

Specialty Treatments

Rebecca E. Ibach, Research Chemist

Contents

Plasticizing Wood 19–1
Principles of Plasticizing and Bending 19–1
Bent Wood Members 19–2
Laminated Members 19–2
Veneered Curved Members 19–3
Bending of Solid Members 19–3
Selection of Stock 19–3
Moisture Content of Bending Stock 19–3
Bending Operation and Apparatus 19–4
Fixing the Bend 19–4
Characteristics of Bent Wood 19–4
Modified Woods 19–4
Resin-Treated Wood—Not Compressed (Impreg) 19–4
Resin-Treated Wood—Compressed (Compreg) 19–5
Heat Treatments 19–9
Heating Wet Wood 19–9
Heating Wet Wood Followed by Compression 19–10
Heating Dry Wood 19–10
Heating Dry Wood Followed by Compression 19–10
Wood Treated with Polyethylene Glycol (PEG) 19–10
Wood–Polymer Composites 19–11
Chemical Modification 19–12
Paper-Based Plastic Laminates 19–12
Industrial Laminates 19–12
Decorative Laminates 19–13
Lignin-Filled Laminates 19–14
Paper-Face Overlays 19–14
References 19–14

Many specialty treatments can be applied to wood to either improve its performance or change its properties. Treatments addressed in this chapter are those that make permanent changes in the shape of a wood product, improvements in dimensional stability, or improvements in performance through combinations with nonwood resources.

Plasticizing Wood

Principles of Plasticizing and Bending

In simple terms, the wood cell wall is a composite made of a rigid cellulose polymer in a matrix of lignin and the hemicelluloses. The lignin polymer in the middle lamella and S2 layer is thermoplastic; that is, it softens upon heating. The glass transition temperature T_g of the lignin in the matrix is approximately 170 °C (338 °F). Above the matrix T_g , it is possible to cause the lignin to undergo thermoplastic flow and, upon cooling, reset in the same or modified configuration. This is the principle behind bending of wood.

The matrix can be thermoplasticized by heat alone, but the T_g of the unmodified matrix is so high that some fiber decomposition can occur if high temperatures are maintained for a lengthy period. The T_g of the matrix can be decreased with the addition of moisture or through the use of plasticizers or softeners.

Heat and moisture make certain species of wood sufficiently plastic for bending operations. Steaming at atmospheric or a low gauge pressure, soaking in boiling or nearly boiling water, or microwave heating moist wood are satisfactory methods of plasticizing wood. Wood at 20% to 25% moisture content needs to be heated without losing moisture; at lower moisture content, heat and moisture must be added. As a consequence, the recommended plasticizing processes are steaming or boiling for about 15 min cm⁻¹ (38 min in⁻¹) of thickness for wood at 20% to 25% moisture content and steaming or boiling for about 30 min cm⁻¹ (75 min in⁻¹) of thickness for wood at lower moisture content levels. Steaming at high pressures causes wood to become plastic, but wood treated with high pressure steam generally does not bend as successfully as does wood treated at atmospheric or low pressure. Microwave heating requires much shorter times.

Wood can be plasticized by a variety of chemicals in addition to water. Common chemicals that plasticize wood include urea, dimethylol urea, low-molecular-weight phenol-formaldehyde resin, dimethyl sulfoxide, and liquid ammonia. Urea and dimethylol urea have received limited

commercial attention, and a bending process using liquid ammonia has been patented. Wood members can be readily molded or shaped after immersion in liquid ammonia or treatment under pressure with ammonia in the gas phase. As the ammonia evaporates, the lignin resets, the wood stiffens and retains its new shape. Plasticization of the lignin matrix alone can be done using chemical modification technologies, which are covered later in this chapter.

It is also possible to bend wood without softening or plasticizing treatments. However, the stability of the final product may not be as permanent as from treatments in which softening and plasticizing methods are used.

Bent Wood Members

Bending can provide a variety of functional and esthetically pleasing wood members, ranging from large curved arches to small furniture components. The curvature of the bend, size of the member, and intended use of the product determine the production method.

Laminated Members

At one time in the United States, curved pieces of wood were laminated chiefly to produce small items such as parts for furniture and pianos. However, the principle was extended to the manufacture of arches for roof supports in farm, industrial, and public buildings and other types of structural members (see Chap. 11). The laminations are bent without end pressure against a form and adhesively bonded together. Both softwoods and hardwoods are suitable for laminated bent structural members, and thin material of any species can be bent satisfactorily for such purposes. The choice of species and adhesive depends primarily on the cost, required strength, and demands of the application.

Laminated curved members are produced from dry stock in a single bending and adhesive bond formation operation. This process has the following advantages compared with bending single-piece members:

- Bending thin laminates to the required radius involves only moderate stress and deformation of the wood fibers, eliminating the need for treatment with steam or hot water and associated drying and conditioning of the finished product. In addition, the moderate stresses involved in curving laminated members result in stronger members when compared with curved single-piece members.
- The tendency of laminated members to change shape with changes in moisture content is less than that of single-piece bent members.
- Ratios of thickness of member to radius of curvature that are impossible to obtain by bending single pieces can be attained readily by laminating.
- Curved members of any desired length can be produced.

Straight-laminated members can be steamed and bent after they are bonded together. However, this type of procedure requires an adhesive that will not be affected by the steaming or boiling treatment and complicates conditioning of the finished product.

Curved Plywood

Curved plywood is produced either by bending and adhesive bonding the plies in one operation or by bending previously bonded flat plywood. Plywood curved by bending and bonding simultaneously is more stable in curvature than plywood curved by bending previously bonded material.

Plywood Bent and Adhesively Bonded Simultaneously

In bending and bonding plywood in a single operation, adhesive-coated pieces of veneer are assembled and pressed over or between curved forms. Pressure and sometimes heat are applied through steam or electrically heated forms until the adhesive sets and holds the assembly to the desired curvature. Some laminations are at an angle, usually 90°, to other laminations, as in the manufacture of flat plywood. The grain direction of the thicker laminations is normally parallel to the axis of the bend to facilitate bending.

A high degree of compound curvature can be obtained in an assembly made up of a considerable number of thin veneers. First, for both the face and back of the assembly, the two outer plies are bonded at 90° to each other in a flat press. The remaining veneers are then adhesive-coated and assembled at any desired angle to each other. The entire assembly is hot-pressed to the desired curvature.

Bonding the two outer plies before molding allows a higher degree of compound curvature without cracking the face plies than could otherwise be obtained. Where a high degree of compound curvature is required, the veneer should be relatively thin (less than 3 mm (1/8 in.)) with a moisture content of about 12%.

The molding of plywood with fluid pressure applied by flexible bags of some impermeable material produces plywood parts of various degrees of compound curvature. In “bag molding,” fluid pressure is applied through a rubber bag by air, steam, or water. The veneer is wrapped around a form, and the whole assembly is enclosed in a bag and subjected to pressure in an autoclave, the pressure in the bag being “bled.” Or the veneer may be inserted inside a metal form and, after the ends have been attached and sealed, pressure is applied by inflating a rubber bag. The form may be heated electrically or by steam.

The advantages of bending and bonding plywood simultaneously to form a curved shape are similar to those for curved-laminated members. In addition, the cross plies give the curved members properties that are characteristic of cross-banded plywood. Curved plywood shells for furniture manufacture are examples of these bent veneer and adhesive-bonded products.

Plywood Bent after Bonding

After the plies are bonded together, flat plywood is often bent by methods that are somewhat similar to those used in bending solid wood. To bend plywood properly to shape, it must be plasticized by some means, usually moisture or heat, or a combination of both. The amount of curvature that can be introduced into a flat piece of plywood depends on numerous variables, such as moisture content, direction of grain, thickness and number of plies, species and quality of veneer, and the technique applied in producing the bend. Plywood is normally bent over a form or a bending mandrel.

Flat plywood bonded with a waterproof adhesive can be bent to compound curvatures after bonding. However, no simple criterion is available for predetermining whether a specific compound curvature can be imparted to flat plywood. Soaking the plywood prior to bending and using heat during forming are aids in manipulation. Usually, the plywood to be postformed is first thoroughly soaked in hot water, and then dried between heated forming dies attached to a hydraulic press. If the use of postforming for bending flat plywood to compound curvatures is contemplated, exploratory trials to determine the practicability and the best procedure are recommended. Remember that in postforming plywood to compound curvatures, all the deformation must be by compression or shear because plywood cannot be stretched. Hardwood species, such as birch, poplar, and gum, are usually used in plywood that is to be postformed.

