: p. 166

Picture 7. Basic density, early wood and latewood

Softwood

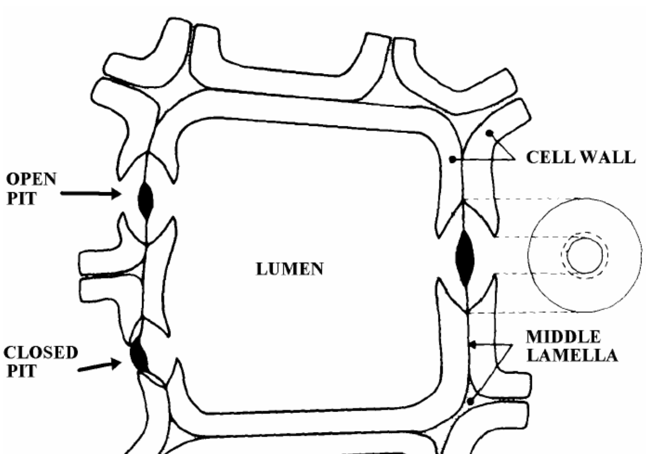
The long tracheid fibers in the longitudinal direction of the tree are the fibers that are most valuable in papermaking as the long fibers give good paper technical properties. These fibers form about 90% of the cross-sectional area of the tree. The shorter radial cells form about 5%-10% of the volume but only a few percent of the weight.

The schematic illustration of pine in Picture 8 shows the structure. Section A shows the cross section with an annual ring and a vertical resin duct; B is the radial direction plane, and C is the tangential direction plane. Axially aligned tracheids (TR) form the basis of papermaking fibers. Other cell types include wood rays (WR). Cells surrounding the horizontal and vertical resin ducts are denoted with HRD and VRD.



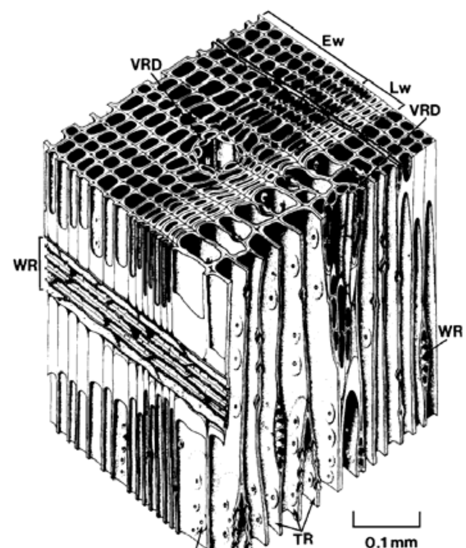
Fapet 6A: p.A22

Picture 8. DA cubic section of pine (Pinus silvestris)



Fapet 6A: p.A24

Picture 9. Cross section of one tracheid showing bordered pits



Fapet 6A: p.A24

Picture 10. Schematic section of pine: BP=Bordered Pit, Ew=Early wood, Lw=Latewood, TR=Tracheid, VRD=Vertical Resin Duct, WR=Wood Ray

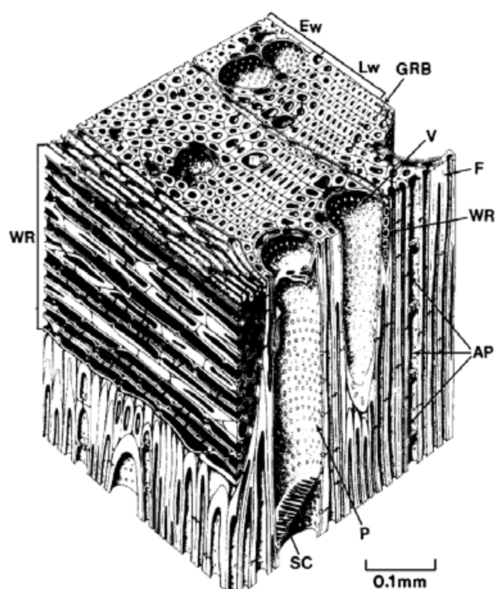
Picture 9 shows the cross section of one softwood tracheid showing bordered pits. Adjacent walls can have voids (“pits”) between them. The pits provide a horizontal liquid transport path from cell to cell. Softwood pits have a valving arrangement called bordered pits (BP) with a membrane of thickened cellular material called torus. This membrane can close during dry seasons to stop liquid loss from cells. Picture 10 shows a cubic section of pine. The long tracheid fibers in the longitudinal direction of the tree are crossed by the short wood ray cells in the radial direction.

Hardwood

The structure of hardwoods is much more varied and complex than that of softwoods. Also here, the main component is the wood fiber (F), but it is much shorter than the corresponding tracheid of softwoods. Hardwoods also contain a significant portion of short, large-diameter cells called vessel elements (V) through which sap is transported. The size and number of vessel elements vary strongly from species to species. Vessels have open ends and a grate-like connecting tissue called scalar form plate (SC).

The hardwood fibers in the longitudinal direction of the tree are the fibers most valuable in papermaking and the hardwood fibers often give good optical properties to the paper.

The fibers form about 60%-70% and the vessel elements 20%-25% of the cross-sectional area of the tree. The fibers constitute about 85 % of the weight in the case of birch. The variations are large between different wood species and the variation in weight is 75%-90%.



Fapet 6A: p.A24

Picture 11. Schematic section of hardwood: AP=Axial Parenchyma, F=Fiber, Ew=Early wood, Lw=Latewood, GRB=Growth Ring Boundary, P=Pit, WR=Wood Ray, SC=Scalariform plate

Properties of fibers

Fibers from wood and annual plants are used for paper and board making. The length and width of the fibers vary depending on the type of raw material used. Table 2 shows typical dimensions of Finnish softwood and hardwood fibers and of some common annual plant fibers. It should be pointed out that there are large variations in fiber dimensions within species and also within a single plant.

