

Fig. 2-16. Chip thickness screen for overthick chip removal. The insert shows a close-up of disks.

Like any method to insure quality, a representative sample from each truckload of incoming chips must be obtained. Some mills use continuous samplers to insure the sample represents the entire truckload, but most mills use a simple bucket sampler that is filled from the first 5% of the truckload. Fig. 2-18 shows a continuous sampler and a bucket sampler that grabs a sample from one section of the truck. Plate 10 shows a chip truck dumping in an arrangement that also uses a bucket-type sampler. (Stories circulate about unscrupulous suppliers that water-down or use inferior chips in the part of the truck that they know will not be sampled.) Many mills may also have a person collect a sample every hour of the chips going to the digester to see how the screening system is working. (Stories also circulate about the person who collects all eight samples for a given shift at one time and submits one sample every hour.)

Ideally, laboratory determinations are made for moisture content, chip size distribution, and bark, rot, and dirt contents. Determinations of wood species, extractives content, chip bulk density, and chip damage are made less often. Chip size distributions are determined in the laboratory using oscillating screen systems, systems with adjustable thicknesses between bars (Fig. 2-19), or other suitable systems. Collection of representative wood chip samples from rail cars or barges can be quite challenging (Fig. 2-20.)

Miscellaneous analyses

TAPPI Standard T 257 describes the sampling and preparation of wood for analysis whether logs, chips or sawdust. The basic density and moisture content of pulpwood is determined according to TAPPI Standard T 258. In this test, volume is measured by water displacement and moisture content by the difference in mass before and after drying at 105° C \pm 3°. The overall weight-volume of stacked roundwood is determined according to TAPPI Standard T 268. TAPPI Standard T 265 is used to measure the natural (wood derived) dirt in wood chips. Dirt originates from the outer and inner barks, knots,



Fig. 2-17. Laboratory chip size distribution analysis. The top shows the pan configuration; the bottom shows the actual equipment.

stains, rot (decay), etc. Color photographs help with identification for the novice. The ash content (i.e., the mineral content including metals and their anions and silicates) of wood and pulp is determined by ignition in a muffle furnace at 575 \pm 25°C as described by TAPPI Standard T 211.

TAPPI Standard T 263, with numerous diagrams and photomicrographs, covers identifi-



Fig. 2-18. Continuous sampling during chip truck emptying on the left; on the right a bucket that is filled when it swings out, obtaining a sample that represents only one section of the load.

cation of wood and fibers from conifers. One should consult the references listed in this method for additional information and high quality photomicrographs unless experienced in microscopy and, more particularly, wood anatomy.

The amount of hardwood and softwood in wood chips is easily determined with the Mäule test (Section 21.18), which gives a purple color for hardwoods while leaving softwoods uncolored.

2.4 SOLID WOOD MEASUREMENT

Wood is measured and sold on a variety of bases. The volume of solid wood in stacked roundwood can be determined by *scaling* (a laborintensive method of sampling volume and log sizes and converting to solid wood volume with tables) or by *water displacement* methods. In practice, it is easier to weigh the wood (using truck scales) and determine the bone dry weight using moisture contents of the wood. Table 2-2 gives the conversion factors for different units of solid wood and wood chips that are described below.

Board foot

A board foot is a volumetric measurement of solid wood. It is equal to 12 in. \times 12 in. \times 1 in. or 1/12 cubic foot of solid wood.

Cord

A cord is stacked roundwood occupying a total volume of 4 ft by 8 ft by 4 ft. Typically, a cord of stacked wood contains 80-90 cubic feet of solid wood, although this can vary widely, and will yield about 500 bd. ft. of lumber or 1.2 BDU of chips. (A face cord is used to sell firewood in some locations; it is 4 ft by 8 ft by the width of the wood pieces.)



Fig. 2-19. Chip size classification (left) and moisture content determination (right) in a mill's wood quality control laboratory.

Cunit

A cunit is 100 cubic feet of solid wood in stacked roundwood. It is used to determine the wood content of pulp logs.



Fig. 2-20. Rail cars ready to be unloaded. They will be tipped back on the special platform to discharge their contents. Over six cars per hour can be unloaded by this method.

2.5 WOOD CHIP MEASUREMENT

Bulk density

The bulk density is the oven-dry weight of chips (or sawdust, or other wood residue) contained in a given volume of space. The bulk density of the chips depends on the specific gravity of the wood source, the chip geometry, and the chip size distribution. For example, Douglas-fir chips from roundwood are typically 192 kg/m³ (12 lb/ft³) (dry wood weights), while Douglas-fir chips made from veneer are 184 kg/m³ (11.5 lb/ft³). White fir and pine chips are about 168 kg/m³ (10.5 lb/ft³), and those of redwood are about 160 kg/m³ (10 lb/ft³). A rule of thumb is that 1 m³ of wood yields about 2.6 m³ of chips (1 ft³ yields about 2.6 ft³).

Bone dry unit, BDU

A bone dry unit is the equivalent of 2400 lb of oven-dry chips, sawdust, or other wood particles. A BDU of packed Douglas-fir chips occupies approximately 200 cu. ft.

Unit

A unit is 200 cu. ft. of wood chips, sawdust, or other wood particles. A 40 foot open-top chip truck carries about 18 units. One unit of Douglas-fir or western hemlock chips is about

Table 2-2. Approximate conversion factors of wood of 0.45 specific gravity in various forms (for 85 ft³ of solid wood per cord and 2.6 ft³ of chips per ft³ of solid wood). Entries with five significant digits are exact for any wood. Conversion factors for wood varying from these parameters should be calculated for individual situations. Board feet values do not include sawing loses.

Convert from↓	Convert to↓ by multiplication						
	m ³ stacked wood	m ³ of solid wood	MT of bone dry wood	m ³ of wood chips			
1000 board ft	3.55	2.3598	1.06	6.1			
cord	3.6247	2.41	1.08	6.3			
cunit	4.26	2.8318	1.27	7.4			
BDU	3.64	2.42	1.0886	6.3			
unit	3.28	2.18	0.98	5.6636			
ft ³ chips	0.0164	0.0109	0.0049	0.028318			

0.85 cords of logs or 67 ft^3 of solid wood. One unit of Douglas-fir or western hemlock sawdust is about 80 ft^3 of solid wood.

Table 2-3. Typical compositions of NorthAmerican woods (percent).

	<u>Hardwoods</u>	Softwoods
Cellulose	40-50	45-50
Hemicelluloses		
(Galacto)glucomannans	2-5	20-25
Xylans	15-30	5-10
Lignin	18-25	25-35
Extractives	1-5	3-8
Ash	0.4-0.8	0.2-0.5

Table 2-4. The ultimate analysis of NorthAmerican woods in percent.

Carbon	С	49.0-50.5	%
Oxygen	Ο	43.5-44.5	%
Hydrogen	н	5.8- 6.1	%
Nitrogen	Ν	0.2- 0.5	%

Physically, cellulose is a white solid material that may exist in crystalline or amorphous states. Cellulose in wood is about 50-70% crystalline and forms the "back-bone" structure of a wood fiber.

2.6 WOOD CHEMISTRY

The composition of hardwoods and softwoods by the class of compounds is given in Table 2-3. The ultimate (elemental) analysis of wood is given in Table 2-4.

Lignin is more highly concentrated in the middle lamella and primary cell wall regions of the wood fiber than any other part of the cell wall. Most of the lignin, however, is actually in the secondary cell wall since the secondary cell wall accounts for most of the mass of the fiber. The concentration of the major components with varying cell wall position is shown in Fig. 2-21.

Cellulose

On the molecular level, cellulose is a linear polymer of anhydro-D-glucose connected by β -(1-4)-linkages as shown in Fig. 2-22. The *degree of polymerization* (DP), which is the number of units (glucose in this case) that make up the polymer, is above 10,000 in unaltered (so-called "native") wood, but less than 1000 in highly bleached kraft pulps.



Fig. 2-21. Typical composition of a conifer fiber across its cell wall. From Krahmer, R.L. and Van Vliet, A.C., Eds., *Wood Technology and Utilization*, O.S.U. Bookstores, Corvallis, Oregon 1983.



Fig. 2-22. The primary structure of cellulose.