Veneered Curved Members

Veneered curved members are usually produced by bonding veneer to one or both faces of a curved solid-wood base. The bases are ordinarily sawn to the desired shape or bent from a piece grooved with saw kerfs on the concave side at right angles to the direction of bend. Pieces bent by making saw kerfs on the concave side are commonly reinforced and kept to the required curvature by bonding splines, veneer, or other pieces to the curved base. Veneering over curved solid wood is used mainly in furniture. The grain of the veneer is commonly laid in the same general direction as the grain of the curved wood base. The use of crossband veneers, that is, veneers lay with the grain at right angles to the grain of the back and face veneer, decreases the tendency of the member to split.

Bending of Solid Members

Wood of certain species that is steamed, microwaved, or soaked in boiling water can be compressed as much as 25% to 30% parallel to the grain. The same wood can be stretched only 1% to 2%. Because of the relation between attainable tensile and compressive deformations, if bending involves severe deformation, then most of the deformation must be compression. The inner or concave side must assume the maximum amount of compression, and the outer or convex side must experience zero strain or a slight tension. To accomplish this, a metal strap equipped with end

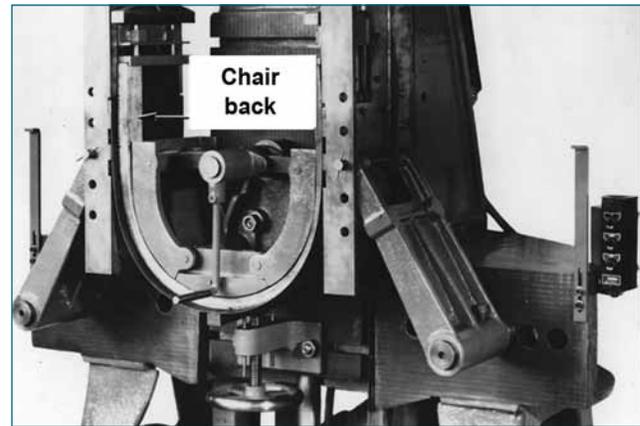


Figure 19–1. Chair back being bent through an arc of 180° in a bending machine.

fittings is customarily used. The strap makes contact with the outer or convex side and, acting through the end fittings, places the whole piece of wood in compression. The tensile stress that would normally develop in the outer side of the piece of wood during bending is borne by the metal strap. A bending form is shown in Figure 19–1.

Selection of Stock

In general, hardwoods possess better bending quality than softwoods, and certain hardwoods surpass others in this quality. This is interesting from a theoretical point of view because hardwoods contain less lignin than softwoods. Hardwoods also contain much more hemicelluloses in the matrix than do softwoods. The species commonly used to produce bent members are white oak, red oak, elm, hickory, ash, beech, birch, maple, walnut, sweetgum, and mahogany. As stated, most softwoods have a poor bending quality and are not often used in bending operations. However, Pacific yew and yellow-cedar are exceptions to this rule. In addition, Douglas-fir, southern yellow pine, northern and Atlantic white-cedar, and redwood are used for ship and boat planking for which purpose they are often bent to moderate curvature after being steamed or soaked.

Bending stock should be free from serious cross grain and distorted grain, such as may occur near knots. The slope of cross grain should not be steeper than about 1 to 15. Decay, knots, shake, pith, surface checks, and exceptionally light or brittle wood should be avoided.

Moisture Content of Bending Stock

Although green wood can be bent to produce many curved members, difficulties are encountered in drying and fixing the bend. Another disadvantage with green stock is that hydrostatic pressure may be developed during bending. Hydrostatic pressure can cause compression failures on the concave side if the wood is compressed by an amount greater than the air space in the cells of the green wood.

Bending stock that has been dried to low moisture content level requires a lengthy steaming or soaking process to increase its moisture content to the point where it can be made sufficiently plastic for successful bending. For most chair and furniture parts, the moisture content of the bending stock should be 12% to 20% before it is steamed or microwave heated. The preferred moisture content level varies with the severity of the curvature to which the wood is bent and the method used in drying and fixing the bent member. For example, chair-back slats, which have a slight curvature and are subjected to severe drying conditions between steam-heated platens, can be produced successfully from stock at 12% moisture content. For furniture parts that need a more severe bend where the part must be bent over a form, 15% to 20% moisture content is recommended.

Bending Operation and Apparatus

After being plasticized, the stock should be quickly placed in the bending apparatus and bent to shape. The bending apparatus consists essentially of a form (or forms) and a means of forcing the piece of steamed wood against the form. If the curvature to be obtained demands a difference of much more than 3% between lengths of the outer and inner surfaces of the pieces, then the apparatus should include a device for applying end pressure. This generally takes the form of a metal strap or pan provided with end blocks, end bars, or clamps.

Fixing the Bend

After being bent, the piece should be cooled and dried while held in its curved shape. One method is to dry the piece in the bending machine between the plates of a hot-plate press. Another method is to secure the bent piece to the form and place both the piece and the form in a drying room. Still another is to keep the bent piece in a minor strap with tie rods or stays so that it can be removed from the form and placed in a drying room. When the bent member has cooled and dried to moisture content suitable for its intended use, the restraining devices can be removed and the piece will hold its curved shape.

Characteristics of Bent Wood

After a bent piece of wood is cooled and dried, the curvature will be maintained. An increase in moisture content may cause the piece to lose some of its curvature. A decrease in moisture content may cause the curve to become sharper, although repeated changes in moisture content bring about a gradual straightening. These changes are caused primarily by lengthwise swelling or shrinking of the inner (concave) face, the fibers of which were wrinkled or folded during the bending operation.

A bent piece of wood has less strength than a similar unbent piece. However, the reduction in strength brought about by bending is seldom serious enough to affect the utility value of the member.

Modified Woods

Wood can be chemically modified to improve water repellency, dimensional stability, resistance to acids or bases, ultraviolet radiation, biodeterioration, and thermal degradation. Wood can also be chemically treated, then compressed to improve dimensional stability and increase hardness. Sheets of paper treated with resins or polymers can be laminated and hot pressed into thick panels that have the appearance of plastic rather than paper. These sheets are used in special applications because of their structural properties and in items requiring hard, impervious, and decorative surfaces.

Modified woods, modified wood-based materials, and paper-based laminates are usually more expensive than wood because of the cost of the chemicals and the special processing required producing them. Thus, modified wood use is generally limited to special applications where the increased cost is justified by the special properties needed.

Wood is treated with chemicals to increase hardness and other mechanical properties, as well as its resistance to decay, fire, weathering, and moisture. The rate and extent of swelling and shrinking of the wood when in contact with water is decreased by application of water-resistant chemicals to the surface of wood, impregnation of the wood with such chemicals dissolved in water or volatile solvents, or bonding chemicals to the cell wall polymer. Such treatments may also decrease the rate at which wood changes dimension as a result of humidity, even though these treatments do not affect the final dimensional changes caused by lengthy duration exposures. Paints, varnishes, lacquers, wood-penetrating water repellents, and plastic and metallic films retard the rate of moisture absorption but have little effect on total dimensional change if exposure to moisture is extensive and prolonged.

Resin-Treated Wood—Not Compressed (Impreg)

Permanent stabilization of the dimensions of wood is needed for certain specialty uses. This can be accomplished by depositing a bulking agent within the swollen structure of the wood fibers. The most successful bulking agents that have been commercially applied are highly water-soluble, thermosetting, phenol-formaldehyde resin-forming systems, with initially low molecular weights. No thermoplastic resins have been found that effectively stabilize the dimensions of wood.

Wood treated with a thermosetting, fiber-penetrating resin and cured without compression is known as impreg. The wood (preferably green veneer to facilitate resin pickup) is soaked in the aqueous resin-forming solution or, if air dry, is impregnated with the solution under pressure until the resin content equals 25% to 35% of the weight of dry wood. The treated wood is allowed to stand under nondrying conditions

for 1 to 2 days to permit uniform distribution of the solution throughout the wood. The resin-containing wood is dried at moderate temperatures to remove the water, and then heated to higher temperatures to cure the resin.

Uniform distribution of the resin has been effectively accomplished with thick wood specimens only in sapwood of readily penetrated species. Although thicker material can be treated, the process is usually applied to veneers up to about 8 mm (0.3 in.) thick, because treating time increases rapidly with increases in thickness. Drying thick, resin-treated wood may result in checking and honeycombing. For these reasons, treatments should be confined to veneer and the treated-cured veneer used to build the desired products. Any species can be used for the veneer except the resinous pines. The stronger the original wood, the stronger the end product.

Impreg has a number of properties differing from those of normal wood and ordinary plywood. These properties are given in Table 19–1, with similar generalized findings for other modified woods. Data for the strength properties of yellow birch impreg are given in Table 19–2. Information on thermal expansion properties of ovendry impreg is given in Table 19–3.