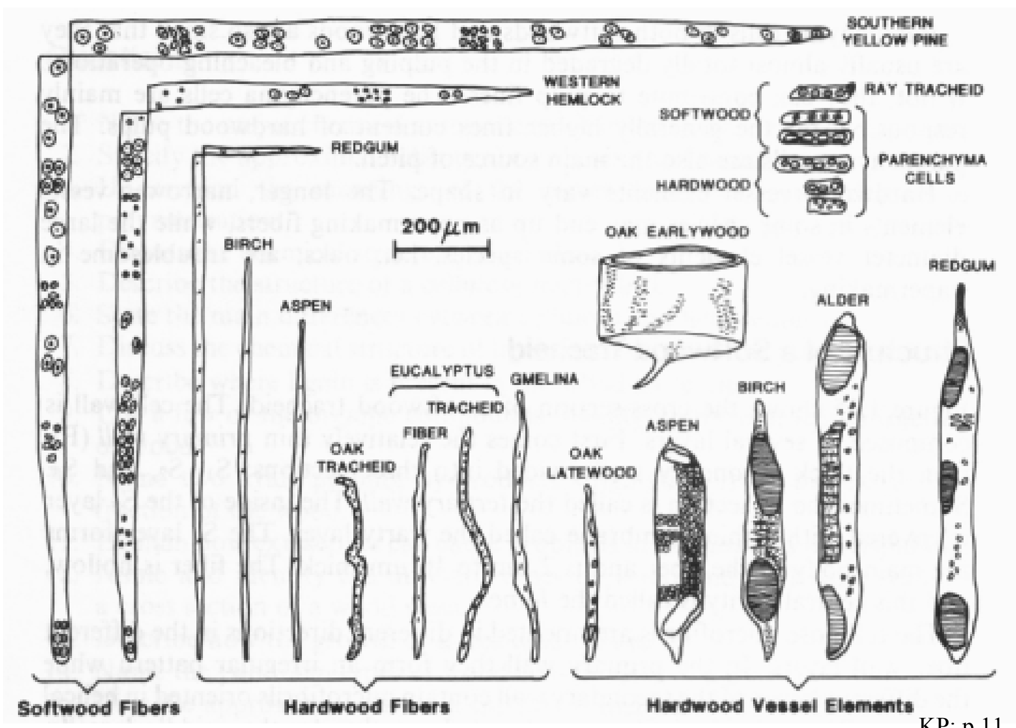
Table 2. Typical fiber dimensions

Fiber source	Fiber length, mm	Fiber width, µm
Softwood	3.0	30
Hardwood	1.0	16
Straw	1.5	13
Rice	1.5	9
Bamboo	2.7	14
Bagasse	1.7	20

PV, Modified by KH

There are also other fiber properties than the length and width of the fiber that influence the papermaking potential of the fibers. The physical dimension of a fiber does not provide enough information to evaluate the suitability of a certain fiber for papermaking.

Picture 12 shows major cell types of some hardwood and softwood fibers. The hardwood vessel elements are weak and are mostly broken down into fines during fiber handling. Also ray tracheids and parenchyma cells are fines that are partly lost during fiber processing and papermaking. Hardwood vessel elements can end up in the paper sheet and may cause problems if they are loosely attached to the surface of the paper and cause linting and dushing on the paper machine, for instance.



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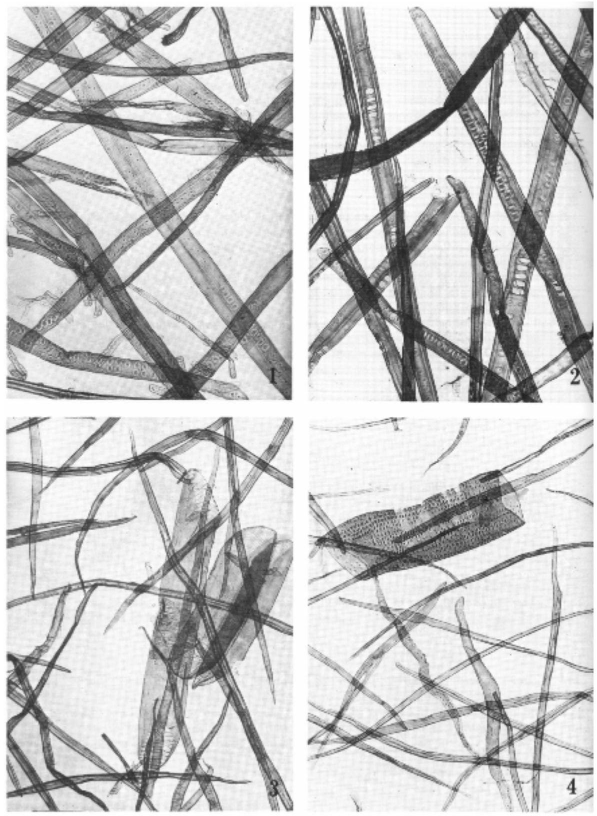
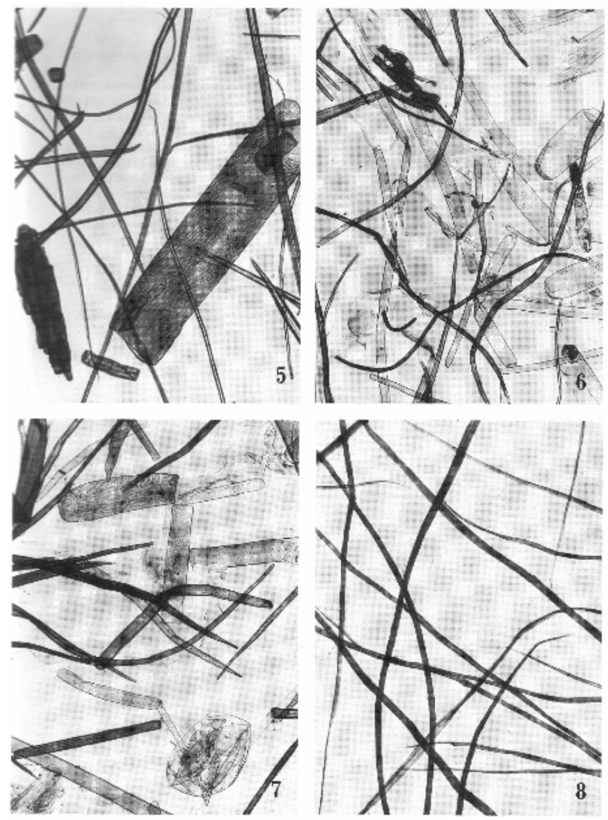
Picture 12. Major cell types in hardwoods and softwoods

