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# 11 Chemistry of Wood Strength

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The source of strength in solid wood is the wood fiber. Wood is basically a series of tubular fibers or cells cemented together. Each fiber wall is composed of various quantities of three polymers: cellulose, hemicelluloses, and lignin. Cellulose is the strongest polymer in wood and, thus, is highly responsible for strength in the wood fiber because of its high degree of polymerization and linear orientation. The hemicelluloses act as a matrix for the cellulose and increase the packing density of the cell wall; hemicelluloses and lignin are also closely associated. The actual role of hemicelluloses in wood strength has recently been shown to be far more critical toward the overall engineering performance of wood than had previously been assumed. We suspect the primary role of hemicelluloses is to act as a highly specific coupling agent capable of associating both with the more random areas (i.e., noncrystalline) of hydrophilic cellulose and the more amorphous hydrophobic lignin. Lignin not only holds wood fibers themselves together but also helps bind carbohydrate molecules together within the cell wall of the wood fiber. The chemical components of wood that are responsible for mechanical properties can be viewed from three levels: macroscopic (cellular), microscopic (cell wall), and molecular (polymeric) (Winandy and Rowell 1984). Mechanical properties change with changes in the thermal, chemical, and/or biochemical environment. Changes in temperature, pressure, humidity, pH, chemical adsorption from the environment, UV radiation, fire, or biological degradation can have significant effects on the strength of wood.

Cellulose has long been thought to be primarily responsible for strength in the wood fiber because of its high degree of polymerization and linear orientation. Hemicellulose may act as a link between the fibrous cellulose and the amorphous lignin. Hemicellulose definitely acts as a matrix for the cellulose and to increase the packing density of the cell wall. Lignin, a phenolic compound, not only holds the fibers together but also acts as a stiffening agent for the cellulose molecules within the fiber cell wall. All three cell wall components contribute in different degrees to the strength of wood. Together the tubular structure and the polymeric construction are responsible for most of the physical and chemical properties exhibited by wood.

The strength of wood can be altered by environmental agents. The changes in pH, moisture, and temperature; the influence of decay, fire, and UV radiation; and the adsorption of chemicals from the environment can have a significant effect on strength properties. Environmentally induced changes must be considered in any discussion on the strength of treated or untreated wood. This susceptibility of wood to strength loss, and the magnitude of that degrade, is directly related to the severity of its thermal/chemical/biochemical exposure.

The strength of wood can also be altered by preservative and fire-retardant compounds used to prevent environmental degradation. In some cases, the loss in mechanical properties caused by these treatments may be large enough that the treated material can no longer be considered the same as the untreated material. The treated wood may now resist environmental degradation but may be structurally inferior to the untreated material. A long-term study of this problem has helped engineers account for these potential alterations from untreated wood in the structural design process. The approach is based on a cumulative-damage approach relating thermal and chemical degradation of the polymers responsible for wood strength to kinetic- or mechanical-based models (Lebow and Winandy 1999a, Winandy and Lebow 2001). With preservative-treated wood, a large amount of work was undertaken in the late 1980s and early 1990s to address treatment-related concerns in the structural design process. This work developed an understanding of the thermochemical issues that primarily control preservative-related strength loss (Winandy 1996a) and was then used to limit treatment-processing levels in standards, especially post-treatment kiln-drying temperatures (Winandy 1996b). With fire-retardant treated (FRT) wood, a large amount of work has recently addressed past problems with in-service thermal degradation of FRT wood exposed to elevated in-service temperatures and that work has been summarized (Winandy 2001).

This chapter presents a theoretical model to explain the relationship between the mechanical properties and the chemical components of wood. This model is then used to describe the effects of altered composition on those mechanical properties. Many of the theories presented are only partially proven and just beginning to be understood. These theories should be considered as a starting point for dialogue between chemists and engineers that will eventually lead to a better understanding of the chemistry of wood strength.