Cotton is about 95% crystalline cellulose. The crystalline form of cellulose is particularly resistant to chemical attack and degradation. Hydrogen bonding between cellulose molecules results in the high strength of cellulose fibers.

Microfibrils are aggregations of cellulose molecules into thread-like structures approximately 3.5 nm in diameter, containing both crystalline and amorphous regions. Microfibrils occur in the secondary cell wall. Microfibrils are oriented in different directions in each of the three layers within the secondary cell wall; the fibril angle is measured from the longitudinal axis of the cell.

Hemicellulose(s)

Hemicellulose(s) are actually a class of materials. The plural form should be used to describe them generically, but the singular form should be used to describe a particular type such as the hardwood xylan hemicellulose. Physically, hemicelluloses are white solid materials that are rarely crystalline or fibrous in nature; they form some of the "flesh" that helps fill out the fiber. Hemicelluloses increase the strength of paper (especially tensile, burst, and fold) and the pulp yield, but are not desired in dissolving pulps. (Dissolving pulps are relatively pure forms of cellulose used to make cellulose-based plastics.) Starch is often added to pulp to increase the strength of paper and probably has a very similar mechanism of effect as the hemicelluloses.

Hemicelluloses chemically are a class of polymers of sugars including the six-carbon sugars mannose, galactose, glucose, and 4-O-methyl-D-glucuronic acid and the five-carbon sugars xylose and arabinose. The structures of these monosaccharides are shown in Fig. 2-23. (Pectin, a related compound, occurs to a small degree in the middle lamella, especially in the pith and young tissue, and consists of polygalacturonic acid.) Hemicelluloses are condensation polymers with a molecule of water removed with every linkage. All of the monosaccharides that make up the hemicelluloses have the D configuration and occur in the six-member pyranoside forms, except arabinose, which has the L configuration and occurs as a five-member furanoside. The number average DP is about 100-200 sugar units per hemicellulose molecule.

Hemicelluloses are much more soluble and labile, that is, susceptible to chemical degradation, than is cellulose. They are soluble in 18.5% NaOH (which is the basis of their measurement in Tappi Test Method T203). Low molecular weight hemicelluloses become soluble in dilute alkali at elevated temperatures, such as in kraft cooking. Hemicelluloses are essentially linear polymers except for single-sugar side chains and acetyl substituents. Hemicellulose chemistry is described below; representative hemicellulose structures are shown in Fig. 2-24.

Softwood hemicelluloses

Galactoglucomannans are polymers of glucose and mannose in the backbone linked by β -(1-4) bonds with galactose units as side chains connected by α -(1-6) bonds. Acetylation is also present. The ratio of glucose:mannose:galactose: acetyl groups is on the order of 3:1:1:1, respectively. Galactoglucomannans make up about 6% of the weight of softwoods.

Glucomannans have structures analogous to galactoglucomannans, but with about 90% of the galactose units replaced by mannose units. They make up 10-15% of the weight of softwoods.

Xylans or arabinoglucuronoxylans are found in all land based plants and have a backbone of poly- β -(1-4)xylose; corncobs are highly concentrated in xylans. In softwoods, side chains of α -(1-3) linked arabinose and (1-3) linked 4-Omethylglucuronic acid occur. The ratio of xylose to 4-O-methylglucuronic acid to arabinose is 4-7:1:>1. These xylans have a DP of 100-120, lack acetyl groups, and make up 5-10% of their mass.

Arabinogalactans are composed of poly- β -(1- \rightarrow 3)-galactose with numerous (1- \rightarrow 6) arabinose and galactose side chains (side chains of DP 2 or less are common) and an overall DP of 200. The ratio of galactose to arabinose is 6:1 in western larch. They occur at about 1% in most softwoods, but compose 5-30% of the weight of larch species. In larch they occur as two types: the first with a DP of 80-100 and the second with a DP of 500-600. Arabinoxylans are water-soluble, unlike other hemicelluloses, and for this reason they are occasionally classified with the extractives.

Hardwood hemicelluloses

Glucuronoxylans (xylans) are the principal hemicellulose of hardwoods. Side branches of 4-O-methylglucuronic acid are linked by α -(1 \rightarrow 2) linkages. The ratio of xylose to 4-Omethylglucuronic acid is typically 7:1 but varies from 3-20:1. About 70-80% of the xylose units are acetylated at the C-2 or C-3 positions. These xylans have a DP of 40-200 (typically 180) and make up 15-30% of hardwoods.

Glucomannans have a backbone of β -(1->4) linked glucose and mannose groups in a 1:1 to 2:1 ratio with very small amounts of acetylation and a DP of 40-100. They occur at 2-5%.

Implications of hemicellulose chemistry

The carboxylic acid groups (RCOOH) of 4-O-methylglucuronic acid residues of xylans contribute to hemicellulose acidity, presumably contribute to hemicellulose solubility under alkaline conditions (by the formation of carboxylate salts), and, contribute to the ease of rosin sizing (hardwoods, containing more xylans, are easier to size with alum and rosin than softwoods). The 4-Omethyl-glucuronic acid groups tend to be preferentially removed during alkaline pulping either by selective cleavage or, if they are not evenly distributed among the xylans, by selective solubilization.

Acetyl groups are saponified (hydrolyzed to give free acetic acid) very quickly under alkaline conditions. The free acetic acid consumes a significant portion of the alkali used during kraft cooking. Typically softwoods have 1-2% acetyl groups, while hardwoods have 3-5%.

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Fig. 2-23. The principal monosaccharides of wood hemicelluloses.

Softwood galactoglucomannans: O-Acetylgalactoglucomannans (p is 6 member pyranose ring)

Softwood xylans: Arabino-4-O-methylglucurononxylan (f is 5 member furanose ring)

$$\begin{array}{ccc} -\beta \text{-D-Xyl}p\text{-}(1 \rightarrow 4) - \beta \text{-}D\text{-}Xylp\text{-}(1 \rightarrow 4) - \beta \text{-}D\text{-$$

Hardwood glucomannans:

Hardwood xylans: O-acetyl-4-O-methylglucuronoxylan

$$-\beta - D - Xylp - (1 \rightarrow 4) - \beta - D - Xylp - (1$$

Fig. 2-24, Representative structures of the predominant hemicelluloses.



Fig. 2-25. Lignin precursors for plants. Softwoods have coniferyl alcohol, while hardwoods have coniferyl and sinapyl alcohols.



Fig. 2-26. Formation of free radicals from coniferyl alcohol. *Positions where the free radical occurs in resonance structures.

Lignin

Lignin is a complex polymer consisting of phenylpropane units and has an amorphous, threedimensional structure. It is found in plants. Its molecular weight in wood is very high and not easily measured. Lignin is the adhesive or binder in wood that holds the fibers together. Lignin is highly concentrated in the middle lamella; during chemical pulping its removal allows the fibers to be separated easily. The glass transition temperature (softening temperature) is approximately 130-150°C (265-300°F). Moisture (steam) decreases the glass transition temperature slightly.

There are three basic lignin monomers that are found in lignins (Fig. 2-25.) Grasses and straws contain all three lignin monomers, hardwoods contain both coniferyl alcohol (50-75%) and sinapyl alcohol (25-50%), and softwoods contain only coniferyl alcohol.

Using coniferyl alcohol as an example, the first step of lignin polymerization in the plant cell

wall involves formation of a free radical at the phenolic hydroxyl group (Fig. 2-26). This structure has five resonance structures with the free radical occurring at various atoms as shown on the right of Fig. 2-26. Carbon atoms C-1 and C-3 in softwoods and C-1, C-3 and C-5 in hardwoods do not form linkages due to steric hindrance (crowding). Carbon atoms of the propane unit are labelled from the aromatic ring outward as α , β , and γ , respectively. Carbon atoms of the aromatic ring are labelled from the propane group towards the methoxy group from 1 to 6, respectively. Some commonly occurring lignin linkages are also shown in Fig. 2-27. A "representative" lignin molecule is shown in Fig. 2-28.

Extractives

Extractives are compounds of diverse nature with low to moderately high molecular weights, which by definition are soluble (extracted) in organic solvents or water. They impart color, odor, taste, and, occasionally, decay resistance to wood. There are hundreds of compounds in the extractives of a single sample of wood. The composition of extractives varies widely from species to species and from heartwood to sapwood. Heartwood has many high molecular weight polyphenols and other aromatic compounds not found in sapwood, and these give the heartwood of many species (such as cedar and redwood) their dark color and resistance to decay. Some classes of extractives (Figs. 2-29 to 2-31) important to the pulp and paper industry are described with representative compounds.