The good dimensional stability of impreg is the basis of one use where its cost is not a deterrent. Wood dies of automobile body parts serve as the master from which the metal-forming dies are made for actual manufacture of parts. Small changes in moisture content, even with the most dimensionally stable wood, produce changes in dimension and curvature of an unmodified wood die. Such changes create major problems in making the metal-forming dies where close final tolerances are required. The use of impreg, with its high antishrink efficiency (ASE) (Table 19–4), almost entirely eliminated the problem of dimensional change during the entire period that the wood master dies were needed. Despite the tendency of the resins to dull cutting tools, pattern makers accepted the impreg readily because it machines with less splitting than unmodified wood.

Patterns made from impreg are also superior to unmodified wood in resisting heat when used with shell-molding techniques where temperatures as high as 205 °C (400 °F) are required to cure the resin in the molding sand.

Resin-Treated Wood—Compressed (Compreg)

Compreg is similar to impreg except that it is compressed before the resin is cured within the wood. The resin-forming chemicals (usually phenol-formaldehyde) act as plasticizers for the wood so that it can be compressed under modest pressure (6.9 MPa, 1,000 lb in⁻²) to a specific gravity of 1.35. Some properties of compreg are similar to those of impreg, and others vary considerably (Tables 19–1 and 19–2). Compared with impreg, the advantages of compreg are its natural lustrous finish that can be developed on any cut

surface by sanding with fine-grit paper and buffing, its greater strength properties, and its ability to mold (Tables 19–1 and 19–2). However, thermal expansion coefficients of ovendry compreg are also increased (Table 19–3).

Compreg can be molded by (a) gluing blocks of resin-treated (but still uncured) wood with a phenolic glue so that the gluelines and resin within the plies are only partially set; (b) cutting to the desired length and width but two to three times the desired thickness; and (c) compressing in a split mold at about 150 °C (300 °F). Only a small flash squeeze out at the parting line between the two halves of the mold needs to be machined off. This technique was used for motor-test propellers and airplane antenna masts during World War II.

A more satisfactory molding technique, known as expansion molding, has been developed. The method consists of rapidly precompressing dry but uncured single sheets of resin-treated veneer in a cold press after preheating the sheets at 90 to 120 °C (195 to 250 °F). The heat-plasticized wood responds to compression before cooling. The heat is insufficient to cure the resin, but the subsequent cooling sets the resin temporarily. These compressed sheets are cut to the desired size, and the assembly of plies is placed in a split mold of the final desired dimensions. Because the wood was precompressed, the filled mold can be closed and locked. When the mold is heated, the wood is again plasticized and tends to recover its uncompressed dimensions. This exerts an internal pressure in all directions against the mold equal to about half the original compressing pressure. On continued heating, the resin is set. After cooling, the object may be removed from the mold in finished form. Metal inserts or metal surfaces can be molded to compreg or its handles are molded onto tools by this means. Compreg bands have been molded to the outside of turned wood cylinders without compressing the core. Compreg tubes and small airplane propellers have been molded in this way.

Past uses of compreg were related largely to aircraft; however, it is a suitable material where bolt-bearing strength is required, as in connector plates, because of its good specific strength (strength per unit of weight). Layers of veneer making up the compreg for such uses are often cross laminated (alternate plies at right angles to each other, as in plywood) to give nearly equal properties in all directions.

As a result of its excellent strength properties, dimensional stability, low thermal conductivity, and ease of fabrication, compreg is extremely useful for aluminum drawing and forming dies, drilling jigs, and jigs for holding parts in place while welding.

Compreg has also been used in silent gears, pulleys, water-lubricated bearings, fan blades, shuttles, bobbins, and picker sticks for looms, nuts and bolts, instrument bases and cases, musical instruments, electrical insulators, tool handles, and various novelties. At present, compreg finds considerable

Table 19–1. Properties of modified woods

Property	Impreg	Compreg	Staypak
Specific gravity	15% to 20% greater than normal wood	Usually 1.0 to 1.4	1.25 to 1.40
Equilibrium swelling and shrinking	1/4 to 1/3 that of normal wood	1/4 to 1/3 that of normal wood at right angle to direction of compression, greater in direction of compression but very slow to attain	Same as normal wood at right angle to direction of compression, greater in direction of compression but very slow to attain
Springback	None	Very small when properly made	Moderate when properly made
Face checking	Practically eliminated	Practically eliminated for specific gravities less than 1.3	About the same as in normal wood
Grain raising	Greatly reduced	Greatly reduced for uniform-texture woods, considerable for contrasting grain woods	About the same as in normal wood
Surface finish	Similar to normal wood	Varnished-like appearance for specific gravities greater than about 1.0; cut surfaces can be given this surface by sanding and buffing	Varnished-like appearance; cut surfaces can be given this surface by sanding and buffing
Permeability to water vapor	About 1/10 that of normal wood	No data, but presumably much less than impreg	No data, but presumably less than impreg
Decay and termite resistance	Considerably better than normal wood	Considerably better than normal wood	Normal, but decay occurs somewhat more slowly
Acid resistance	Considerably better than normal wood	Better than impreg because of impermeability	Better than normal wood because of impermeability, but not as good as compreg
Alkali resistance	Same as normal wood	Somewhat better than normal wood because of impermeability	Somewhat better than normal wood because of impermeability
Fire resistance	Same as normal wood	Same as normal wood for long exposures, somewhat better for short exposures	Same as normal wood for long exposures, somewhat better for short exposures
Heat resistance	Greatly increased	Greatly increased	No data
Electrical conductivity	1/10 that of normal wood at 30% RH; 1/1,000 that of normal wood at 90% RH	Slightly more than impreg at low relative humidity values due to entrapped water	No data
Heat conductivity	Slightly increased	Increased about in proportion to specific gravity increase	No data, but should increase about in proportion to specific gravity increase
Compressive strength	Increased more than proportional to specific gravity increase	Increased considerably more than proportional to specific gravity increase	Increased about in proportion to specific gravity increase parallel to grain, increased more perpendicular to grain
Tensile strength	Decreased significantly	Increased less than proportional to specific gravity increase	Increased about in proportion to specific gravity increase
Flexural strength	Increased less than proportional to specific gravity increase	Increased less than proportional to specific gravity increase parallel to grain, increased more perpendicular to grain	Increased proportional to specific gravity increase parallel to grain, increased more perpendicular to grain
Hardness	Increased considerably more than proportional to specific gravity increase	10 to 20 times that of normal wood	10 to 18 times that of normal wood
Impact strength			
Toughness	About 1/2 of value for normal wood, but very susceptible to the variables of manufacture	1/2 to 3/4 of value for normal wood, but very susceptible to the variables of manufacture	Same to somewhat greater than normal wood
Izod	About 1/5 of value for normal wood	1/3 to 3/4 of value for normal wood	Same to somewhat greater than normal wood
Abrasion resistance (tangential)	About 1/2 of value for normal wood	Increased about in proportion to specific gravity increase	Increased about in proportion to specific gravity increase
Machinability	Cuts cleaner than normal wood, but dulls tools more	Requires metalworking tools and metalworking tool speeds	Requires metalworking tools and metalworking tool speeds
Moldability	Cannot be molded but can be formed to single curvatures at time of assembly	Can be molded by compression and expansion molding methods	Cannot be molded
Gluability	Same as normal wood	Same as normal wood after light sanding or in the case of thick stock, machining surfaces plane	Same as normal wood after light sanding, or in the case of thick stock, machining surfaces plane

Table 19–2. Strength properties of normal and modified laminates^a of yellow birch and a laminated paper plastic