## 11.1 MECHANICAL PROPERTIES

Even wood that has no discernible defects has extremely variable properties as a result of its heterogeneous composition and natural growth patterns. Wood is an anisotropic material in that the mechanical properties vary with respect to the three mutually perpendicular axes of the material (radial, tangential, and longitudinal). These natural characteristics are compounded further by the environmental influences encountered during the growth of the living tree. Yet wood is a viable construction material because workable estimates of the mechanical properties have been developed.

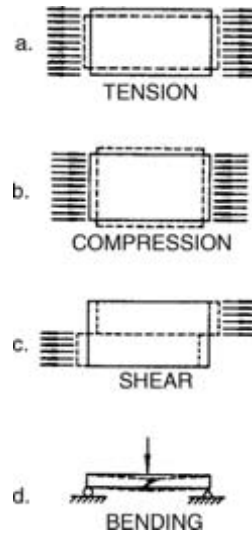
Mechanical properties relate a material's resistance to imposed loads (i.e., forces). Mechanical properties include the following: (1) measures of resistance to deformations and distortions (elastic properties), (2) measures of failure-related (strength) properties, and (3) measures of other performance-related issues. To preface any discussion concerning mechanical properties, two concepts need to be explained: stress ( $\sigma$ ) and strain ( $\epsilon$ ).

Stress is a measure of the internal forces exerted in a material as a result of an application of an external force (i.e., load). Three types of primary stress exist: tensile stress, which pulls or elongates an object (Figure 11.1a); compressive stress, which pushes or compresses an object (Figure 11.1b); and shear stress, which causes two contiguous segments (i.e., internal planes) of a body to rotate (i.e., slide) within the object (Figure 11.1c). Bending stress (Figure 11.1d) is a combination of all three of the primary stresses and causes rotational distortion or flexure in an object.

Strain is the measure of a material's ability to deform—that is, elongate, compress, or rotate—while under stress. Over the elastic range of a material, stress and strain are related to each other in a linear manner. In elastic materials, a unit of stress ( $\sigma$ ) will cause a corresponding unit of strain ( $\epsilon$ ). This elastic theory yields one of the most critical engineering properties of a material, the elastic modulus ( $E$ ). The theory is commonly known as Hooke's law (Larson and Cox 1938):

$$E = \sigma/\epsilon \quad (11.1)$$

It applies to all elastic materials at points below their elastic or proportional limits.



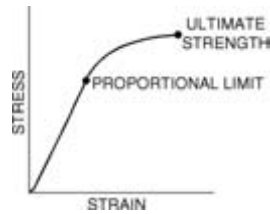
**FIGURE 11.1** Examples of the three axial and one flexural types of stress.

Elastic theory relates a material's ability to be deformed by a stress to its ability to regain its original dimensions when the stress is removed. The criterion for elasticity is not the amount of deformation but the ability of a material to completely regain its original dimensions when the stress is removed. The opposite quality is viscosity, which can also be thought of as plasticity. A perfectly plastic body is one that makes no recovery of its original dimensions upon the removal of a stress. Wood is not ideally elastic; it will not completely recover deformation immediately on unloading, but in time, residual deformations tend to be recoverable. Wood is considered a viscoelastic material. This viscoelasticity explains the creep phenomenon in which a given load will induce an immediate deformation, and if that load is allowed to remain on that piece, additional secondary deformation (i.e., creep) will continue to occur over long time periods. However, for simplicity's sake and because the engineering community often also assumes such, wood will be considered as an elastic material in this chapter.

The two main elastic moduli are modulus of elasticity, which describes the relationship of load (stress) to axial deformation (strain), and modulus of rigidity or shear modulus, which describes the internal distribution of shearing stress to shear strain or, more precisely, angular (i.e., rotational) displacement within a material.

Strength values are numerical estimates of the material's ultimate ability to resist applied forces. The major strength properties are limit values for the stress-strain relationship within a material. Strength, in these terms, is the quality that determines the greatest unit stress a material can withstand without fracture or excessive distortion. In many cases the unqualified term strength is somewhat vague. It is sometimes more useful to think of specific strengths, such as compressive, tensile, shear, or ultimate bending strengths.