Picture 13 shows pictures of some important Finnish wood fibers and eucalyptus fibers. Picture 14 shows pictures of some annual plant fibers. The source of different fibers can be determined visually with a light microscope.



Picture 13. Some wood fibers: 1.Spruce 2.Pine 3.Birch 4.Eucalyptus (Oy Keskuslaboratorio Ab)



Picture 14. Some annual fibers: 5.Bamboo, 6.Wheat 7.Bagasse 8.Kenaf (Oy Keskuslaboratorio Ab)

Softwood fibers

There are considerable variations in fiber (tracheid) dimensions between softwood species, between trees of the same species, within a single trunk, in tension wood, in branches and roots, and in individual annual rings (Table 3). This variation is related to genetic factors, the age of the tree, the rate of growth and environmental factors.

The dimensions of the tracheids within a tree trunk vary both in the radial and longitudinal directions. Tracheid length generally increases in the radial direction outwards and from the root upwards to the middle of the height of the stem, then declining again towards the top. Branches and roots have much shorter fibers.

Table 3. Tracheid dimensions of some common softwood species

Species	Latin name	Length, mm	Tangential width, µm
Spruce	Picea abies	3.4 (1.1-6.0)[1]	31 (21-40)[1]
Pine	Pinus silvestris	3.1 (1.8-4.5)	35 (14-86)
Larch	Larix deciduas	3.5 (1.4-6.2)	38 (24-52)
German spruce	Abies alba	3.7 (1.6-5.7)	38 (18-58)
Ponderosa pine	Pinus ponderosa	3.6 (1.5.-5.0)	35-45
Canadian larch	Larix laricana	3.6 (1.7-5.6)	25-35
Black spruce	Picea mariana	3.3 (1.3-4.9)	25-30
Sitka spruce	Picea sitchensis	5.6 (3.6-7.3)	35-45
Redwood	Sequola sempervirens	6.1 (2.9-9.3)	50-56
Western hemlock	Tsuga heterophylla	3.9 (1.7-7.0)	35-45

1) Numbers in brackets are variation limits.

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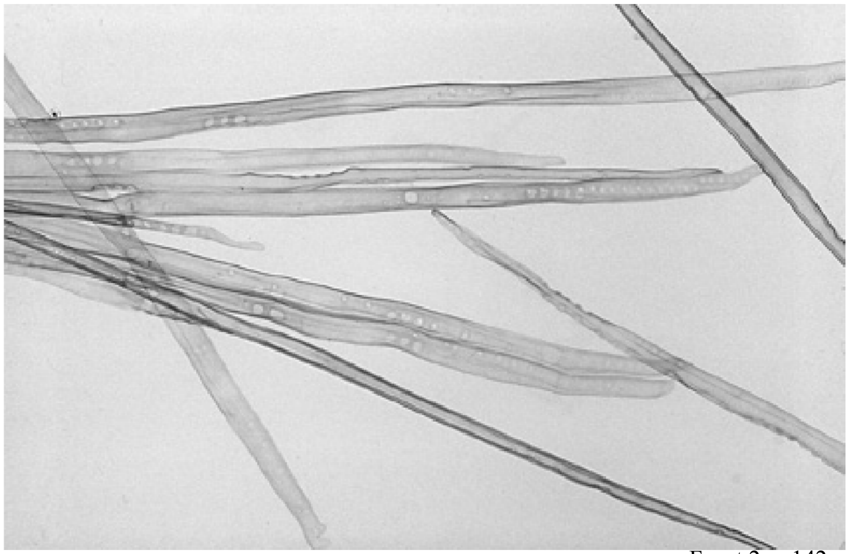


Fapet 2: p.142

Picture 15. Softwood tracheids for Pinus silvestris (Photo by Pekka Saranpää)