Property	Normal laminated wood ^b	Impreg (impregnated, uncompressed) ^c	Compreg (impregnated, highly compressed) ^c	Staypak (unimpregnated, highly compressed) ^b	Paper laminate (impregnated, highly compressed) ^d
Thickness of laminate (mm (in.))	23.9 (0.94)	26.2 (1.03)	16.0 (0.63)	12.2 (0.48)	3.2 (0.126) 13.0 (0.512)
Moisture content at time of test (%)	9.2	5.0	5.0	4.0	—
Specific gravity (based on weight and volume at test)	0.7	0.8	1.3	1.4	1.4
Parallel laminates					
Flexure—grain parallel to span (flatwise) ^e					
Proportional limit stress (MPa (lb in ⁻²))	79.3 (11,500)	109.6 (15,900)	184.1 (26,700)	138.6 (20,100)	109.6 (15,900)
Modulus of rupture (MPa (lb in ⁻²))	140.6 (20,400)	129.6 (18,800)	250.3 (36,300)	271.6 (39,400)	252.3 (36,600)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	16.0 (2,320)	16.4 (2,380)	25.4 (3,690)	30.7 (4,450)	20.8 (3,010)
Flexure—grain perpendicular to span (flatwise) ^e					
Proportional limit stress (MPa (lb in ⁻²))	6.9 (1,000)	9.0 (1,300)	29.0 (4,200)	22.1 (3,200)	72.4 (10,500)
Modulus of rupture (MPa (lb in ⁻²))	13.1 (1,900)	11.7 (1,700)	31.7 (4,600)	34.5 (5,000)	167.5 (24,300)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	1.0 (153)	1.5 (220)	4.3 (626)	4.2 (602)	10.2 (1,480)
Compression parallel to grain (edgewise) ^e					
Proportional limit stress (MPa (lb in ⁻²))	44.1 (6,400)	70.3 (10,200)	113.1 (16,400)	66.9 (9,700)	49.6 (7,200)
Ultimate strength (MPa (lb in ⁻²))	65.5 (9,500)	106.2 (15,400)	180.0 (26,100)	131.7 (19,100)	144.1 (20,900)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	15.8 (2,300)	17.0 (2,470)	26.1 (3,790)	32.2 (4,670)	21.5 (3,120)
Compression perpendicular to grain (edgewise) ^f					
Proportional limit stress (MPa (lb in ⁻²))	4.6 (670)	6.9 (1,000)	33.1 (4,800)	17.9 (2,600)	29.0 (4,200)
Ultimate strength (MPa (lb in ⁻²))	14.5 (2,100)	24.8 (3,600)	96.5 (14,000)	64.8 (9,400)	125.5 (18,200)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	1.1 (162)	1.7 (243)	3.9 (571)	4.0 (583)	11.0 (1,600)
Compression perpendicular to grain (flatwise) ^e					
Maximum crushing strength (MPa (lb in ⁻²))	—	29.5 (4,280)	115.1 (16,700)	91.0 (13,200)	291.0 (42,200)
Tension parallel to grain (lengthwise)					
Ultimate strength (MPa (lb in ⁻²))	153.1 (22,200)	108.9 (15,800)	255.1 (37,000)	310.3 (45,000)	245.4 (35,600)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	15.8 (2,300)	17.3 (2,510)	27.2 (3,950)	31.8 (4,610)	25.1 (3,640)
Tension perpendicular to grain (edgewise)					
Ultimate strength (MPa (lb in ⁻²))	9.6 (1,400)	9.6 (1,400)	22.1 (3,200)	22.8 (3,300)	137.9 (20,000)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	1.1 (166)	1.6 (227)	4.3 (622)	4.0 (575)	11.8 (1,710)
Shear strength parallel to grain (edgewise) ^f					
Johnson double shear across laminations (MPa (lb in ⁻²))	20.5 (2,980)	23.8 (3,460)	50.8 (7,370)	43.9 (6,370)	122.7 (17,800)
Cylindrical double shear parallel to laminations (MPa (lb in ⁻²))	20.8 (3,020)	24.5 (3,560)	39.2 (5,690)	21.2 (3,080)	20.7 (3,000)
Shear modulus					
Tension method (GPa (1,000 lb in ⁻²))	1.2 (182)	1.8 (255)	3.1 (454)	—	—
Plate shear method (FPL test) (GPa (1,000 lb in ⁻²))	—	—	—	2.6 (385)	6.3 (909)
Toughness (FPL test edgewise) ^f (J (in-lb))	26.6 (235)	14.1 (125)	16.4 (145)	28.2 (250)	—
Toughness (FPL test edgewise) ^f (J mm ⁻¹ of width (in-lb in ⁻¹ of width))	1.1 (250)	0.53 (120)	1.0 (230)	2.3 (515)	—
Impact strength (Izod)—grain lengthwise					
Flatwise (notch in face) (J mm ⁻¹ of notch (ft-lb in ⁻¹ of notch))	0.75 (14.0)	0.12 (2.3)	0.23 (4.3)	0.68 (12.7)	0.25 (4.7)
Edgewise (notch in face) (J mm ⁻¹ of notch (ft-lb in ⁻¹ of notch))	0.60 (11.3)	0.10 (1.9)	0.17 (3.2) ^g	—	0.036 (0.67)
Hardness					
Rockwell flatwise ^e (M–numbers)					
Load to embed 11.3-mm (0.444-in.) steel ball to 1/2 its diameter (kN (lb))	7.1 (1,600)	10.7 (2,400)	—	—	—
Hardness modulus (H_M) ^h (MPa (lb in ⁻²))	37.2 (5,400)	63.4 (9,200)	284.8 (41,300)	302.0 (43,800)	245.4 (35,600)
Abrasion—Navy wear-test machine (flatwise) ^e wear per 1,000 revolutions (mm (in.))	0.76 (0.030)	1.45 (0.057)	0.46 (0.018)	0.38 (0.015)	0.46 (0.018)

Table 19–2. Strength properties of normal and modified laminates^a of yellow birch and a laminated paper plastic—con.

Property	Normal laminated wood ^b	Impreg (impregnated, uncompressed) ^c	Compreg (impregnated, highly compressed) ^c	Staypak (unimpregnated, highly compressed) ^b	Paper laminate (impregnated, highly compressed) ^d
Water absorption (24-h immersion) increase in weight (%)	43.6	13.7	2.7	4.3	2.2
Dimensional stability in thickness direction					
Equilibrium swelling (%)	9.9	2.8	8.0	29	—
Recovery from compression (%)	—	0	0	4	—
Crossband laminates					
Flexure—face grain parallel to span (flatwise) ^e					
Proportional limit stress (MPa (lb in ⁻²))	47.6 (6,900)	55.8 (8,100)	99.3 (14,400)	78.6 (11,400)	86.9 (12,600)
Modulus of rupture (MPa (lb in ⁻²))	90.3 (13,100)	78.6 (11,400)	157.2 (22,800)	173.0 (25,100)	215.8 (31,300)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	9.0 (1,310)	11.5 (1,670)	17.1 (2,480)	20.0 (2,900)	15.4 (2,240)
Compression parallel to face grain (edgewise) ^f					
Proportional limit stress (MPa (lb in ⁻²))	22.8 (3,300)	35.8 (5,200)	60.0 (8,700)	35.8 (5,200)	34.5 (5,000)
Ultimate strength (MPa (lb in ⁻²))	40.0 (5,800)	78.6 (11,400)	164.8 (23,900)	96.5 (14,000)	130.3 (18,900)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	9.4 (1,360)	10.3 (1,500)	15.8 (2,300)	18.6 (2,700)	16.3 (2,370)
Tension parallel to face grain (lengthwise)					
Ultimate strength (MPa (lb in ⁻²))	84.8 (12,300)	54.5 (7,900)	113.8 (16,500)	168.9 (24,500)	187.5 (27,200)
Modulus of elasticity (GPa (1,000 lb in ⁻²))	8.9 (1,290)	10.1 (1,460)	15.1 (2,190)	17.7 (2,570)	18.6 (2,700)
Toughness (FPL test edgewise) ^f (J mm ⁻¹ of width (in-lb in ⁻¹ of width))	0.47 (105)	0.18 (40)	0.51 (115)	1.4 (320)	—

^aLaminates made from 17 plies of 1.6-mm (1/16-in.) rotary-cut yellow birch veneer.

^bVeneer conditioned at 27 °C (80 °F) and 65% relative humidity before assembly with phenol resin film adhesive.

^cImpregnation, 25% to 30% of water-soluble phenol-formaldehyde resin based on the dry weight of untreated veneer.

^dHigh-strength paper (0.076-mm (0.003-in.) thickness) made from commercial unbleached black spruce pulp (*Mitscherlich subtilis*), phenol resin content 36.3% based on weight of treated paper, Izod impact abrasion, flatwise compression, and shear specimens, all on 12.7-mm- (1/2-in.-) thick laminate.

^eLoad applied to the surface of the original material (parallel to laminating pressure direction).

^fForest Products Laboratory (FPL) test procedure: load applied to edge of laminations (perpendicular to laminating pressure direction).

^gValues as high as 0.53 J mm⁻¹ (10.0 ft-lb in⁻¹) of notch have been reported for compreg made with alcohol-soluble resins and 0.37 J mm⁻¹ (7.0 ft-lb in⁻¹) with water-soluble resins.

^hValues based on the average slope of load–penetration plots where H_M is an expression for load per unit of spherical area of penetration of the 11.3-mm (0.444-in.) steel ball expressed in MPa (lb in⁻²).