Terpenes are a broad class of compounds appearing in relatively high quantities in the softwoods, where they collect in the resin ducts of those species with resin ducts. Species such as pines have large amounts of terpenes. Mills pulping highly resinous species with the kraft process collect the terpenes and sell them. Hardwoods have very small amounts of the terpenes.

Terpenes are made from phosphated isoprene units (Fig. 2-29) in the living wood cells. It is usually very easy to identify the individual isoprene building blocks of a terpene. Isoprene has the empirical formula of $C_{5}H_{8}$, monoterpenes have the empirical formula of $C_{10}H_{16}$, sesquiterpenes are $C_{15}H_{24}$, and the resin acids are oxygenated diter-

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4-*O*-*β*-aryl ether linkage

4-0-α-aryl ether linkage



Fig. 2-27. Example linkages between lignin monomers.



Fig. 2-28. A hypothetical depiction of a portion of a softwood lignin molecule.





Fig. 2-31. Examples of fatty acids with 18 carbon atoms in wood.

penes and have the empirical formula of $C_{20}H_{32}O_2$. Higher terpenes are also found. Oxygenated terpenes with alcohol and ketone groups become prevalent with exposure to air, as in the case of pine stumps. *Turpentine* consists of the volatile oils, especially the *monoterpenes* such as α - or β - pinene; these are also used in household pine oil cleaners that act as mild disinfectants and have a pleasant aroma. (According to the *Merck Index*, α -pinene from North American woods is usually the dextrorotary type, whereas that of European woods is of the levorotatory type.) Because

turpentine consists of volatile compounds, it is recovered from the vent gases given off while heating the digester. *Resin acids* such as abietic and pimaric acids, whose structures are shown in Fig. 2-30, are used in rosin size and are obtained in the *tall oil* fraction.

The triglycerides and their component fatty acids are another important class of extractives. Triglycerides are esters of glycerol (a trifuntional alcohol) and three fatty acids. Most fatty acids exist as triglycerides in the wood; however, triglycerides are saponified during kraft cooking to liberate the free fatty acids. (Saponification is the breaking of an ester bond by alkali-catalyzed hydrolysis to liberate the alcohol and free carboxylic acid. Saponification of triglycerides is how soap is made; this is how the reaction got its name. Sodium based soaps are liquids; potassium based soaps are solid.)

The principal components are the C-18 fatty acids with varying amounts of unsaturation, that is, the presence of carbon-carbon double bonds, whose structures are shown in Fig. 2-31. [Polyunsaturated fats, a term used to describe "healthy" food fats, are fatty acids (or triglycerides containing fatty acids) with two or three carbon-carbon double bonds like linoleic or linolenic acids.] Stearic acid is the saturated (with no double bonds) C-18 fatty acid. Other fatty acids, mostly with even numbers of carbon atoms, may be present as well depending on the species of wood.

Just as animal triglycerides (fats) contain small amounts of cholesterols, plant fats contain small amounts of *sterols* that are very similar to the cholesterols' structures. One example is β sitosterol. *Fatty acids* and *resin acids* constitute the *tall oil* fraction recovered during black liquor evaporation by skimming the surface. The resin acids are separated by fractional distillation.

Phenolic compounds are more common in heartwood than sapwood and are major constituents in the bark of many wood species. In a few species these compounds can interfere with bisulfite pulping; for example, dihydroquercetin (Fig. 2-30) interferes with sulfite pulping of Douglas-fir. These compounds contain C_6 aromatic rings with varying amounts of hydroxyl groups. Some classes of these compounds are the *flavonoids*, which have a $C_6C_3C_6$ structure; the *tannins*, which are water-soluble; polyflavonoids and other polyphenol compounds that are used to convert animal hides into leather; and the *lignans*, which have two phenyl propane units ($C_6C_3-C_3C_6$) connected between the β -carbon atoms.

Ash

Ash consists of the metallic ions of sodium, potassium, calcium, and the corresponding anions of carbonate, phosphate, silicate, sulfate, chloride, etc. remaining after the controlled combustion of wood. Wood ash is sufficiently alkaline so that when added to triglycerides it can be used to make soap; this was practiced by many cultures for centuries using animal fats.

Holocellulose

Holocellulose is a term for the entire carbohydrate fraction of wood, i.e., cellulose plus hemicelluloses.

Alpha cellulose

Alpha cellulose is a fraction of wood or pulp isolated by a caustic extraction procedure. While generally it is considered to be "pure" cellulose, actually it is about 96-98% cellulose.

Cellulose polymers and derivatives

Cellulose polymers (Fig. 2-32) are made from *dissolving* pulp. They include cellulose xanthate (a bright orange colored solution formed by reaction of alkali cellulose with carbon disulfide, which is an intermediate product that, upon acidification forms regenerated cellulose such as cellophane, rayon, and meat casings), cellulose acetate (a plastic used in films, eyeglass frames, cigarette filters, etc.), cellulose nitrate (smokeless powder, which replaces gunpowder in certain carboxymethyl applications), cellulose (a water-soluble thickener and dispersant), and methyl cellulose (a thickener and plastic).

Chemical analysis of wood

Wood is usually ground to 40 mesh (0.6 mm) before chemical analysis. Various chemical analyses of wood are covered in the TAPPI Standards. T 246 describes preparation of wood for chemical analysis including extraction with neutral solvents, such as ethanol and benzene, to remove the wood extractives. (If one is doing wood extractions I highly recommend using toluene in place of

Fig. 2-32. Commercial cellulose-based polymers.					
	Regeneration:	ROCSS $Na^+ + H^+ \rightarrow ROH + CS_2 + Na^+$			
Xanthation:	Formation:	$ROH + CS_2 + NaOH \rightarrow ROCSS^{-}Na^{+} + H_2O$			
	Carboxymethylation:	$ROH + ClCH_2COOH/NaOH \rightarrow ROCH_2COO^- Na^+$			
Etherification:	Methylation:	$2 \text{ ROH} + (\text{CH}_3)_2 \text{SO}_4/\text{NaOH} \rightarrow 2 \text{ ROCH}_3 + \text{H}_2 \text{SO}_4$			
	Acetylation:	$ROH + Ac_2O/HAc/H_2SO_4 \rightarrow ROCOCH_3 + H_2O$			
Esterification:	Nitration:	$ROH + HNO_3/H_2SO_4 \rightarrow RONO_2 + H_2O$			

benzene; benzene is harmful and toxic. The difference in results will be negligible!)

After acid hydrolysis of the cellulose and hemicellulose, the monosaccharides can be measured by chromatography. T 250 is an archaic method of monosaccharide analysis by paper chromatography. T 249 uses gas chromatography to separate and measure the monosaccharides, but much faster and better methods have been developed. (See Section 34.4 for the reference on carbohydrate analysis.) Pentosans in wood and pulp are measured by T 223; the pentoses are converted to furfural which is measured colorimetrically. The solubility of wood or pulp with 1% sodium hydroxide, T 212, is a measure of hemicellulose and cellulose degraded by decay, oxygen, chemicals, etc.

2.7 WOOD AND FIBER PHYSICS

Equilibrium moisture content

Because wood and paper are hygroscopic materials, when fully dried they adsorb water vapor from the atmosphere. The equilibrium moisture content of wood or wood pulp depends on the temperature and relative humidity of the atmosphere surrounding the specimen. Relative humidity is the partial pressure of water vapor divided by the maximum water vapor pressure of saturation at the same temperature.

Fiber saturation point, FSP

The fiber saturation point represents the

moisture content of a lignocellulosic material such that additionally adsorbed water is not chemically absorbed to the wood. This occurs at about 30% MC_{OD} (at room temperature) in wood. For example, wood taken at room temperature and 99% relative humidity will have a moisture content approaching 30%. At lower humidities the equilibrium moisture content will be lower. Chemically adsorbed water requires additional energy to remove it from wood beyond the water's heat of vaporization.