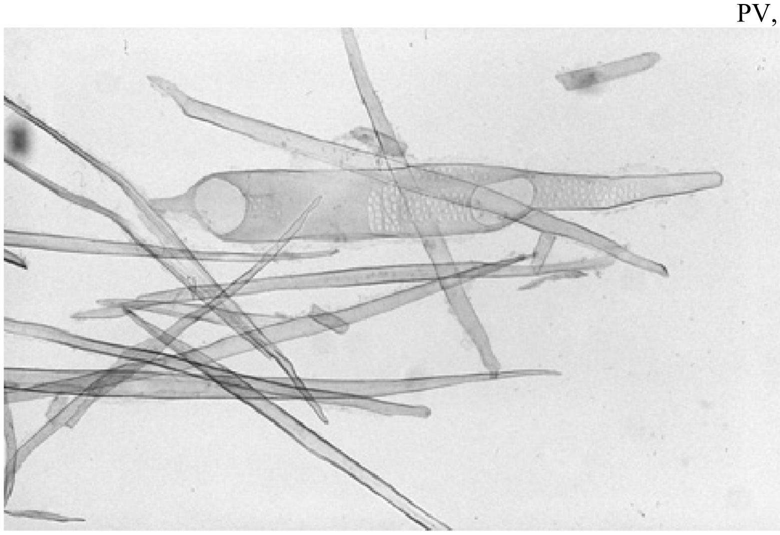
Hardwood fibers

Table 4 shows some properties of some hardwood fibers. The variations in dimensions are smaller than in the case of softwoods. For hardwood fibers, the most interesting papermaking properties are related to the optical properties of the papers. These optical properties depend largely on the number of fibers per weight.

Table 4. Properties of some hardwood fibers

Wood species	Number of fibers (mill. fibers / g)	Typical fiber length (mm)	Hemicellulose content %
Birch	10	0.9	25
Eucalyptus grandis	17	0.75	20
Acacia	19	0.7	20
Mixed tropical hardwood	6.6	1.18	5-20
Aspen	11	0.85	24

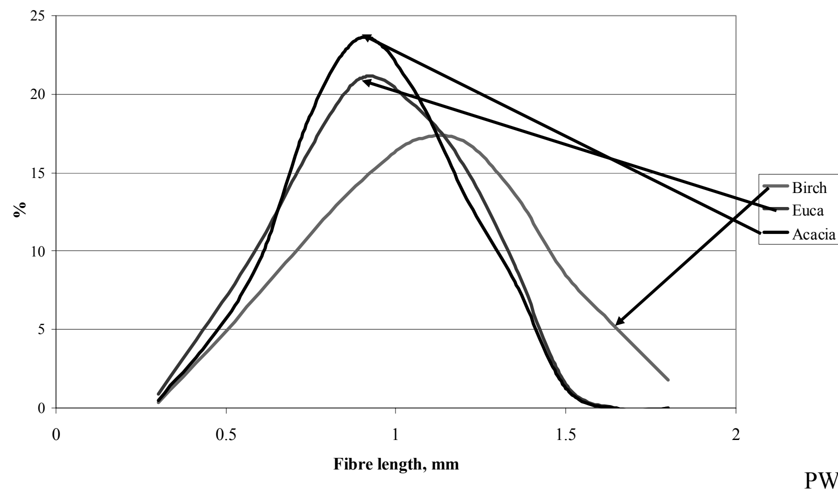
PV, Modified by KH



Picture 16. Fibers and a vessel segment of a diffuse-porous hardwood for Populus tremula (Photo by Pekka Saranpää) Fapet 2: p.142

The fiber length distribution for hardwoods is narrower than for softwoods. Hardwoods from fast growing species and regions have a narrower fiber length distribution than Scandinavian hardwoods. The optical properties of eucalyptus and acacia are in some respect better than those of Scandinavian birch. The strength properties of Scandinavian birch are higher than those for eucalyptus and acacia.

Properties of hardwood fibres



PWF, Jokela

Picture 17. Fiber length distribution of birch, eucalyptus and acacia

	Birch	Eucalyptus	Acacia
Whiteness	0	+	+
Opacity	0	+	++
Formation	0	+	++
Strength	+	0	-
Bulk/stiffness	-	+	-

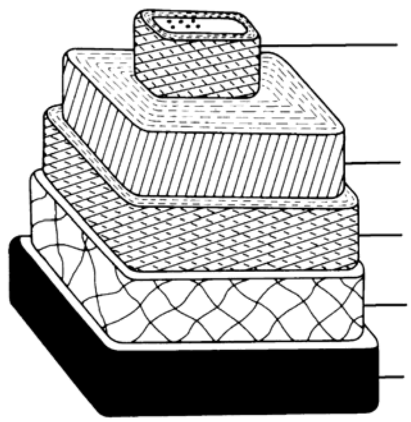
Picture 18. The suitability of some hardwoods for paper production

PWF, Jokela

Physical and chemical structure of fibers

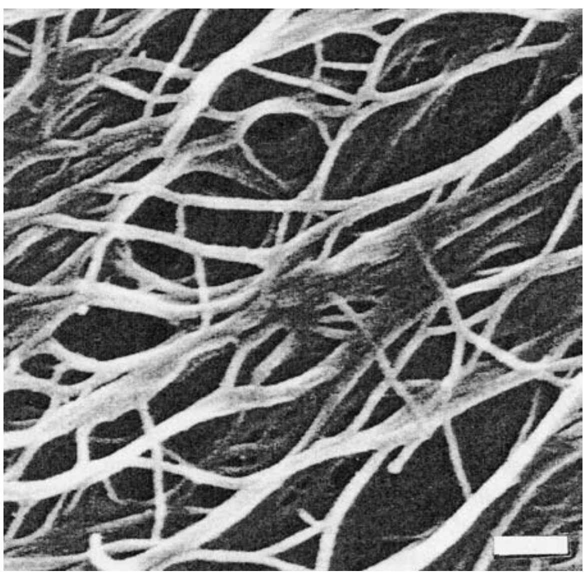
Physical structure

The cell wall consists of the primary wall, the secondary wall and the middle lamella, which binds two cells together. The secondary wall is built of microfibrils embedded in a structure of lignin and hemicellulose. The secondary cell wall can be divided into three parts; S_1, S_2 and S_3. The fibril angle is different in the different layers of the secondary wall.