Table 19–3. Coefficients of linear thermal expansion per degree Celsius of wood, hydrolyzed wood, and paper products^a

Material ^b	Specific gravity of product	Resin content ^c (%)	Fiber or machine direction	Linear expansion per °C (values multiplied by 10 ⁶)		
				Perpendicular to fiber or machine direction in plane of laminations	Pressing direction	Cubical expansion per °C (values multiplied by 10 ⁶)
Yellow birch laminate	0.72	3.1	3.254	40.29	36.64	80.18
Yellow birch staypak laminate	1.30	4.7	3.406	37.88	65.34	106.63
Yellow birch impreg laminate	0.86	33.2	4.648	35.11	37.05	76.81
Yellow birch compreg laminate	1.30	24.8	4.251	39.47	59.14	102.86
	1.31	34.3	4.931	39.32	54.83	99.08
Sitka spruce laminate	0.53	6.0 ^d	3.887	37.14	27.67	68.65
Parallel-laminated paper laminate	1.40	36.5	5.73	15.14	65.10	85.97
Crossbanded paper laminate	1.40	36.5	10.89	11.0 ^e	62.2	84.09
Molded hydrolyzed-wood plastic	1.33	25	42.69	42.69	42.69	128.07
Hydrolyzed-wood sheet laminate	1.39	18	13.49	224.68	77.41	115.58

^aThese coefficients refer to bone-dry material. Generally, air-dry material has a negative thermal coefficient, because the shrinkage resulting from the loss in moisture is greater than the normal thermal expansion.

^bAll wood laminates made from rotary-cut veneer, annual rings in plane of sheet.

^cOn basis of dry weight of product.

^dApproximate.

^eCalculated value.

Table 19–4. Comparison of wood treatments and the degree of dimensional stability achieved

Treatment	Antishrink efficiency (%)
Simple wax dip	2 to 5
Wood–plastic combination	10 to 15
Staypak/Staybwood	30 to 40
Impreg	65 to 70
Chemical modification	65 to 75
Polyethylene glycol	80 to 85
Formaldehyde	82 to 87
Compreg	90 to 95

use in handles for knives and other cutlery. The expansion-molding techniques of forming and curing of the compreg around the metal parts of the handle as well as attaching previously made compreg with rivets are two methods used. Compreg is currently manufactured worldwide, including the United States, United Kingdom, Pakistan, and India.

Veneer of any nonresinous species can be used for making compreg. Most properties depend upon the specific gravity to which the wood is compressed rather than the species used.

Heat Treatments

Heating wood changes the properties of wood. It can decrease the hygroscopicity and improve the dimensional stability and decay resistance. Yet, at the same time, the increase in stability and durability also increases the brittleness and loss in some strength properties, including impact toughness, modulus of rupture, and work to failure. The treatments usually cause a darkening of the wood and the wood has a tendency to crack and split.

Wood can be heated various ways: heating in the presence of moisture, heating in the presence of moisture followed by compression, heating dry wood, and heating dry wood followed by compression. The effect of the heating process on wood properties depends on the process itself. As the wood is heated, the first weight loss is due to the loss of water, followed by a variety of chemistries that produce degradation products and volatile gasses. As the temperature increases, wood cell wall polymers start to degrade. Pyrolysis of the hemicelluloses takes place about 270 °C followed closely by cellulose. Lignin is much more stable to high temperature.

Many of the commercial heat treating processes take place in the absence of air at temperatures ranging from 180 to 260 °C for times ranging from a few minutes to several hours. Temperatures lower than 140 °C result in less change in physical properties, and heating above 300 °C results in severe wood degradation. Wood has been heated in steam, in an inert gas, below molten metal, and in hot oil baths. Improved dimensional stability and durability are thought to be due to a loss of hydroscopic hemicellulose sugars and their conversion to furan-based polymers that are much less

hydroscopic, and the lost sugars decrease the ability of fungi to attack the heated wood. The weight loss is proportional to the square of the reduction in swelling.

A variety of thermal modification processes have been developed. The results of the process depend on several variables, including time and temperature, treatment atmosphere, wood species, moisture content, wood dimensions, and the use of a catalyst. Temperature and time of treatment are the most critical elements. Treatments done in air result in oxidation reactions not leading to the desired properties of the treated wood. Generally, weight loss occurs to a greater extent in hardwoods than in softwoods.

Several names have been given to the various heat-treated products and treatments for wood, including Staypak and Staybwood in the United States, Lignostone and Lignofol in Germany, Jicwood and Jablo in the United Kingdom, ThermoWood in Finland, Plato in the Netherlands, and Perdure and Retification in France.

Heating wood under a variety of conditions is an environmentally benign process requiring no added chemicals and gives rise to a variety of products with decreased moisture contents and some durability against biological degradation. However, it is not recommended to be used in ground contact. Most physical properties are decreased, especially abrasion resistance and toughness, and it is therefore not suitable for load-bearing applications.

Heating Wet Wood

Wood with moisture content close to its equilibrium moisture content (EMC) that is heated to 180 to 200 °C results in a wood with greatly decreased moisture content. The high temperature degrades the hemicellulose sugars to furan-based intermediates and volatile gasses. The furan intermediates have a lower EMC than the sugars and increase bonding of the wood structure. At a weight loss of approximately 25%, the EMC is lowered by almost the same percentage. Dimensional stability is also increased but not as much as heating followed by compression (discussed in the following section).

Two current processes are based on heating wet wood for stability and increased biological resistance. ThermoWood was developed by VTT in Finland and is a three-stage process done in the presence of steam, which helps protect the wood from oxidative reactions. In the first stage, the wood is heated to 100 °C for almost 20 h. In the second stage, the wood is heated to 185 to 230 °C for 10 h, followed by the lowering of the temperature in the presence of a water spray.

Plato (Proving Lasting Advanced Timber Option) wood was developed by Royal Dutch Shell in The Netherlands and involves a four-stage process. The first stage involves heating the wood to 150 to 180 °C under high-pressure steam for 4 to 5 h. The wood is then dried to a moisture content of 8% to 10% and then heated again at 150 to 190 °C for 12 to

16 h, resulting in a drop in moisture content to less than 1%. The wood is then conditioned to 4% to 6% moisture over a 3-day period. The wood is dark brown in color but will weather to the normal gray color in time. It has a 5% to 20% decrease in modulus of rupture but a slightly higher modulus of elasticity.

The Le Bois Perdure process was developed by the French company BCI in the mid-1990s and has been commercialized by PCI Industries, Inc., based in Quebec. The process involves drying and heating the wood at 200 to 230 °C in steam.

All heat-treated wood is gluable and paintable and can be used for furniture, flooring, decking, door and window components, and exterior joinery.

Heating Wet Wood Followed by Compression

When wet wood is heated to 180 to 220 °C and compressed, the wood structure is compressed and remains in this compressed state when dried. The compressed wood is much harder and has a much higher modulus of rupture and elongation. Re-wetting the compressed wood reverses the process and it swells back to its original thickness.

Heating Dry Wood

Heating wood under drying conditions at higher temperatures (95 to 320 °C (200 to 600 °F)) than those normally used in kiln drying produces a product known as Staybwood that decreases the hygroscopicity and subsequent swelling and shrinking of the wood appreciably. However, the stabilization is always accompanied by loss of mechanical properties. Toughness and resistance to abrasion are most seriously affected.

Under conditions that cause a reduction of 40% in shrinking and swelling, the toughness is decreased to less than half that of the original wood. Extensive research to minimize this loss was not successful. Because of the reduction in strength properties from heating at such high temperatures, wood that is dimensionally stabilized in this manner was never commercialized.

One commercial process produces dry-heated wood products. Retification is a process developed in France by École des Mines de St. Etienne and involves heating wood in a nitrogen atmosphere to 180 to 250 °C for several hours.

Heating Dry Wood Followed by Compression

To meet the demand for a tougher compressed product than compreg, a compressed wood containing no resin (staypak) was developed. A temperature range of 150 to 170 °C is used, and the wood is compressed while heated. It does not lose its compression under swelling conditions as does untreated compressed wood. In making staypak, the compressing conditions are modified so that the lignin-cementing material between the cellulose fibers flows sufficiently to eliminate internal stresses.

Staypak is not as water resistant as compreg, but it is about twice as tough and has higher tensile and flexural strength properties (Tables 19–1 and 19–2). The natural finish of staypak is almost equal to that of compreg. Under weathering conditions, however, it is definitely inferior to compreg. For outdoor use, a good synthetic resin varnish or paint finish should be applied to staypak.

Staypak can be used in the same way as compreg where extremely high water resistance is not needed. It shows promise in tool handles, forming dies, connector plates, propellers, and picker sticks and shuttles for weaving, where high impact strength is needed. Staypak is not impregnated; therefore, it can be made from solid wood as well as from veneer. The cost of staypak is less than that of compreg.

A material similar to staypak was produced in Germany prior to World War II. It was a compressed solid wood with much less dimensional stability than staypak and was known as lignostone. Another similar German product was a laminated compressed wood known as lignofol.