The American Society for Testing and Materials (ASTM) is the ISO-accredited organization in North America that standardizes testing procedures to provide reliable and universally comparable estimates of wood strength. Several ASTM Standards for wood (see ASTM) outline procedures for determining basic mechanical properties and deriving allowable design stresses. In performing a test, a load is applied to a specimen in a particular manner and the resulting deformation is monitored. The load information allows the internal forces within the specimen (stress) to be calculated. The deformation information allows the internal distortion (strain) to be calculated when accepting specific assumptions. When stress and strain are plotted against each other on a graph, a stress-strain diagram is developed (Figure 11.2).



**FIGURE 11.2** A typical stress–strain diagram for wood.

The unit stress corresponding to the upper limit of the linear segment of the stress–strain diagram is known as the proportional limit (Figure 11.2, Point A). This proportional or elastic limit measures the boundary of a material’s completely recoverable strength. At stress levels below the proportional limit, a perfectly elastic material will regain its original dimensions and form. At stress levels in excess of the proportional limit, an elastic material will not regain its original shape; it will be permanently distorted.

The unit stress represented by the maximum ordinate is the ultimate (maximum) strength (Figure 11.2, Point B). This point estimates the maximum stress at the time of failure. Many of the mechanical properties of interest to the engineer, such as maximum crushing strength or ultimate bending strength, describe this point of maximum stress.

## 11.2 FACTORS AFFECTING STRENGTH

### 11.2.1 MATERIAL FACTORS

#### 11.2.1.1 Specific Gravity

Specific gravity is the ratio of the weight of a given volume of wood to that of an equal volume of water. As specific gravity increases, strength properties increase (USDA 1999) because internal stresses are distributed among more molecular material. Mathematical approximations of the relationship between specific gravity and various mechanical properties are shown in Table 11.1.

#### 11.2.1.2 Growth Characteristics

As a fibrous product from living trees, wood is subjected to many environmental influences as it is formed and during its lifetime. These environmental influences can increase the variability of the wood material and, thus, increase the variability of the mechanical properties. To reduce the effect of this inherent variability, standardized testing procedures using small, clear specimens of wood are often used. Small, clear specimens do not have knots, checks, splits, or reaction wood. However, the wood products used and of economic importance in the real world have these defects. Strength estimates derived from small clear specimens are reported because most chemical treatment data have been generated from small clear specimens. Further, comparative analyses of chemical treatment-related effects has clearly shown that clear wood material is affected more than material containing knots and voids (Winandy 1996a), such that it is now commonly assumed within the wood-engineering community that treatment effects are greater the more defect-free the wood material and the straighter its grain.

Because strength is affected by material factors, such as specific gravity and growth characteristics, it is important to always consider property variability. The coefficient of variation is the statistical parameter used to approximate the variability associated with each strength property. The estimated coefficient of variation of various strength properties can be found in Table 11.2.

**TABLE 11.1**  
**Relationship between Specific Gravity and Mechanical Properties**

Property	Green Wood		Wood at 12% Moisture Content	
	Softwoods	Hardwoods	Softwoods	Hardwoods
Static Bending				
MOR (KPa)	109,600	118,700	170,700	171,300
MOE (MPa)	16,100	13,900	20,500	16,500
WML (KJ/m <sup>3</sup> )	147	229	179	219
Impact Bending (N)	353	422	346	423
Compression parallel (KPa)	49,700	49,000	93,700	76,000
Compression perpendicular (KPa)	8,800	18,500	16,500	21,600
Shear parallel (KPa)	11,000	17,800	16,600	21,900
Tension perpendicular (KPa)	3,800	10,500	6,000	10,100
Side hardness (N)	6,230	16,550	85,900	15,300

*Source:* U.S. Department of Agriculture, Forest Service, 1999.