Shrinkage

Wood shrinks and swells as a function of moisture content. Above the fiber saturation point there is no change in wood dimensions according to moisture content, but as wood dries below the FSP, it shrinks. Since the microfibrils are almost parallel to the longitudinal axis of the fiber in the thick S2 cell wall layer, and since water molecules do not increase the length of microfibrils but are added between them, there is very little shrinkage in the longitudinal direction, but about 4% shrinkage in the radial direction and 6% in the tangential direction. The difference in shrinkage between the radial and tangential directions occurs due to orientation of microfibrils around the cell wall pits and other factors.

Uneven grain orientation may cause severe warping or fracturing of lumber and furniture dueto tremendous stresses that develop from uneven shrinkage as the wood dries.



Fig. 2-33. Fiber strength versus S-2 fibril angle. (60% yield, kraft spruce fibers.) After Page, et al, 1972.

Fiber strength

Fiber strength is the strength of an individual fiber. Using small test devices, the strength of individual fibers can be measured. Paper strength can be viewed as a trade off between the strength of individual fibers and the strength of interfiber bonding (the strength of the bonds between fibers that hold them together). In unrefined pulp, the "weak link" in the paper strength is fiber-fiber bonding. In pulp which is overly refined, the weak link often becomes the strength of the individual fibers. Thus, with increased refining the properties influenced by interfiber bonding (tensile and burst) increase and the properties mostly influenced by fiber strength (tear) decrease.

The situation becomes more complicated if we consider the microfibril angle of the S-2 cell wall layer. Fig 2-33, after the work of Page, et al (1972), shows that the tensile strength of individual fibers in the longitudinal direction depends principally on the S-2 fibril angle (in the absence of fiber defects, etc.), and that the tensile strength decreases rapidly with increasing fibril angle. This work also showed that the fibril angle of latewood tends to be lower than that of earlywood in spruce, and the latewood fibers were stronger than the early wood fibers, which has been reported in the literature with other species as well. (Black spruce also tends to have a lower fibril angle than white spruce; this indicates that the average fibril angle of wood species is as important as the average fiber length.) The authors concluded "fibres of the same fibril angle have similar strength, independent of species." The maximum fiber tensile strength of 17,000 N/cm² corresponds to a breaking length of over 100 km, or about 10 times stronger than paper!

Fiber bonding in paper, hydrogen bonding

In paper, fibers are held together by hydrogen bonding of the hydroxyl groups of cellulose and hemicelluloses. The carboxylic acid groups of hemicelluloses, also play an important role. Water interferes with hydrogen bonding between fibers: thus, paper losses much of its strength when wet. Hemicelluloses increase the strength of paper, while lignin on the surface of fibers, which is not able to form hydrogen bonds, decreases the strength of paper. Using water in the formation of paper greatly increases its strength as capillary action of water pulls the fibers together, and may partially solubilize the carbohydrates, so hydrogen bonding can occur. There are no methods available for dry formation of paper with appreciable strength, although such a process could make papermaking much more economical.

Hydrogen bonding holds lignocellulosic fibers together in paper. The strength of R-OH--R-OH hydrogen bonding is 3-4 kcal/mol. This is relatively weak compared to covalent bonds, which are on the order of 100 kcal/mol. However, the large number of potential hydrogen bonds along the length of the holocellulose molecules means that paper can be quite strong. Modification of hydroxyl groups by acetylation, methylation, etc. prevents hydrogen bonding and decreases the strength of paper dramatically. Also, paper made from a slurry in a solvent of low polarity is weak as the formation of hydrogen bonds is hindered.

Factors which increase the fiber surface area (or the area of fiber to fiber contact) increase interfiber bonding. Refining tends to allow the interfiber bonding to increase by fibrillation (increasing the surface area) and hydration of fibers (making them more flexible to mold around each other better), but the strength of the individual fibers decreases. More information on fiber physics is found in Sections 17.8-17.10.

2.8 PROPERTIES OF SELECTED WOOD SPECIES

This section presents wood properties of selected wood species. Much of the information presented here is from the reports of the U.S. Department of Agriculture Forest Product Laboratory (USDA-FPL) in Madison, Wisconsin, These reports are very useful to demonstrate wood properties and variability in individual species of Remember that there is considerable wood. variation in wood properties and, therefore, reported wood properties! Table 2-5 and Table 2-6 show the average fiber lengths, basic densities, basic specific gravities (oven dry weight divided by green volume), and chemical pulp yields for softwoods and hardwoods, respectively. The data are from "Pulp yields for various processes and wood species", USDA For. Ser., FPL-031 (Feb., 1964), which is a slight revision of "Density, fiber length, and yields of pulp for various species of wood", Tech. Note No. 191 (1923).

Table 2-7 and Table 2-8 show chemical compositions, basic specific gravities, and select-

ed solubilities for softwoods and hardwoods, respectively. The data is from the USDA-FPL.

2.9 NONWOOD AND RECYCLED FIBER CONSIDERATIONS

Recycled or secondary fiber

Recycled fiber is fiber whose source is paper or paperboard arising outside of the mill. It is distinguished from *broke*, which is off-specification paper produced and reused within the mill. Recycled fiber is obtained from recycled paper.

It is very important to have "pure" sources of paper from which to make recycled fiber. Newspapers should not be contaminated with magazines and brown paper and boxes. Office papers should not be contaminated with newsprint or brown papers. For example, mixed waste paper is worth about \$10-20/ton while clean paper clippings from an envelope factory are worth over \$250/ton. In the U.S. almost 30% of the paper consumed in 1989 was recycled. This compares to a recovery rate of 50% in Japan, one of the highest rates. Other developed nations tend to have higher recovery rates than the U.S.

Species	Scientific name	Aver. fiber length (mm)	Dens. lb/ft ³	Spec. Grav.	<u>Pulp y</u> Kraft	ield, % ¹ Sulfite
Baldcypress	Taxodium distichum	6.00	26	0.42	48	46
Cedar:						
Atlantic white	Chamaecyparis thyoides	2.10	19	0.30	45	
Eastern redcedar	Juniperus virginiana	2.80	27	0.43	45	
Incense	Libocedrus decurrens	2.00	22	0.35	45	40
Port-Orford	Chamaecyparis lawsoniar	ia 2.60	25	0.40	45	45
Western redcedar	Thuja plicata	3.80	19	0.30	40	43
Douglas-fir, coastal	Pseudotsuga menziesii	4.50	28	0.45	48	48
Fir:	2					
Balsam	Abies balsamea	3.50	21	0.34	50	47
California red	A. magnifica	3.25	23	0.37	48	48
Grand	A. grandis	5.00	23	0.37	48	49
Noble	A. procera	4.00	22	0.35	47	48
Pacific silver	A. amabilis	3.55	22	0.35	49	49
Subalpine	A. lasiocarpa	3.15	21	0.34	48	48
White	A. concolor	3.50	22	0.35	48	48

Table 2-5. Basic pulping properties of U.S. softwoods. From USDA FPL-031 (1923, 1964).

¹Screened yield for nonbleachable kraft (for bleachable subtract 2-3%) and bleachable sulfite.

Species	Scientific name	Aver. fiber length (mm)	Dens. lb/ft ³	Spec. Grav.	<u>Pulp y</u> Kraft	<u>ield, %1</u> Sulfite	
Hemlock:							
Carolina	Tsuga caroliniana	3.10	30	0.48	45	48	
Eastern	T. canadensis	3.50	24	0.38	45	44	
Mountain	T. mertensiana	3.70	26	0.42	45		
Western	T. heterophylla	4.00	24	0.38	47	46	
Larch:							
Tamarack	Larix laricina	3.50	31	0.50	48	42	
Western	L. occidentalis	5.00	32	0.51	48	42	
Pine:							
Jack	Pinus banksiana	3.50	25	0.40	48	45	
Loblolly	P. taeda	4.00	29	0.46	48	45	
Lodgepole	P. contorta	3.50	24	0.38	48	45	
Longleaf	P. palustris	4.00	34	0.54	48	45	
Monterey	P. radiata	2.60	29	0.46	48	45	
Ponderosa	P. ponderosa	3.60	45	0.72	48	45	
Red	P. resinosa	3.70	26	0.42	48	45	
Shortleaf	P. echinata	4.00	29	0.46	48	45	
Slash	P. elliottii	4.00	35	0.56	48	45	
Sugar	P. lambertiana	4.10	22	0.35	48	45	
Virginia	P. virginiana	2.80	28	0.45	48	43	
White, eastern	P. strobus	3.70	21	0.34	48		
White, western	P. monticola	4.40	23	0.37	48	45	
Redwood	Sequois sempervirens	7.00	24	0.38	38		
Spruce:							
Black	Picea mariana	3.50	24	0.38	50	48	
Blue	P. pungens	2.80	23	0.37	43	48	
Englemann	P. engelmannii	3.00	20	0.33	47	48	
Red	P. rubens	3.70	24	0.38	50	48	
Sitka	P. sitchensis	5.50	23	0.37	47	48	
White	P. glauca	3.50	23	0.37	50	48	

Table 2-5. Basic pulping properties of U.S. softwoods. Continued.