Wood Treated with Polyethylene Glycol (PEG)

The dimensional stabilization of wood with polyethylene glycol-1000 (PEG), also known as Carbowax, is accomplished by bulking the fiber to keep the wood in a partially swollen condition. PEG acts in the same manner as does the previously described phenolic resin. It cannot be further cured. The only reason for heating the wood after treatment is to drive off water. PEG remains water soluble in the wood. Above 60% relative humidity, it is a strong humectant and, unless used with care and properly protected, PEG-treated wood can become sticky at high levels of relative humidity. Because of this, PEG-treated wood is usually finished with a polyurethane varnish.

Treatment with PEG is facilitated by using green wood. Here, pressure is not applied because the treatment is based on diffusion. Treating times are such that uniform uptakes of 25% to 30% of chemical are achieved (based on dry weight of wood). The time necessary for this uptake depends on the thickness of the wood and may require weeks. The PEG treatment is being effectively used for cross-sectional wood plaques and other decorative items. Table tops of high quality furniture stay remarkably flat and dimensionally stable when made from PEG-treated wood.

Another application of this chemical is to decrease the checking of green wood during drying. For this application, a high degree of PEG penetration is not required. This method of treatment has been used to decrease checking during drying of small wood blanks or turnings.

Cracking and distortion that old, waterlogged wood undergoes when it is dried can be substantially decreased by treating the wood with PEG. The process was used to dry 200-year-old waterlogged wooden boats raised from Lake George, New York. The “Vasa,” a Swedish ship that sank

Table 19–5. Strength properties of wood–polymer composites^a

Strength property	Unit	Untreated ^b	Treated ^b
Static bending			
Modulus of elasticity	MPa ($\times 10^3$ lb in ⁻²)	9.3 (1,356)	11.6 (1,691)
Fiber stress at proportional limit	MPa (lb in ⁻²)	44.0 (6,387)	79.8 (11,582)
Modulus of rupture	MPa (lb in ⁻²)	73.4 (10,649)	130.6 (18,944)
Work to proportional limit	$\mu\text{J mm}^{-3}$ (in-lb in ⁻³)	11.4 (1.66)	29.1 (4.22)
Work to maximum load	$\mu\text{J mm}^{-3}$ (in-lb in ⁻³)	69.4 (10.06)	122.8 (17.81)
Compression parallel to grain			
Modulus of elasticity	GPa ($\times 10^6$ lb in ⁻²)	7.7 (1,113)	11.4 (1,650)
Fiber stress at proportional limit	MPa (lb in ⁻²)	29.6 (4,295)	52.0 (7,543)
Maximum crushing strength	MPa (lb in ⁻²)	44.8 (6,505)	68.0 (9,864)
Work to proportional limit	$\mu\text{J mm}^{-3}$ (in-lb in ⁻³)	77.8 (11.28)	147.6 (21.41)
Toughness	$\mu\text{J mm}^{-3}$ (in-lb in ⁻³)	288.2 (41.8)	431.6 (62.6)

^aMethyl methacrylate impregnated basswood.

^bMoisture content 7.2%.

on its initial trial voyage in 1628, was also treated after it was raised. There have been many applications of PEG treatment for the restoration of waterlogged wood from archeological sites.

Wood–Polymer Composites

In the modified wood products previously discussed, most of the chemical resides in cell walls; the lumens are essentially empty. If wood is vacuum impregnated with certain liquid vinyl monomers that do not swell wood and are later polymerized *in situ* by gamma radiation or chemical catalyst-heat systems, the resulting polymer resides almost exclusively in the lumens. Methyl methacrylate is a common monomer used for wood–polymer composites. It is converted to polymethyl methacrylate. The hygroscopic characteristics of the wood substance are not altered because little, if any, polymer penetrates the cell walls. However, because of the high polymer content (70% to 100% based on the dry weight of wood), the normally high void volume of wood is greatly decreased. With the elimination of this very important pathway for vapor or liquid water diffusion, the response of the wood substance to changes in relative humidity or water is very slow, and moisture resistance or water-repellent effectiveness (WRE) is greatly improved. Water-repellent effectiveness is measured as follows:

$$\text{WRE} = \frac{S_1}{S_2} \times 100 \quad (19-1)$$

where S_1 is the swelling or moisture uptake of the control specimen during exposure to water for t minutes, and S_2 is the swelling or moisture uptake of the treated specimen during exposure to water also for t minutes.

Wood–polymer composite materials offer desirable aesthetic appearance, high compression strength and abrasion resistance, and increase in hardness and are much stronger than untreated wood (Table 19–5). Commercial application of these products is largely based on increased strength and hardness properties. Improvements in physical properties

of wood–polymer composites are related to polymer loading. This, in turn, depends not only on the permeability of the wood species but also on the particular piece of wood being treated. Sapwood is filled to a much greater extent than heartwood for most species. The most commonly used monomers include styrene, methyl methacrylate, vinyl acetate, and acrylonitrile. Industrial applications include certain sporting equipment, musical instruments, decorative objects, and high-performance flooring.

At present, the main commercial use of wood–polymer composites is hardwood flooring. Comparative tests with conventional wood flooring indicate that wood–polymer materials resisted indentation from rolling, concentrated, and impact loads better than did white oak. This is largely attributed to improved hardness. Abrasion resistance is also increased. A finish is usually used on these products to increase hardness and wear resistance even more. Wood–polymer composites are also being used for sporting goods, musical instruments, and novelty items.

In addition to the use of vinyl monomers for wood–polymer composites, polysaccharides from renewable resources are also used. Examples include the use of furfuryl alcohol from primarily corn cobs and the use of modified polysaccharides primarily from soy and corn starch. The process (Indurite) involves the impregnation of wood with a water-soluble polysaccharide solution made from soy and corn starch, followed by a curing step at 70 °C. The treatment improves the dimensional stability and hardness of wood and is used in production of flooring materials.

Modification of wood with furfuryl alcohol is called furfurylation. Stamm started research on furfurylation at the Forest Products Laboratory in the 1950s. The process was industrialized in the mid-1960s in the United States, and furfurylated wood products included knife handles, bench tops, and rotor blades, but production ceased by the 1970s. Interest renewed in the late 1980s, and now products are marketed in the United States and Europe. Furfurylation

involves a full cell impregnation step of the treatment solution, an intermediate drying step, a reaction curing step, and a final kiln-drying step. Products are available for decking, marine application, cladding, window joinery, poles, roofs, garden furniture, building materials, and flooring. Impact strength is strongly decreased (from –25% at 15% WPG to –65% at 125% WPG). Stiffness increases from 30% to 80%. The ASE ranges from 30% to 80%. Fungal durability and insect resistance are high at high weight gains.

Chemical Modification

Through chemical reactions, it is possible to add an organic chemical to the hydroxyl groups on wood cell wall components. This type of treatment bulks the cell wall with a permanently bonded chemical. Many reactive chemicals have been used experimentally to chemically modify wood. For best results, chemicals used should be capable of reacting with wood hydroxyls under neutral or mildly alkaline conditions at temperatures less than 120 °C. The chemical system should be simple and must be capable of swelling the wood structure to facilitate penetration. The complete molecule should react quickly with wood components to yield stable chemical bonds while the treated wood retains the desirable properties of untreated wood. Reaction of wood with chemicals such as anhydrides, epoxides, isocyanates, acid chlorides, carboxylic acids, lactones, alkyl chlorides, and nitriles result in antishrink efficiency (ASE) values (Table 19–4) of 65% to 75% at chemical weight gains of 20% to 30%. Antishrink efficiency is determined as follows:

$$S = \frac{V_2 - V_1}{V_1} \times 100 \quad (19-2)$$

where S is volumetric swelling coefficient, V_2 is wood volume after humidity conditioning or wetting with water, and V_1 is wood volume of oven-dried sample before conditioning or wetting. Then,

$$ASE = \frac{S_2 - S_1}{S_1} \times 100 \quad (19-3)$$

where ASE is reduction in swelling or antishrink efficiency resulting from a treatment, S_2 is treated volumetric swelling coefficient, and S_1 is untreated volumetric swelling coefficient.

Reaction of these chemicals with wood yields a modified wood with increased dimensional stability and improved resistance to termites, decay, and marine organisms.

Mechanical properties of chemically modified wood are essentially unchanged compared with untreated wood.

Modification of wood with acetic anhydride has been researched extensively. The acetylation process involves impregnation of acetic anhydride followed by heat to start the reaction. The last step is to remove the acetic acid by-product and any remaining acetic anhydride. The hydroxyl groups of the cell wall polymers are converted to acetyl

groups, making the wood hydrophobic. As a result, biological durability and dimensional stability increase significantly compared with unmodified wood. Acetylated wood is now commercially available.