Picture 19. Schematic illustration of the wood cell wall structure, including microfibril directions and the lamella structure of the cell wall PV, Modified by KH

The microfibrils are the elements that form the cell wall. They are built from the cellulose molecules that form crystalline and amorphous regions in the microfibrils. The angles of the microfibrils in the cell wall layers vary not only between wood species but also between cells within the tree.



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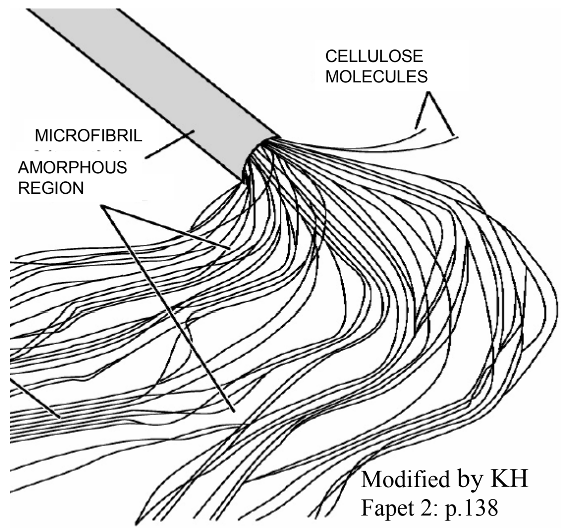
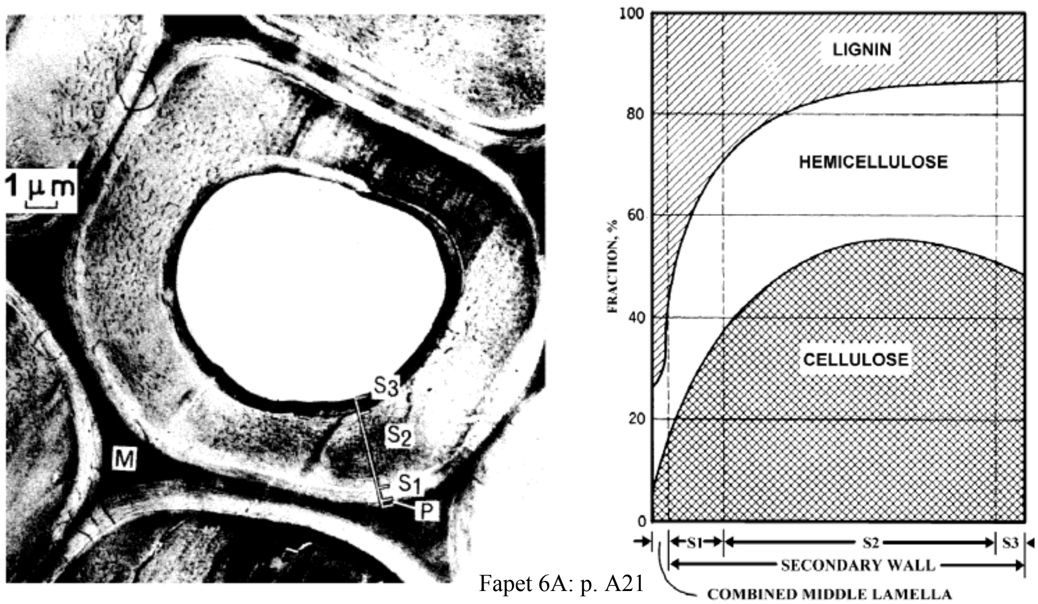
Picture 20. SEM micrographs of freeze dried, swollen unbeaten kraft fiber surface, illustrating the separation of fibrils and formation of openings (white bar on the right at the bottom of the picture is 100 nm)



Picture 21. Microfibril, schematic picture of cellulose molecules



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A B

Picture 22. A: Microscopic picture of the cross section of a cell wall, the middle lamella (M), the primary wall (P), the outer (S_1), middle (S_2) and inner (S_3) layers of the secondary wall. B: Schematic diagram of the construction of the wood fiber wall, the distribution of the chemical components across the fiber wall.

The chemical composition of the cell wall varies in the different layers of the wall. The main components – cellulose, hemicelluloses and lignin – are distributed in softwood as shown in Picture 22. The lignin concentration is highest in the middle lamella and lowest in the S2 and S3 layers. The S2 layer is richest in cellulose. Because of the different thicknesses of the layers, there is in absolute amounts more lignin in the secondary wall than in the middle lamella.

Chemical structure

Wood consists mainly of cellulose, hemicellulose, lignin, extractives and ash. The chemical composition of wood varies from species to species. The average composition of hardwood and softwood can be seen in Table 5. In general, hardwoods contain more hemicellulose than softwoods but less lignin and extractives. When pulping, one wants to retain as much of the cellulose and the hemicellulose as possible, while lignin and extractives are the components removed from wood fibers during pulping.