¹Screened yield of nonbleachable kraft (for bleachable subtract 2-3%) and bleachable sulfite.

Species	Scientific name	Aver. fiber length (mm)	Dens. lb/ft ³	Basic Spec. Grav.	<u>Pulp y</u> Kraft	ield, % ¹ Sulfite
Ailanthus	Ailanthus, altissima	1.20	23	0.37		
Alder, red	Alnus, rubra	1.20	25	0.40	50	
Ash, green	Fraxinus pennsylvanica	1.05	33	0.53	44	
Ash, white	F. americana	1.20	34	0.54		47
Basswood, American	Tilia americana	1.20	20	0.32		
Beech, American	Fagus grandifolia	1.20	35	0.56	49	44
Birch, paper	Betula papyrifera	1.20	30	0.48	50	46
Birch, yellow	B. alleghaniensis	1.50	34	0.54	53	45
Buckeye, Ohio	Aesculus glabra	0.90	21	0.34		47
Butternut	Juglans cinerea	1.20	22	0.35		47
Chestnut, American	Castanea dentata	1.00	25	0.40		42
Cucumber tree	Magnolia acuminata	1.30	27	0.43		45
Elm, American	Ulmus americana	1.50	29	0.46	46	
Elm, rock	U. thomasii	1.30	36	0.58		47
Elm, slippery	U. rubra	1.70	30	0.48		47
Hickory, mockernut	Carya tomentosa	1.40	40	0.64	48	40
Hickory, shagbark	C. ovata	1.35	40	0.64		
Mangrove	Rhizophora mangle	1.40	55	0.88		
Maple, red	Acer rubrum	1.00	31	0.50	43	45
Maple, silver	A. saccharinum	1.75	28	0.45		
Maple, sugar	A. saccharum	1.10	35	0.56	43	45
Oak, blackjack	Quercus marilandica	1.00	40	0.64	42	41
Oak, chestnut	Q. prinus	1.35	36	0.58	45	
Oak, northern red	Q. rubra	1.40	35	0.56	46	45
Oak, overcup	Q. lyrata	1.35	36	0.58	46	
Oak, post	Q. stellata	1.50	37	0.59		45
Poplar:						
aspen, quaking	Populus tremuloides	1.20	22	0.35	54	52
aspen, bigtooth	P. grandidentata	1.20	22		50	
balsam	P. balsamifera	1.00	19	0.30	50	49
cottonwood, eastern	P. deltoides	1.30	23	0.37	52	52
cottonwood, swamp	P. heterophylla	1.30	24	0.38	47	47
Sugarberry	Celtis laevigata	1.10	29	0.46	46	44
Sweetgum	Liquidambar styraciflua	1.60	29	0.46	50	46
Sycamore, American	Platanus occidentalis	1.70	29	0.46		47
Tupelo, black	Nyssa sylvatica var. sylvatica	1.70	29	0.46	48	48
Tupelo, swamp	N. sylvatica var. biflora	1.70	34	0.54	48	46
Tupelo, water	N. aquatica	1.60	29	0.46		47
Willow, black	Salix nigra	1.00	24	0.38	52	52
Yellow-poplar	Liriodendron tulipifera	1.80	24	0.38	47	47

Table 2-6. Basic pulping properties of U.S. hardwoods. From USDA FPL-031 (1923,1964).

¹Screened yield of nonbleachable kraft (for bleachable subtract 2-3%) and bleachable sulfite.

Species location	Sample	Basic	Chemical composition, %				Solubility		
average diameter	Ave. Age Years	Spec. Grav.	Holo– cellul.	Alpha cellul.	Lignin	Total pento- sans	Hot, 1% NaOH	EtOH- Benzene	
Cedar:					-				
Western red, res., west.US, 24.5"	205	0.306	48.7	38.0	31.8	9.0	21.0	14.1	
Douglas-fir, Oregon, old growth, residues		0.439	67.0	50.4	27.2	6.8	15.1	4.5	
Oakridge, Ore, second growth, residues			69.9	52.6	28.0	4.9	9.7		
Wyoming, US, 7.8"	182	0.417	65.7	46.9	27.2	6.5	15.8	5.2	
Fir:									
Balsam, Mich. US, 6.5"	48	0.330		42.2	28.5	10.8	11.1	3.5	
Pacific silver, res., west, US, 19.6"	1 69	0.385	60.7	43.2	30.5	9.2	10.8	2.6	
Subalpine, Mont, US, 6.4"	44	0.304	67.1	44.2	29.6	8.9	11.5	2.2	
White, Calif. US		0.363	65.5	49.1	27.8	5.5	12.7	2.1	
Hemlock:									
Eastern		0.38	68	43	32	10	13		
Western, Washington, US			66.5	50.0	29.9	8.8	18.1	5.2	
Larch:									
Tamarack, Wisconsin, US, 4.7"	43	0.491	60.4	43.3	25.8	8.6	18.2	3.6	
Western, Washington, US, 5.4"	53	0.514	66.5	50.0	26.6	7.8	13.4	1.4	
Pine:									
Jack, Wisconsin, US		0.43	67.0	47.0	27.0	9.1	13.5	3.5	
Lobiolly, Arkansas, US		0.45		48.7	27.7	8.9	12.0	2.7	
Lodgepole, Montana, U.S.									
Sound, 5.1", little decay	25	0.373	68.8	44.3	26.7	10.3	12.8	3.0	
Sound, 7.4", little decay	135	0.415	71.6	47.3	25.9	10.9	11.6	2.8	
Insect-killed, 8.9", some decay	109	0.400	65.1	44.1	26.5	9.2	1 4.9	4.2	
" ", Down, 9.2", sig. decay	112	0.429	67.9	45.2	27.9	10.0	12.9	3.1	
Ponderosa, 4.9", 1.9% heartwood	39	0.40	67.7	45.0	25.1	10.2	13.4	5.6	
Red		0.43			24	11			
Shortleaf, Ark., US, 6.0"	27	0.49	69.3	48.5	27.6	8.9	12.2	3.3	
Slash, thinnings, Louis., US, 3.9"	10	0.484	64.7	47.2	28.5	9.1	11.5	3.2	
White, eastern, Maine, US, 8.6"	38	0.336	66.3	43.9	26.1	6.6	15.9	5. 9	
White, western, Idaho, US			73.8	50.4	25.4	7.8	11.3	2.9	
Redwood, Calif. US, oldgrowth		0.358	55.1	42.6	33.4	7.2	18.8	9.9	
" " second growth		0.344	60.5	45.7	33.1	7.2	13.9	0.4	
Spruce:									
Black, Michigan, US, 6.5"	49	0.392		43.1	26.8	11.4	11.4	1.8	
Englemann, Colorado, 13.6"	169	0.333	67.3	45.2	28.2	7.4	11.6	1.7	
Red		0.38	73	43	27	12			
White		0.38	73	44	27	11	12		

Table 2-7. Chemical composition of softwoods.