The reaction of formaldehyde with wood hydroxyl groups is an interesting variation of chemical modification. At weight gains as low as 2%, formaldehyde-treated wood is not attacked by wood-destroying fungi. An antishrink efficiency (Table 19–4) of 47% is achieved at a weight gain of 3.1%, 55% at 4.1%, 60% at 5.5%, and 90% at 7%. The mechanical properties of formaldehyde-treated wood are all decreased from those of untreated wood. A definite embrittlement is observed, toughness and abrasion resistance are greatly decreased, crushing strength and bending strength are decreased about 20%, and impact bending strength is decreased up to 50%.

Paper-Based Plastic Laminates

Commercially, paper-based plastic laminates are of two types: industrial and decorative. Total annual production is equally divided between the two types. They are made by superimposing layers of paper that have been impregnated with a resinous binder and curing the assembly under heat and pressure.

Industrial Laminates

Industrial laminates are produced to perform specific functions requiring materials with predetermined balances of mechanical, electrical, and chemical properties. The most common use of such laminates is electrical insulation. The paper reinforcements used in the laminates are kraft pulp, alpha pulp, cotton linters, or blends of these. Kraft paper emphasizes mechanical strength and dielectric strength perpendicular to laminations. Alpha paper is used for its electric and electronic properties, machineability, and dimensional stability. Cotton linter paper combines greater strength than alpha paper with excellent moisture resistance.

Phenolic resins are the most suitable resins for impregnating the paper from the standpoint of high water resistance, low swelling and shrinking, and high strength properties (except for impact). Phenolics also cost less than do other resins that give comparable properties. Water-soluble resins of the type used for impreg impart the highest water resistance and compressive strength properties to the product, but they make the product brittle (low impact strength). Alcohol-soluble phenolic resins produce a considerably tougher product, but the resins fail to penetrate the fibers as well as water-soluble resins, thus imparting less water resistance and dimensional stability to the product. In practice, alcohol-soluble phenolic resins are generally used.

Paper-based plastic laminates inherit their final properties from the paper from which they are made. High-strength papers yield higher strength plastic laminates than do low-strength papers. Papers with definite directional properties

Chapter 19 Specialty Treatments

result in plastic laminates with definite directional properties unless they are cross laminated (alternate sheets oriented with the machine direction at 90° to each other).

The use of higher strength paper has helped in the development of paper-based laminates suitable for structural use. Pulping under milder conditions and operating the paper machines to give optimum orientation of the fibers in one direction, together with the desired absorbency, contribute markedly to improvements in strength.

Strength and other properties of a paper-plastic laminate are shown in Table 19-2. The National Electrical Manufacturers Association L1-1 specification has additional information on industrial laminates. Paper is considerably less expensive than glass fabric or other woven fabric mats and can be molded at considerably lower pressures; therefore, the paper-based laminates generally have an appreciable price advantage over fabric laminates. However, some fabric laminates give superior electrical properties and higher impact properties. Glass fabric laminates can be molded to greater double curvatures than can paper laminates.

During World War II, a high-strength paper plastic known as papreg was used for molding nonstructural and semistructural airplane parts such as gunner's seats and turrets, ammunition boxes, wing tabs, and the surfaces of cargo aircraft flooring and catwalks. Papreg was used to a limited extent for the skin surface of airplane structural parts, such as wing tips. One major objection to its use for such parts is that it is more brittle than aluminum and requires special fittings. Papreg has been used to some extent for heavy-duty truck floors and industrial processing trays for nonedible materials. Because it can be molded at low pressures and is made from thin paper, papreg is advantageous for use where accurate control of panel thickness is required.

Decorative Laminates

Although made by the same process as industrial laminates, decorative laminates are used for different purposes and bear little outward resemblance to industrial laminate. They are used as facings for doors and walls and tops of counters, flooring, tables, desks, and other furniture.

These decorative laminates are usually composed of a combination of phenolic- and melamine-impregnated sheets of paper. Phenolic-impregnated sheets are brown because of the impregnating resins and make up most of the built-up thickness of the laminate. Phenolic sheets are overlaid with paper impregnated with melamine resin. One sheet of the overlay is usually a relatively thick one of high opacity and has the color or design printed on it. Then, one or more tissue-thin sheets, which become transparent after the resin is cured, are overlaid on the printed sheet to protect it in service. The thin sheets generally contain more melamine resin than do the printed sheets, providing stain and abrasion resistance as well as resistance to cigarette burns, boiling water, and common household solvents.

The resin-impregnated sheets of paper are hot pressed, cured, and then bonded to a wood-based core, usually plywood, hardboard, or particleboard. The thin transparent (when cured) papers impregnated with melamine resin can be used alone as a covering for decorative veneers in furniture to provide a permanent finish. In this use, the impregnated sheet is bonded to the wood surface in hot presses at the same time the resin is cured. The heat and stain resistance and the strength of this kind of film make it a superior finish.

The overall thickness of a laminate may obviously be varied by the number of sheets of kraft-phenolic used in the core assembly. Some years ago, a 2-mm (0.08-in.) thickness was used with little exception because of its high impact strength and resistance to substrate show through. Recently, a 1-mm (0.04-in.) thickness has become popular on vertical surfaces such as walls, cabinet doors, and vertical furniture faces. This results in better economy, and the greater strength of the heavier laminate is not necessary. As applications have proliferated, a series of thicknesses have been offered, from 20 to 60 mm (0.8 to 2.4 in.), even up to 150 mm (6 in.) when self-supportive types are needed. These laminates may have decorative faces on both sides if desired, especially in the heavier thicknesses. Replacement bowling lanes made from high-density fiberboard core and phenolic-melamine, high-pressure laminated paper on the face and back are commercially used.

The phenolic sheets may also contain special postforming-type phenolic resins or extensible papers that make it possible to postform the laminate. By heating to 160 °C (320 °F) for a short time, the structure can readily undergo simple bending to a radius of 10 mm (0.4 in.), and 5 to 6 mm (0.20 to 0.24 in.) with careful control. Rolled furniture edges, decorative moldings, curved counter tops, shower enclosures, and many other applications are served by this technique. Finally, the core composition may be modified to yield a fire-retardant, low-smoking laminate to comply with fire codes. These high-pressure decorative laminates are covered by the National Electrical Manufacturers Association Specification LD-3.

Paper will absorb or give off moisture, depending upon conditions of exposure. This moisture change causes paper to shrink and swell, usually more across the machine direction than along it. In the same manner, the laminated paper plastics shrink and swell, although at a much slower rate. Cross laminating minimizes the amount of this shrinking and swelling. In many furniture uses where laminates are bonded to cores, the changes in dimension as a result of moisture fluctuating with the seasons are different than those of the core material. To balance the construction, a paper plastic with similar properties may be glued to the opposite face of the core to prevent bowing or cupping caused by moisture variation.

Lignin-Filled Laminates

The cost of phenolic resins at one time resulted in considerable effort to find impregnating and bonding agents that were less expensive and yet readily available. Lignin-filled laminates made with lignin recovered from the spent liquor of the soda pulping process were developed as a result of this search. Lignin is precipitated from solution within the pulp or added in a pre-precipitated form before the paper is made. The lignin-filled sheets of paper can be laminated without the addition of other resins, but their water resistance is considerably enhanced when some phenolic resin is applied to the paper in a second operation. The water resistance can also be improved by impregnating only the surface sheet with phenolic resin. It is also possible to introduce lignin, together with phenolic resin, into untreated paper sheets. The lignin-filled laminates are always dark brown or black. They have better toughness than phenolic laminates; in most other strength properties, they are comparable or lower.

Reduction in cost of phenolic resins has virtually eliminated the lignin-filled laminates from U.S. commerce. These laminates have several potential applications, however, where a cheaper laminate with less critical properties than phenolic laminates can be used.

Paper-Face Overlays

Paper has found considerable use as an overlay material for veneer or plywood. Overlays can be classified into three different types according to their use—masking, structural, and decorative. Masking overlays are used to cover minor defects in plywood, such as face checks and patches, minimize grain raising, and provide a more uniform paintable surface, thus making possible the use of lower grade veneer. Paper for this purpose need not be of high strength, because the overlays do not need to add strength to the product. For adequate masking, a single surface sheet with a thickness of 0.5 to 1 mm (0.02 to 0.04 in.) is desirable. Paper impregnated with phenolic resins at 17% to 25% of the weight of the paper gives the best all-around product. Higher resin content makes the product too costly and tends to make the overlay more transparent. Appreciably lower resin content gives a product with low scratch and abrasion resistance, especially when the panels are wet or exposed to high relative humidities.