Table 5. Gross chemical composition of wood

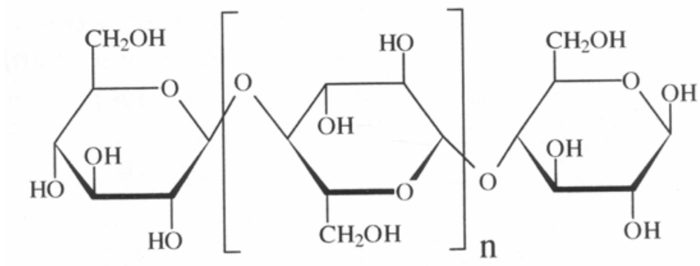
Component	Hardwood, %	Softwood, %
Cellulose	42 – 49	41 – 46
Hemicellulose	23 – 34	25 – 32
Lignin	20 – 26	26 – 31
Extractives	3 – 8	10 – 25
Ash	0.2 – 0.8	0.2 – 0.4

Fapet 6A: s. A27

Cellulose

Cellulose, which is the main part of the cell walls of wood, is a linear polymer composed of glucose units as can be seen in Picture 23.

The chemical formula for cellulose is $(C_6H_{10}O_5)_n$ where n is the number of repeating glucose units, and n is also called the degree of polymerization. The degree of polymerization (DP) in wood can be up to 10,000. The value of n varies between different sources of cellulose. During pulping, the DP decreases to a certain degree. The DP should not decrease too much since shorter cellulose chains will ultimately result in weaker pulp.



WC, Modified by KH

Picture 23. Structure of a cellulose molecule as a linear polysaccharide of glucose units

Hemicellulose

Hemicelluloses are a group of branched polysaccharide polymers built of xylan, glucomannan, glactoglykomannan, arabinogalactan and galactan. They exist in an amorphous form and this is the reason why these polymers are not as stable to chemical attacks as cellulose. Hemicellulose is to some extent watersoluble and partly dissolves in both acidic and alkaline pulping conditions. The type of hemicellulose varies depending on the location within the wood structure. In pulping, hemicellulose reacts faster than cellulose. In wood, the hemicelluloses are mostly found around the cellulose microfibrils, which they support. Hemicelluloses attach to the surface of cellulose, due to their similar structure. In papermaking, the hemicelluloses aid in making the paper stronger.

Table 6. Main types of hemicelluloses in wood

Hemicellulose type	Occurrence	Amount (% of wood)	$\overline{DP}_n$
Galactoglucomannan	Softwood	5-8	100
(Galacto)glucomannan	Softwood	10-15	100
Arabinoglucoronoxylan	Softwood	7-10	100
Arabinogalactan	Larch wood	5-35	200
Glucuronoxylan	Hardwood	15-30	200
Glucomannan	Hardwood	2-5	200

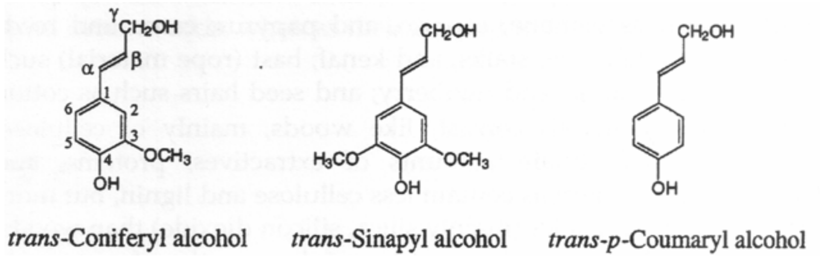
WC, Modified by KH

Lignin

Lignin exists mainly in the wood cell walls, but also in the middle lamella. Lignin polymer in wood behaves as a three-dimensional network and is insoluble. The lignin content of softwoods (25%-33% of the wood d.s.) is typically higher than that of hardwoods (20%-25% of the wood d.s.). Lignin is an amorphous heteropolymer and its chemical structure is irregular in the sense that the different structural elements are not linked to each other in any systematic order, as they are in wood carbohydrates. The molar mass of lignin is approximately 20.000g/mol for softwood and less than 20.000g/mol for hardwood.

The structural elements of lignin are three phenylpropanoid monomers, trans-coniferyl, trans-sinapyl and trans-p-coumaryl alcohols, from which the lignin is formed by enzymatic dehydrogenation

(Picture 24). The mass proportion of the different phenylpropanoid units varies between softwoods and hardwoods.



Picture 24. Lignin precursors for plants WC, Modified by KH

Extractives

Wood usually contains a small amount of various substances that are called "extractives". Extractives are partly soluble in water or in organic solvents. The organic-soluble extractive content averages between 2%-10% depending on the wood species and may cause major difficulties in the pulping of wood. Extractives are mainly resins and fatty acids, resin acids and esters. Terpenes are volatile and will evaporate when chips are steamed before cooking. Fatty acids and resin acids are converted to soaps by the kraft process and dissolve in the cooking liquor. These soaps are later separated from the black liquor and recovered as tall oil. The tall oil is further purified and the products are used to manufacture different chemical products.

Some of the less soluble extractives can cause pitch problems during kraft pulping, especially during bleaching, and in papermaking. Pitch consists of small aggregates of undissolved extractives. Pitch also appears as tiny specks in the manufactured paper.

Analyzing pulp

There are many special tests to evaluate the properties of pulps and their suitability for papermaking. Many of these tests are developed to evaluate the pulp regarding some special feature while some other are more commonly used to give a general picture of the chemical and physical characteristics of the pulps.

Pulp can be analyzed in several ways, for instance:

A Analyses of pulp samples made to determine the chemical properties of the pulp; for instance the following can be determined from a pulp sample:
- Kappa number indicates the residual lignin content after cooking
- Viscosity indicates the degree of polymerization

B Single fibers can be analyzed to determine for example:
- The physical shape of the fiber
- Fiber damages

C Analyses made to determine the papermaking properties of pulps.