Species, location,	Sample	Basic	Cl	hemical co	mposition, '	%	Solu	ıbility
average diameter	Ave. Age Years	Spec. Grav.	Holo cellul.	Alpha cellul.	Lignin	Total pento– sans	Hot, 1% NaOH	EtOH- Benzene
Alder, red, Washington US, 7.8"	21	0.385	70.5	44.0	24.1	19.2	17.3	1.9
Ash, green, Ark., US, 10.2"	46	0.519		41.0	25.3	16.5	18.4	5.5
Ash, white		0.56						
Birch, paper, New York, US		0.49	78.0	46.9	20.5	21.8		
Birch, yellow		0.55						
Elm, American, Ark., US, 13.7"	56	0.470		46.9	24.3	18.1	16.7	2.6
Eucalyptus								
E. saligna, Brazil, 5", fibers 0.87 mm		0.546	72.3	49.7	25.3	14.7	13.3	1.7
E. kertoniana, ", 4.5", fibers 0.93 mm		0.513	74.3	50.3	28.1	15.0	13.6	1.5
E. robusta, Puerto Rico,		0.490	66.6	47.7	27.5	16.2	12.2	2.1
Hickory, mockernut, N.C.US, 7.2"	65	0.676	69.8	45.0	18.9	16.4	18.5	5.1
Hickory, shagbark, N.C. US, 4.4"	29	0.703	71.3	48.4	21.4	18.0	17.6	3.4
Maple, red, Mich. U.S.		0.45	77. 6	48.6	20.6	18.3	15.9	3.0
Maple, sugar, Mich. U.S.				49.2	21.5	18.6	16.7	
Oak, blackjack, Ark., US, 5.6"	48	0.635		43.9	26.3	20.1	15.0	3.5
Oak, northern red, Mich. US, 5.9"	36	0.582	69.1	46.0	23.9	21.5	21.7	5.2
Oak, white, Virginia, US, 5.4"	41	0.616	62.6	46.1	27.7	18.4	19.8	3.0
Michigan, 7.3"	69	0.613	72.2	47.5	25.3	21.3	19.0	2.7
Poplar:								
aspen, quaking, Wisc. US		0.35	78.5	48.8	19.3	18.8	18.7	2.9
cottonwood, eastern		0.37		46	24	19	15	
Sugarberry, Ark., US, 9.9"	47	0.489		40.2	20.8	21.6	22.7	3.1
Tanoak, Calif. US, 11.3"	99	0.601	70.4	45.2	19.0	18.3	18.9	2.0
Tupelo, black, Miss. US, 6.3"		0.513	71.7	48.1	26.2	14.5	12.8	2.3
Willow, black, Ark., US, 15.5"	28	0.377		46.6	21.9	18.8	17.4	2.2
Yellow-poplar		0.40		45	20	19	17	

Table 2-8. Chemical composition of hardwoods.

REFERENCES FOR TABLES 2-7 AND 2-8.

PP-110, Physical characteristics and chemical analysis of certain domestic hardwoods received at the Forest Products Laboratory for Pulping from October 1, 1948, to November, 1957. PP-112, Physical characteristics and chemical analysis of certain domestic pine woods received at the Forest Products Laboratory for Pulping from October 1, 1948, to September 4, 1956. PP-114, Physical characteristics and chemical analysis of certain softwoods (other than pine) received at the Forest Products Laboratory from October 1, 1948, to August 7, 1947.

Details of some wood samples (with four digit FPL shipment numbers) were obtained from reports. Occasionally, missing numbers have been filled in from other FPL reports that were used to verify the plausibility of numbers, when available. Softwoods: Douglas-fir residues, old growth ship. 2655 and second growth ship. 2467, Rep. no. 1912 (Rev. July, 1956). Lodgepole pine, ship. 2414–2417, 2434, Rep. no. R1792 (June, 1951). Ponderosa pine sample was 20% w/w, 21% v/v, bark as received, Rep. no. R1909 (Oct., 1951). Pacific silver fir sawmill residues, ship. 2128, heartwood was 16.1" diameter, Rep. no. R1641 (Feb., 1947). Western redcedar sawmill residues, ship. 2132, heartwood was 22.7" diameter, Rep. no. R1641 (Feb., 1947). Eastern hemlock, red pine, red spruce, and white spruce, Rep. no. 1675 (Rev. Nov., 1955).

Hardwoods: Red alder, ship. 3050, Rep. no. 1912 (Revised, July, 1956). Black willow, American elm, sugarberry, green ash, and blackjack oak, ship. 1549, 1550, 1545, and 1508, respectively, Rep. no. R-1491 (Feb. 1944). American beech, eastern cottonwood, and yellow- poplar, Rep. no. 1675 (Rev. Nov. 1955). Eucalyptus, Rep. no. 2126 (Sept., 1958).

The product with the largest recovery by amount and percent in the U.S. is old corrugated containers (OCC). Over 50% of OCC is recovered in the U.S. One reason is that large amounts of OCC are generated at specific sites, such as grocery stores and other retail outlets. Newspapers and other post-consumer wastes are much more expensive to collect and tend to be highly contaminated with unusable papers and trash. Still, 33% of newsprint is recovered, but only onethird of this ends up in new newsprint, with the rest used in chipboard or exported. Several states, however, are in the process of enacting legislation which demands large amounts of recycled fiber (10-50%) in new newsprint. The recovery and reuse of newsprint will change rapidly over the next several years. On the order of 25% of U.S. recovered fiber is exported, and the remaining 75% is reused domestically.

Use of recycled paper

Generally freight costs limit the distance that waste paper may be transported. About 80% of all waste paper comes from one of three sources: corrugated boxes, newspapers, and office papers. Only about 10% of waste paper is deinked to be used in printing or tissue papers; mostly it is used in paperboards and roofing materials where color is not important. However, the percentage of deinked paper is expected to increase considerably over the next few years.

Reuse of discarded paper involves extensive systems for removal of foreign materials. This involves skimmers to remove floating items, removal of heavy items at the bottom of a repulper, and the removal of stringy items such as rope, wet strength papers, etc. The so-called non-attrition pulping method works like a giant blender to separate the fibers. Coarse screening is then used for further cleaning prior to use of fine screens. These processes are discussed in detail in Chapter 10.

Nonwood plant fibers

About 10% of the fiber used to make paper each year worldwide is from nonwood plant fibers, including cotton, straws, canes, grasses, and hemp. Non vegetable fibers such as polyethylene and glass fibers are also used. Fig. 2-34 shows electron micrographs of "paper" made from four nonwood fibers. In the U.S. paper contains only about 2% of nonwood fibers on average. Globally, however, the use of nonwood fiber is increasing faster than wood fiber. Nonwood fiber sources were used for hundreds of years before wood was used as a fiber source for papermaking.

Many factors influence the suitability of raw materials for use in paper. These include the ease of pulping and yield of usable pulp; the availability and dependability of supply; the cost of collection and transportation of the fiber source; the fiber morphology, composition, and strength including the fiber length, diameter, wall thickness, and fibril angle (primarily the thick S-2 layer); the presence of contaminants (silica, dirt, etc.); and the seasonability of the supply (storage to prevent decay is costly.)

Nonwood sources of plant fibers include straws such as wheat, rye, rice, and barley; grasses such as bamboo, esparto, and papyrus; canes and reeds such as bagasse (sugar cane), corn stalks, and kenaf; bast (rope material) such as flax (linen), hemp, jute, ramie, and mulberry; and seed hairs such as cotton. Tappi Standard T 259 describes the identification of nonwood plant materials that are used or have the potential to be used in the paper industry. Many photomicrographs and detailed information make this a particularly useful resource on nonwood fibers.

In the U.S. wood has replaced other fiber sources for a wide variety of reasons (that will be discussed and are later summarized in Table 2-9 for straw). For example, in the U.S. all corrugating medium was made from straw prior to the 1930s. Around this time the chestnut blight made a lot of hardwood available, which was effectively pulped by the new NSSC process to make corrugating board. By the end of the 1950s, most of the straw-using mills had closed or switched to hardwoods. Now almost all corrugating medium in the U.S. is made with hardwoods and/or recycled fiber.

In contrast to this, Europe's largest corrugating medium mill uses pulp from wheat, rye, oat and barley grain straws, along with secondary fiber. The mill is owned by Saica and operates in Zaragoza, Spain. Plate 11 shows some aspects of the process. The mill boasts a production of 1200



Fig. 2-34. Cotton paper (top left); kenaf newsprint press run [top right, see *Tappi J*. 70(11):81-83(1987)]; polyethylene nonwoven material (bottom left); and glass fiber battery separator.

t/day of medium containing 25% or 50% straw pulp, with the higher grade containing the larger amount of straw pulp. The balance of the fiber is from recycled paper. The mill is state-of-the-art with high speed paper machines using extendednip presses. Saica plans to double its capacity and incorporate straw into linerboard using a paper machine with two extended-nip presses in the early 1990s. This mill produces 400 t/day of straw pulp using four continuous digesters operating at atmospheric pressure and about 100°C (212°F) with pulping times of 1 hour. The low temperature allows mild carbon steel to be used, as the sodium hydroxide cooking chemical is not so corrosive at these low temperatures. The mill recovers some of the organic material as fuel by anaerobic fermentation, while the sodium is not recovered. Straw Pulping Technology has sold several of these systems.