The paper faces can be applied at the same time that the veneer is assembled into plywood in a hot press. Thermal stresses that might result in checking are not set up if the machine direction of the paper overlays is at right angles to the grain direction of the face plies of the plywood.

The masking-paper-based overlays or vulcanized fiber sheets have been used for such applications as wood house siding that is to be painted. These overlays mask defects in the wood, prevent bleed-through of resins and extractives in the wood, and provide a better substrate for paint. The

paper-based overlays improve the across-the-board stability from changes in dimension as a result of changes in moisture content.

The structural overlay, also known as the high-density overlay, contains no less than 45% thermosetting resins, generally phenolic. It consists of one or more plies of paper similar to that used in the industrial laminates described previously. The resin-impregnated papers can be bonded directly to the surface of a wood substrate during cure of the sheet, thus requiring only a single pressing operation.

The decorative-type overlay is described in the Decorative Laminates section.

References

- Clark, W.M. 1965. Veneering and wood bending in the furniture industry. New York, NY: Pergamon Press.
- Deka, M.; Saikia, C.N. 2000. Chemical modification of wood with thermosetting resin: effect on dimensional stability and strength property. *Bioresource Technology*. 73(2): 179–181.
- Finnish Thermowood Association. 2000. Helsinki, Finland: Wood Focus Oy, P.O. Box 284, Snellmaninkatu 13, FIN-00171. www.thermowood.fi. (December 2000).
- FPL. 1962. Physical and mechanical properties of lignin-filled laminated paper plastic. FPL Rep. 1579. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
- Franich, R. 2007. The Indurite™ Process—a review from concept to business. In: Hill, C.A.S.; Jones, D.; Miltz, H.; Ormondroyd, G.A., eds. *Proceedings, 3rd European conference on wood modification*. Cardiff, UK: 23–29.
- Goldstein, I.S. 1955. The impregnation of wood to impart resistance to alkali and acid. *Forest Products Journal*. 5: 265–267.
- Heebink, B.G. 1959. Fluid-pressure molding of plywood. FPL Rep. 1624. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
- Heebink, B.G. 1963. Importance of balanced construction in plastic-faced wood panels. Res. Note FPL–021. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
- Heebink, B.G.; Haskell, H.H. 1962. Effect of heat and humidity on the properties of high-pressure laminates. *Forest Products Journal*. 12(11): 542–548.
- Hill, C.A.S. 2006. *Wood modification: chemical, thermal and other processes*. Chichester, West Sussex, UK: John Wiley and Sons, Ltd.
- Hoadley, R.B. 1980. *Understanding wood: a craftsman's guide to wood technology*. Newtown, CT: The Taunton Press.

Chapter 19 Specialty Treatments

- Hurst, K. 1962. Plywood bending. *Australian Timber Journal*. (June.)
- Inoue, M.; Norimoto, M.; Tanahashi, M.; Rowell, R.M. 1993. Steam and heat fixation of compressed wood. *Wood and Fiber Science*. 25(3): 224–235.
- Jorgensen, R.N. 1965. Furniture wood bending, part I. *Furniture Design and Manufacturing*. (December.)
- Jorgensen, R.N. 1966. Furniture wood bending, part II. *Furniture Design and Manufacturing*. (January.)
- Langwig, J.E.; Meyer, J.A.; Davidson, R.W. 1968. Influence of polymer impregnation on mechanical properties of bass-wood. *Forest Products Journal*. 18(7): 33–36.
- McKean, H.B.; Blumenstein, R.R.; Finnorn, W.F. 1952. Laminating and steam bending of treated and untreated oak for ship timbers. *Southern Lumberman*. 185: 2321.
- Meyer, J.A. 1965. Treatment of wood-polymer systems using catalyst-heat techniques. *Forest Products Journal*. 15(9): 362–364.
- Meyer, J.A. 1981. Wood-polymer materials: state of the art. *Wood Science*. 14(2): 49–54.
- Meyer, J.A.; Loos, W.E. 1969. Treating Southern Pine wood for modification of properties. *Forest Products Journal*. 19(12): 32–38.
- NEMA. [Current edition]. Standard specification for industrial laminated thermosetting products, Designation L1–1; standard specification for high-pressure decorative laminates, Designation LD–3. Washington, DC: National Electrical Manufacturers Association.
- Peck, E.C. 1957. Bending solid wood to form. *Agric. Handb.* 125. Washington, DC: U.S. Department of Agriculture.
- Perry, T.D. 1951. Curves from flat plywood. *Wood Products*. 56(4).
- Rapp, A.O. 2001. Review on heat treatments of wood. Cost Action E22. Proceedings of special seminar; 2001 February 9; Antibes, France. 66 p.
- Rowell, R.M. 1975. Chemical modification of wood: advantages and disadvantages. Proceedings, American Wood Protection Association (AWPA), formerly American Wood-Preservers' Association. 71: 41–51.
- Rowell, R.M., ed. 1984. The chemistry of solid wood. *Advances in Chemistry Series No. 207*. Washington, DC: American Chemical Society.
- Rowell, R.M., ed. 2005. *Handbook of wood chemistry and wood composites*. Boca Raton, FL: CRC Press. 487 p.
- Rowell, R.M.; Lange, S.; McSweeney, J.; Davis, M. 2002. Modification of wood fiber using steam. In: Proceedings, 6th Pacific Rim bio-based composites symposium. Portland, OR.
- Schneider, M. 1994. Wood polymer composites. *Wood and Fiber Science*. 26(1): 142–151.
- Schneider, M.; Witt, A.E. 2004. History of wood polymer composites commercialization. *Forest Products Journal*. 54(4): 19–24.
- Schuerch, C. 1964. Principles and potential of wood plasticization. *Forest Products Journal*. 14(9): 377–381.
- Seborg, R.M.; Inverarity, R.B. 1962. Preservation of old, waterlogged wood by treatment with polyethylene glycol. *Science*. 136(3516): 649–650.
- Seborg, R.M.; Vallier, A.E. 1954. Application of impreg for patterns and die models. *Forest Products Journal*. 4(5): 305–312.
- Seborg, R.M.; Millett, M.A.; Stamm, A.J. 1945. Heat-stabilized compressed wood (staypak). *Mechanical Engineering*. 67(1): 25–31.
- Seidl, R.J. 1947. Paper and plastic overlays for veneer and plywood. Madison, WI: Forest Products Research Society Proceedings. 1: 23–32.
- Shafizadeh, F.; Chin, P.P.S. 1977. Thermal degradation of wood. In: Goldstein, I.S., ed. *Wood technology: chemical aspects*. ACS Symposium Series 43: 57–81.
- Spielman, F. 1980. Working green wood with PEG. New York, NY: Sterling Publishing Company.
- Stamm, A.J. 1959. Effect of polyethylene glycol on dimensional stability of wood. *Forest Products Journal*. 9(10): 375–381.
- Stamm, A.J. 1964. *Wood and cellulose science*. New York, NY: Ronald Press.
- Stamm, A.J.; Hansen, L.A. 1937. Minimizing wood shrinkage and swelling. Effect of heating in various gasses. *Industrial and Engineering Chemistry*. 29(7): 831–833.
- Stamm, A.J.; Seborg, R.M. 1951. Forest Products Laboratory resin-treated laminated, compressed wood (compreg). FPL Rep. 1381. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
- Stamm, A.J.; Seborg, R.M. 1962. Forest Products Laboratory resin-treated wood (impreg). FPL Rep. 1380 (rev.). Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
- Stamm, A.J.; Burr, H.K.; Kline, A.A. 1946. Staybwood. Heat stabilized wood. *Industrial and Engineering Chemistry*. 38(6): 630–634.
- Stevens, W.C.; Turner, N. 1970. *Wood bending handbook*. London, England: Her Majesty's Stationery Office.

Tiemann, H.D. 1915. The effect of different methods of drying on the strength of wood. *Lumber World Review*. 28(7): 19–20.

Weatherwax, R.C.; Stamm, A.J. 1945. Electrical resistivity of resin-treated wood (impreg and compreg), hydrolyzed-wood sheet (hydroxylin), and laminated resin-treated paper (papreg). FPL Rep. 1385. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Weatherwax, R.C.; Stamm, A.J. 1946. The coefficients of thermal expansion of wood and wood products. *Transactions of American Society of Mechanical Engineering*. 69(44): 421–432.

Welzbacher, C.R.; Rapp, A.O. 2007. Durability of thermally modified timber from industrial-scale processes in different use classes: results from laboratory and field tests. *Wood Material Science and Engineering*. 2: 4–14.

Westin, M.; Lande, S.; Schneider, M. 2003. Furfurylation of wood—process, properties and commercial production. In: Van Acker, J.; Hill, C.A.S., eds. *Proceedings, 1st European conference on wood modification*. Ghent, Belgium: 289–306.