## 11.2.2 ENVIRONMENTAL FACTORS

### 11.2.2.1 Moisture

Wood, which is a hygroscopic material, gains or loses moisture to equilibrate with its immediate environment. The equilibrium moisture content (EMC) is the steady-state level that wood achieves when subjected to a particular relative humidity and temperature. The eventual EMC of two similar

**TABLE 11.2**  
**Average Coefficients of Variation for Some Mechanical Properties of Clear Wood**

Property	Coefficient of Variation
Static bending	
Modulus of rupture	16
Modulus of elasticity	22
Work to maximum load	34
Impact bending	25
Compression parallel to grain	18
Compression perpendicular to grain	28
Shear parallel to grain	14
Maximum shearing strength	14
Tension parallel to grain	25
Side hardness	20
Toughness	34
Specific gravity	10

*Source:* U.S. Department of Agriculture, Forest Service, 1999.

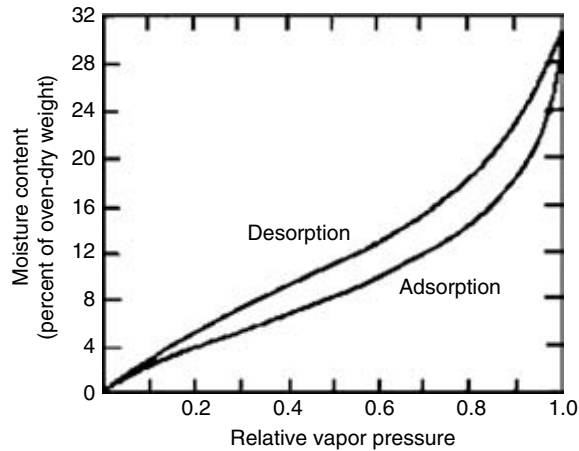


FIGURE 11.3 Adsorption–desorption isotherms for water vapor by spruce at 25°C.

specimens will differ if one approaches EMC under adsorbing conditions and the other approaches EMC under desorbing conditions. For example, if the relative vapor pressure of the environment is 0.65 (i.e., relative humidity of 65%), two similar specimens exposed under either adsorbing or desorbing conditions will equilibrate at moisture contents of approximately 11% and 13%, respectively (USDA 1999) (Figure 11.3).

Wood strength is related to the amount of water in the wood fiber cell wall (USDA 1999, Wilson 1932, Gerhards 1882). At moisture contents from oven-dry (OD) to the fiber-saturation point, water accumulates in the wood cell wall (bound water). Above the fiber-saturation point, water accumulates in the wood cell cavity (free water) and there are no tangible strength effects associated with a changing moisture content. However, at moisture contents between OD and the fiber-saturation point, water does affect strength. Increased amounts of bound water interfere with and reduce hydrogen bonding between the organic polymers of the cell wall (USDA 1999, Rowell 1980), which decreases the strength of wood. The approximate relationships are shown in Tables 11.3 and 11.4.

Not all mechanical properties change with moisture content. The performance of wood under dynamic loading conditions is a dual function of the strength of the material, which is decreased with increased moisture content, and the pliability of the material, which is increased with increased moisture content. Changes in strength and pliability somewhat offset one another, and therefore, mechanical properties that deal with dynamic loading conditions are not nearly as affected by a changing moisture content as are static mechanical properties.

### 11.2.2.2 Temperature

Strength is related to the temperature of the working environment (USDA 1999, Gerhards 1982, Barrett et al. 1989). At constant moisture content, the immediate effect of temperature on strength is linear (Figure 11.4) and usually recoverable when the temperature returns to normal. In general, the immediate strength of wood is higher in cooler temperatures and lower in warmer temperatures. However, permanent (nonrecoverable) effects can occur. This relationship of permanent strength loss during extended high-temperature exposure can be dramatically influenced by higher moisture contents.