Most nonwood fiber is pulped in continuous digesters at temperatures around 130-160°C (265-320°F) for 10-30 min. The Pandia digester, which is a horizontal tube digester with screw feed, is a commonly used digester. However, in Denmark, Frederica Cellulose uses wheat and rye grain straw in batch digesters to make about 140 t/day of bleached straw market pulp. The mill did not have any liquor recovery or treatment before 1985, but is now the only mill in the world using direct alkali recovery (DARS, see Section 34.9 for a description of this process) to regenerate the sodium hydroxide from the spent cooking liquor. The DARS process is used since the mill is so small that a recovery boiler and lime kiln would be uneconomical.

Cotton

Natural cotton (from the seed pods) is a very pure form of cellulose. In its native form, cotton fibers are too long to make good paper, since poor formation (evenness of fiber distribution) in the paper would be the result. Also, cotton suitable for textiles is too expensive for use in paper. *Rag* (cotton remnants of the textiles industry) cotton has relatively short fibers and is much less expensive. Cotton linters (seed hair) have shorter fibers. Cotton rag fibers are typically 10-45 mm long, while cotton linters are 1-2 mm long; both are 0.02-0.04 mm in diameter. Because cotton is almost pure cellulose, it has little hemicellulose and leads to low strength papers. Consequently cotton fibers are mixed with wood pulp to make a suitably strong paper. Fig. 2-34 shows paper made from cotton fibers.

Bast fibers

Hemp (used in ropes), *jute*, and *ramie* grow in subtropical areas, such as in the Philippines, and have long (20 mm), very strong fibers. These materials have specific applications in cigarette papers, tea bags, sack paper, and saturating papers. *Linen* (*flax*) is similar to *hemp*, but the fibers are shorter (2-5 mm by 0.02 mm diameter). These materials are usually processed by kraft or soda processes.

Straw

Straws, the stalks of grain crops obtained after threshing, may be processed into pulp. Straws from most edible grains are suitable. The most important types pulped are wheat, rice, rye, and barley with yields typically about 35% for bleached grades to 65% for high yield pulps suited for corrugating media or linerboard. Straw is low in lignin and is especially suited for fine papers. Because straw pulps have low drainage rates, it takes more water and large washers to wash them. The soda process is the most common pulping method for straw; anthraquinone is sometimes used with soda or kraft pulping of straw. Straw fiber lengths are typically 0.5-2.5 mm with diameters of 0.01-0.2 mm. Straw hemicellulose is mostly xylans. All of these factors make straw pulp similar to hardwood pulp. There are 75 million tons of straw available annually in the U.S. The advantages and disadvantages of straw are summarized in Table 2-9.

Chemical recovery of straw pulping liquors is complex and has not been practiced until environmental pressures in the 1980s forced some mills to begin this practice. Since large amounts of water are required to wash pulps, much energy is needed to concentrate the dilute liquor from the brown stock washers. However, about one-half of the liquor can be pressed out of the pulp and subjected to chemical recovery to avoid high evaporation costs. (Many mills that pulp wood by semi-chemical processes do this as well.) Many straws, espe-

Table 2-9.	The advantages	and	disadvantages	of	straw	as	a fiber	source.
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Advantages	Disadvantages
Byproduct from agriculture	Transportation and storage problems
Often cheaper than wood	Straws are bulky and contain silica
Large annual crop - 1 to 10 tons per acre per year	Short harvest time of 1 to 2 months; thus heavy drain on capital
Needs little refining	Degrades very quickly - high losses
Makes excellent filler, good printing and smoothness	Low freeness (drainage) rates and thus low production rates.

cially rice straw, have large amounts of silica that are removed during alkaline pulping. The silica interferes with the chemical recovery process. There are about 10 countries which pulp significant amounts of rice despite its high silica content. New techniques for desilicanization of black liquor now allow chemical recovery.

Grasses

Grasses are pulped by the soda process and, like straw, are low in lignin. Grasses have long (up to 3 mm), thin (0.01-0.02 mm) fibers suitable for fine, high quality papers with good strength and opacity. Esparto grass grows in southern Europe and Northern Africa. Pulp from *bamboo* (grown in India, China and other Asian countries) is used in fine papers and the resulting paper is stronger than paper of straw pulp. Because of its high silica content, it is pulped using the kraft process. *Bamboo* pulp is somewhat similar to softwood sulfite pulp.

Canes and reeds

Bagasse (sugar cane residue) is pulped by the kraft or soda process. It must be depithed since the inner pith cells are useless for papermaking and decrease the pulp freeness considerably. It is used in fine papers. Improvements in processing bagasse have made it more popular around the world as a fiber source for pulp. Since bagasse is often used as a fuel at sugar processing plants, the plant must replace the bagasse with another fuel if it is to make it available for pulping.

Kenaf has been investigated in the U.S. by the USDA. It is a member of the *hibiscus* group of plants and is being investigated for use in news-

print. Fig. 2-34 shows a sample of newsprint made from kenaf from an actual press run.

Glass and polymers

Nonwovens are fiber mats made using synthetic fibers. They can be formed much like paper into a cloth material instead of using a weaving process, hence the term nonwoven. Paper receives some competition from nonwovens in products such as tote bags, envelopes, and computer diskette sleeves. The long fibers give these products very high tear strengths. Glass fibers (often with chemical additives) are used in products such as battery separators, glass fiber filter mats, and as reinforcement in a large variety of composite materials. Fig. 2-34 shows mats constructed with polyethylene and glass fibers.

2.10 ANNOTATED BIBLIOGRAPHY

Chipping

1. Robinson, M.E., Optimizing chip quality through understanding and controlling chipper design characteristics and other variables, *Proceedings, 1989 TAPPI Pulping Conference*, pp 325-338.

Here the importance of proper chipper maintenance is stressed. Some of the conclusions are: Using knives to chip more than 500 to 1000 tons (dry basis) of chips with dirt or gritty bark in the wood will result in poor chips due to nicks in the knives. Dry wood produces more oversized and overthick chips than green wood. High chipping velocity, post chipping damage to chips due to harsh handling, and frozen wood produces larger amounts of fines, especially in softwoods. Shortwood chips better in gravity feed machines than in horizontal chippers. Since chip thickness is directly proportional to chip length, chip length can be used as a means of controlling chip thickness. Reductions in the pins fraction can be gained by removing the card breakers, or slowing the chipper speed.

 Hartler, N. Chipper design and operation for optimum chip quality, *Tappi J.*, 69(10):62-66(1986) (It is similar in *Proceedings*, 1985 *TAPPI Pulping Conference*, pp 263-271.)

Hartler is a respected expert on wood chip quality. A target cutting speed of 20-25 m/s for the knives is typical. A decrease in the spout angle results in a lower fines content in the wood chips, but has the disadvantages of increased damage to chips, decreased chip bulk density, and a decrease in the maximum diameter of wood that can be processed.

 Twaddle, A.A. and W.F. Watson, Survey of disk chippers in the southeastern USA, and their effects of chip quality, *Proceedings*, 1990 Tappi Pulping Conference, pp 77-86. [Also in Tappi J. 75(10):135-140(1992). The second A of their equations 3 and 4 should be a B.]

The authors found from their survey of 101 chippers that about 40% of the chippers were either the 112 in.-15 knife (powered with 800-2500 hp) or 116 in.-12 knife (powered with 1250-3000 hp, but most with 2500 hp) combinations. Chippers typically ran at 300-450 rpm with almost 40% at 360 rpm. 43% of the chippers were manufactured by Carthage. 15% used disposable knives. About 50% ran with mid disk operating speeds below 25 m/s. 62% of the chippers used passive, gravity *bottom discharge*, while 37% used *blowing discharge*, induced by vanes mounted on the back of the disk.