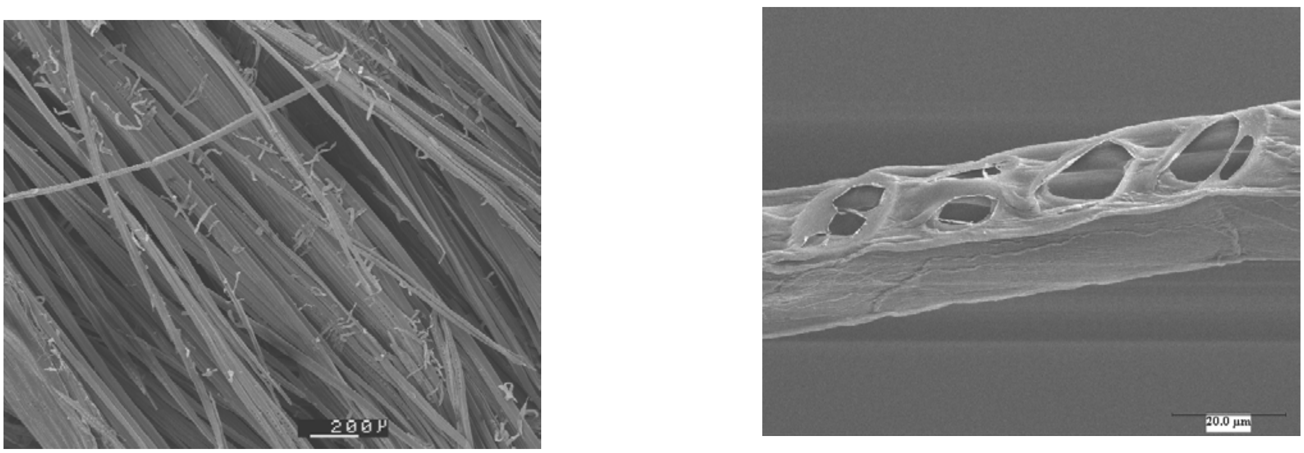
Examples of chemical analyses:

One can get a good estimate of the degree of polymerization of the cellulose (e.g. the average cellulose chain length) by dissolving a pulp sample in a cellulose solvent and then measuring the viscosity of the solution. A lower viscosity means more degraded cellulose consisting of shorter cellulose chains. Once viscosity falls below a certain level, the pulp strength starts to decrease and the change is irreversible. Viscosity is often used as a measure of cellulose degradation during cooking and bleaching. The viscosities of pulps, produced at different mills or from different raw material, are not as such comparable.

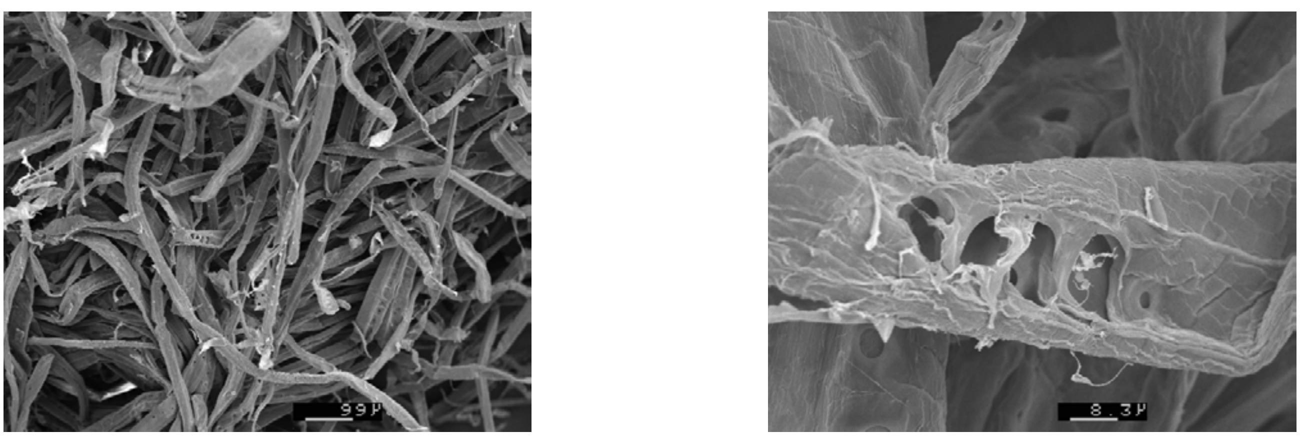
The kappa number is a measure of how much lignin the pulp contains. The kappa number is used to control cooking and to indicate the charge of chemicals needed during bleaching. The kappa number measures the amount of potassium permanganate consumed by the pulp and is a way of expressing the amount of residual lignin in the pulp. Pulps to be bleached are cooked to a kappa number of 16-20 for hardwoods and 24-30 for softwoods. The correlation between kappa number and lignin content varies depending on wood raw material and process conditions, but for kraft pulps, 1% of residual lignin corresponds to about 6 kappa units.

Examples of single fiber analyses:

Fiber samples and single fibers can be analyzed by SEM micrograph. The pictures show shape of single fibers and fibers in pulp samples taken from a pulp mill in Scandinavia.