The immediate effects of increased temperature are an increase in the plasticity of the lignin and an increase in spatial size, which reduces intermolecular contact and is, thus, recoverable. Permanent effects manifest themselves as an actual reduction in wood substance or weight loss via

**TABLE 11.3**  
**Approximate Change in Mechanical Properties of Clear Wood with Each One Percent Change in Moisture Content**

Property	Change per 1% Change in Moisture Content
Static bending	
Fiber stress at proportional limit	5
Modulus of rupture	4
Modulus of elasticity	2
Work to proportional limit	8
Work to maximum load	0.5
Impact bending	
Height of drop causing complete failure	0.5
Compression parallel to grain	
Fiber stress at proportional limit	5
Maximum crushing strength	6
Compression perpendicular to grain	
Fiber stress at proportional limit	5.5
Shear parallel to grain	
Maximum shearing strength	3
Hardness	
End	4
Side	2.5

Source: Winandy and Rowell, 1984.

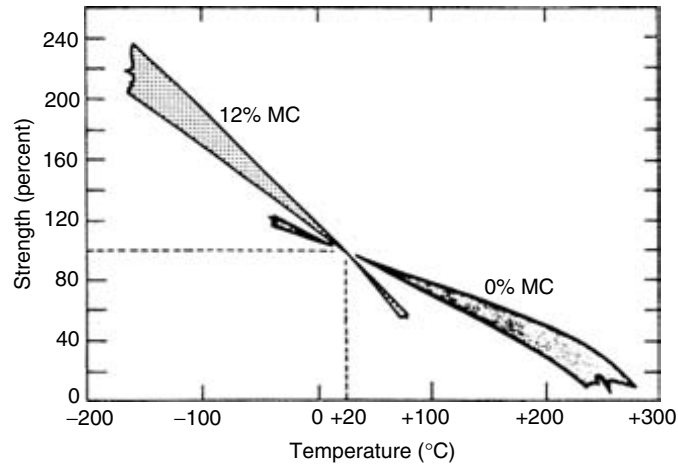
**TABLE 11.4**  
**Relationship between Some Mechanical Properties and Moisture Content**

Property	Moisture Content*				
	Green	19%	12%	8%	Oven-Dry
<b>Douglas-Fir</b>					
Modulus of rupture	62	76	100	117	161
Compression parallel to grain	52	68	100	124	192
Modulus of elasticity	80	88	100	108	125
<b>Loblolly Pine</b>					
Modulus of rupture	57	72	100	121	175
Compression parallel to grain	49	66	100	127	203
Modulus of elasticity	78	87	100	109	128
<b>Aspen</b>					
Modulus of rupture	61	75	100	118	165
Compression parallel to grain	50	67	100	126	199
Modulus of elasticity	73	83	100	111	137

Property at 12% moisture content set at 100%.

Source: Winandy and Rowell, 1984.





**FIGURE 11.4** Immediate effect of temperature on strength properties expressed as a percent of value at 20°C. Trends illustrated are composites from several studies on three strength properties (MOR,  $T_{\perp}$ , and  $C_{\parallel}$ ).

degradative mechanisms and are thereby nonrecoverable. This permanent thermal effect on wood strength has been extensively studied (LeVan et al. 1990, Winandy 2001, Green et al. 2003) and predictive kinetic-based models have been developed (Woo 1981, Lebow and Winandy 1999a, Green et al. 2003). The reasons for these permanent thermal effects on strength relate to changes in the wood polymeric substance and structure, and predictive models have been developed (Winandy and Lebow 2001).

### 11.2.3 LOAD FACTORS

#### 11.2.3.1 Duration of Load

The ability of wood to resist load is dependent upon the length of time the load is applied (USDA 1999, Gerhards 1977, Wood 1951). The load required to cause failure over a long period of time is much less than the load required to cause failure over a very short period of time. Wood under impact loading (duration of load  $> I_s$ ) can sustain nearly twice as great a load as wood subjected to long-term loading (duration of load  $> 10$  years). This time-dependent relationship (Wood 1951) can be seen graphically in Figure 11.5. Hydrolytic chemical treatments have long been known to incur brashness in wood (Wangaard 1950). More recently, the chemistry of this effect on treated wood was shown to be empirically related to loss in the ability of the hydrolyzed wood material to dissipate strain energy away from localized stress concentrations under impact-type, rapid loadings (ultimate in  $<1-2$  s) (Winandy 1995b).