Four correlation equations for pins and fines generation for hardwoods and softwoods each

were developed from the parameters of discharge type, chipper rpm, and chip set-up length. (They defined pins as less than 2 mm thick and retained on a 5 mm round hole pan, and fines as less than 2 mm thick passing through a 5 mm round hole pan, which was the classification used at 70% of the yards measuring fines.) The regression equations can be used to compare the performance of ones chipper with the average, although there can be large variations expected for various species of wood. The equations are as follows with r^2 of 0.27 for softwoods and 0.39 for hardwoods:

<u>softwood pins</u> (subtract 1.58% for bottom discharge units):

 $\% = 6.34 + (0.0092 \times \text{rpm}) + (-0.26 \times \text{chip setup length in mm})$

softwood fines (subtract 1.16% for bottom discharge units):

 $\% = 3.02 + (0.0062 \times \text{rpm}) + (-0.15 \times \text{chip setup length in mm})$

hardwood pins (subtract 0.65% for bottom discharge units):

 $\% = 3.64 + (0.0062 \times \text{rpm}) + (-0.17 \times \text{chip setup length in mm})$

hardwood fines (subtract 1.17% for bottom discharge units):

 $\% = -0.28 + (0.0081 \times \text{rpm})$

These equations show that an increase in speed of 50 rpm will lead to about 0.3-0.4% increase in fines and pins each. Analysis of chippers using softwoods and bottom discharge units showed that there was about a 50% increase in fines content (1% to 1.5%) as new knives aged to mid life, but no decrease from mid-life knives to old knives. Keep in mind that other factors besides the chip size distribution, such as chip bruising and geometry, are important in the pulping and papermaking properties of wood chips.

Chip quality, uniformity, and testing

4. Hatton, J.V. Chip Quality Monograph, Pulp and Paper Series, No. 5, Joint Textbook Committee of the Paper Ind., 1979, 323 p.

> This work is the classic on the topic of wood chip quality. Prior to Hatton's research in the 1970s on wood chip thickness screening for kraft mills, screening of wood chips was done with round-hole screens.

> The importance of uniform chip thickness and quality in kraft pulping cannot be overstressed. Even under ideal cooking conditions, for a cook at a kappa number of 20 some of the fiber from pin chips will have a kappa as low as 10 and other fiber from over thick chips will have a kappa as high as 50, with the concomitant problems of each.

- 5. Christie, D., Chip screening for pulping uniformity, *Tappi J*. 70(4):113-117(1987). The article summarizes the importance of *chip thickness screening* in kraft pulping.
- Luxardo, J. and S. Javid, New technology for chip thickness and fines screening, *Pulp Paper Can.* 93(3):39-46 (T56-T63)(1992). A similar paper appears as Smith, D.E. and S.R. Javid, Trends in chip thickness screening, *Tappi J.* 73(10):185-190(1990). This work also appears in at least three conference proceedings. Recent advances in Acrowood products are given here.
- Nelson, S.L. and P. Bafile, Quinnesec woodyard focuses on chip thickness control at the chipper, *Tappi J.* 72(3):95-106(1989).
- Thimons, T., Chip-thickness screening with an oscillating bar screen, *Tappi J.* 74(11): 183-185 (1991) (*ibid.*, Chip thickness screening without rotating wear surfaces, *1991 TAPPI Pulping Conf. Proc.*, pp 553-555.)

Chip thickness screens have saved mills millions of dollars. Most thickness screens use rotating metal disks that have high wear and must be properly maintained for good perfor-



Fig. 2-35. Diagram of DynagageTM bar screen with bars anchored on left hand side in lower position.

mance. A new system has been developed that uses longitudinal distribution bars attached to two eccentric shafts with bars alternating as to which shaft they are connected. The system looks remarkably simple and effective. Overthick removal is very high while accept carry over is very low. The method is called DynagageTM Bar Screen and is shown in Fig. 2-35.

- Berlyn, R.W. and R.B. Simpson, Upgrading wood chips: the Paprifer process, *Tappi J*. 71(3):99-106(1988). A wide variety of chips including whole-tree chips, chips from partially decayed trees, and logging residues are claimed to be improved by the Paprifer process.
- 10. Marrs, G., Measuring chip moisture and its variations, *Tappi J.* 72(7):45-54(1989). Chip moisture meters, even though they have inherent imprecision, may give the best available estimates of chip moisture during processing.

Chip pile

11. Fuller, W.S., Chip pile storage--a review of practices to avoid deterioration and economic losses, *Tappi J.* 68(8):48-52(1985). This

article is a concise summary of wood chip pile management with 24 references.

Fiber physics

 Page, D.H., F. El-Hosseiny, K. Winkler, and R. Bain, The mechanical properties of single wood-pulp fibres. Part I: A new Approach, *Pulp Paper Mag. Can.* 73(8):72-77(1972).

Nonwood fibers

- Clark, T.F, Annual crop fibers and the bamboos, in *Pulp and Paper Manufacture*, Vol.
 2, 2nd ed., MacDonald, R.G., Ed., McGraw-Hill, New York, 1969, pp 1-74. Processing of a variety of nonwood fibers is considered. It seems likely that the U.S. will start using nonwood fibers in brown papers or newsprint within the next two decades.
- 14. Atchison, J.E., World capacities for nonwood plant fiber pulping increasing faster than wood pulping capacities, *Tappi Proceedings*, 1988 Pulping Conference, pp 25-45. This is a good summary about who is pulping what around the world.

Wood handling

 Lamarche, F.E., Preparation of pulpwood, in *Pulp and Paper Manufacture*, Vol. 1, 2nd ed., MacDonald, R.G., Ed., McGraw-Hill, New York, 1969, pp 73-147.

This is a thorough look at handling roundwood and wood chips at the mill, especially in regards to the equipment. It includes pulpwood measurement, log storage and handling, debarking, chipping and chip quality and handling. Chip screening by *thickness* is not mentioned as the article predates the widespread understanding of the importance of chip thickness screening for kraft pulping. It is well illustrated.

EXERCISES

Wood

1. True or false? Bark in the wood chip supply is unimportant as it has good fiber for making paper. Why?

- 2. Circle the correct choice in each set of parentheses. (White or Brown) rot in wood chips affects the ultimate paper strength properties the most for a given weight loss. (Hardwood or Softwood) pulp is used to make strong paper while (hardwood or softwood) pulp is used to make smoother paper. (Hardwoods or Softwoods) have more lignin. Short storage time of wood chips is most important for (mechanical or kraft) pulping.
- 3. List two changes that take place in chips during storage in a chip pile.
- 4. Wood chip quality is very important in the final properties of paper. List five parameters for chip quality and their effect(s) on the final paper property.
- 5. What chip size fractions cause the most problems in kraft pulping, and what are the problems they cause?

Fraction	Problem
	
·····	

6. Approximately _____ % of the production cost of pulp is due to the cost of wood chips.

Wood chemistry

- 7. What are the three major components of wood?
- Circle the correct choice in each set of parentheses. (Cellulose or Hemicelluloses) provide(s) individual wood fibers with most of their strength. (Cellulose or Hemicelluloses) is/are appreciably soluble in alkaline solutions at elevated temperatures.
- 9. What material holds the fibers together in wood?
- 10. How does softwood lignin differ from hardwood lignin?
- 11. What is turpentine? From what woods is it obtained?

- 12. Name three commercial materials made from dissolving pulp (cellulose). What are their uses?
- 13. Describe the process of making carboxymethyl cellulose and show the principal chemical reaction.

Wood and fiber physics

- 14. In the absence of fiber defects, what factor determines the longitudinal tensile strength of individual fibers? For a similar reason, wood fibers do not shrink nearly as much in their longitudinal direction as in their radial or tangential directions. Why is this so? See Fig. 2-36 to help see why this is so.
- 15. Wood and paper are hygroscopic materials. What does this mean?
- 16. What holds fibers together in paper?

Nonwood and recycled fiber

- 17. Is most recycled fiber deinked? Discuss.
- 18. What is (considered to be) the maximum percentage of fiber recovery that can be sustained. Why is this so? At what levels do the U.S., Japan, and W. Germany recycle?
- 19. The value of mixed paper waste is on the order of \$_____/ton. The value of high quality trimmings from an envelope factory is on the order of \$_____/ton. What concept do these facts demonstrate?



Fig. 2-36. Relative sizes of fibers and fibrils. [©]1982, 1991 James E. Kline. Reprinted from *Paper and Paperboard* with permission.

20. Trees have replaced all other plants as a fiber source for paper around the world. Discuss this statement.