SEM-micrograph of intact softwood pulp after cooking; sample taken after blow valve



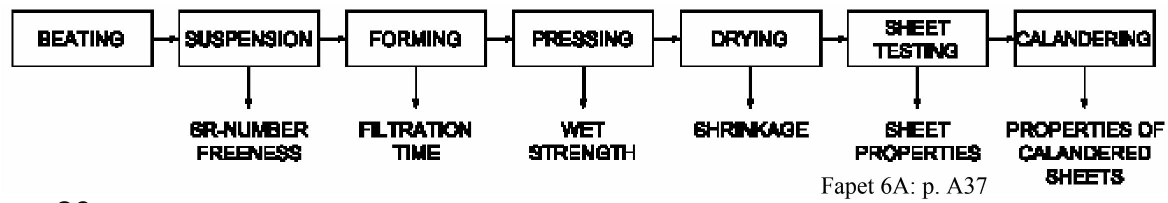
SEM-micrograph of softwood pulp sample taken after mill processing; some fiber damages can be seen

I.Rauvato

Picture 25. SEM pictures of Scandinavian mill softwood fibers

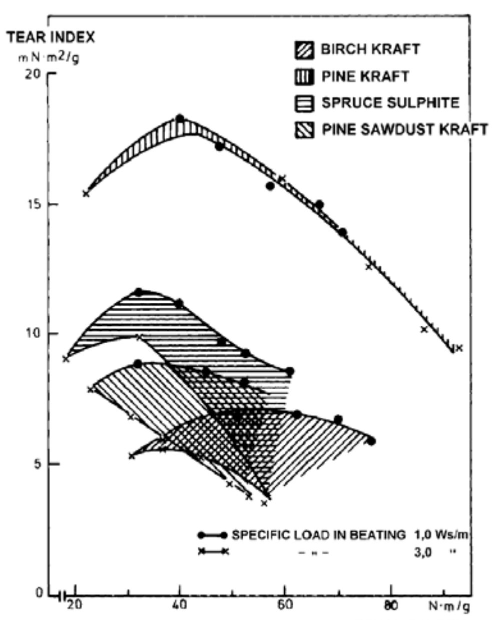
Examples of analyses on paper technical properties:

The papermaking properties of pulp are determined by simulating the papermaking process in standardized laboratory conditions and by measuring the paper properties of laboratory-manufactured standard hand sheets of paper. Picture 26 shows a schematic laboratory papermaking procedure with some corresponding analyses. Pulp suspensions are processed in standard beating devices to various degrees of beating, which can be measured directly from the suspensions (e.g. filtration resistance or freeness). Wet strength properties can be measured from wet-pressed sheets. Standard hand sheets are made from the beaten pulp samples and dried under restraint. Test strips are cut from the hand sheet and measured for strength. Dried sheets can be further calendered to determine the response of the pulp to high linear pressures. Many special tests are done to evaluate particular paper properties of pulps, and the most commonly used are the tear and tensile strengths of the paper sheet.



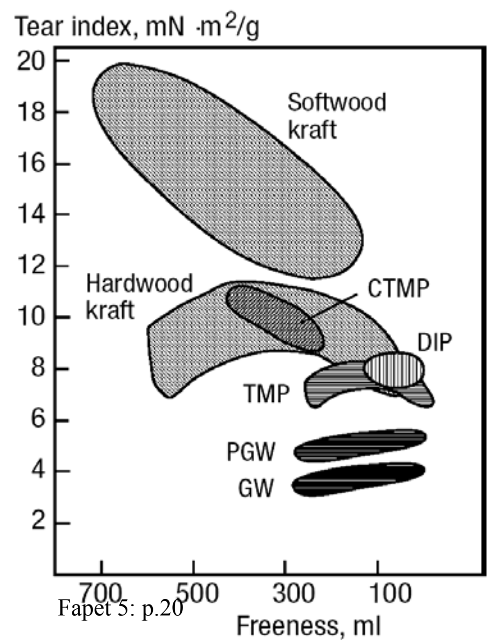
Picture 26. Schematic diagram of simulative testing procedures for paper pulp

Picture 27 shows an example of the tear-tensile strength properties of some paper pulps. One can see that pine kraft pulps have a much higher tear strength than birch and pine sawdust kraft pulps, and that sulfite pulps made from spruce have a much lower tear strength than pine kraft pulps. The difference between pine and birch kraft pulps is determined by fiber morphology. The pine fibers are three times longer than the birch fibers. Pine sawdust kraft pulps are weaker than those made out of chips due to fiber damage in sawdust. The kraft process produces pulp with better strength properties than the sulfite process from similar wood raw material. Picture 28 shows the tear strength of some mechanical, chemi-mechanical and chemical pulps at different freenesses. Freeness is a laboratory measurement of the filtration resistance of pulps and a pulp that is refined loses freeness as the filtration resistance of the fibers increases.



Fapet 6A: p. A57

Picture 27. Strength properties of pine, birch, spruce and pine sawdust kraft pulps



Picture 28. Tear strength of some pulps

Questions

1. The main structure of the wood stem. / Puunrungon pääasiallinen rakenne.
2. Properties of Finnish pulpwoods. / Suomalaisten kuitupuiden ominaisuudet.
3. The growth of a tree and the influence of the way of growth on the properties of softwood fibers. / Puun kasvu ja kasvutavan vaikutus havupuun kuituominaisuuksiin.
4. The differences between early wood and latewood. / Kevät- ja kesäpuun erot.
5. The physical structure of the cell wall. / Puukuidun seinämän fyysinen rakenne.
6. The chemical structure of the cell wall. / Puukuidun seinämän kemiallinen rakenne.
7. Major cell types in softwood and hardwood and their importance in papermaking. / Tärkeimät havu- ja lehtipuun solutyypit ja niiden merkitys paperinvalmistuksessa.
8. Suitability of eucalyptus, acacia and birch fibers for paper production. / Eukalytus-, akasia- ja koivukuidun soveltuvuus paperinvalmistukseen.
9. Analyzing pulp, what is the kappa number? / Massojen analysointi, mikä on kappaluku.