#### 11.2.3.2 Fatigue

Cyclic or repeated loadings often induce fatigue failures. Fatigue resistance is a measure of a material's ability to resist repeating, vibrating, or fluctuating loads without failure. Fatigue failures often result from stress levels far lower than those required to cause static failure. Repeated or fatigue-type stresses usually result in a slow thermal buildup within the material and initiate and propagate tiny micro checks that eventually grow to a terminal size. When wood is subjected to repeated stress (e.g.,  $5.0 \times 10^7$  cycles), fatigue-related failures may be induced by stress levels as low as 25–30% of the anticipated ultimate stress under static conditions (USDA 1999, Wangaard 1950).

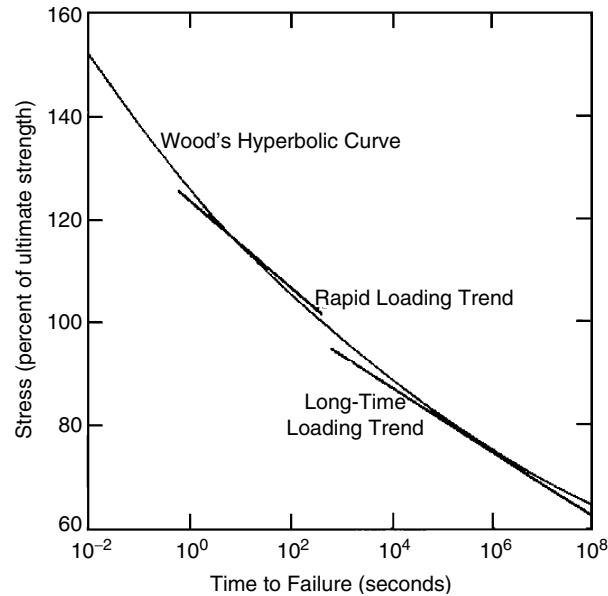


FIGURE 11.5 Hyperbolic load-duration curve with rapid loading and longtime loading trends for bending.

### 11.2.3.3 Mechanical Properties

To design with any material, mechanical property estimates need to be developed. ASTM standard test methods detail the procedures required to determine mechanical properties via stress–strain relationships (see ASTM).

### 11.2.4 FLEXURAL LOADING PROPERTIES

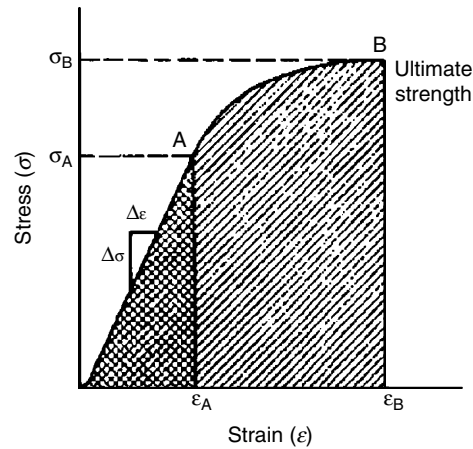
Flexural (bending) properties are important in wood design. Many structural designs recognize either bending strength or some function of bending, such as deflection, as the limiting design criterion. Structural examples in which bending-type stresses are often the limiting consideration are bridges or bookshelves. Five mechanical properties are derived from the stress-strain relationship of a standard bending test: modulus of rupture (MOR), fiber stress at proportional limit (FSPL), modulus of elasticity (MOE), work to proportional limit (WPL), and work to maximum load (WML).

#### 11.2.4.1 Modulus of Rupture

The MOR is the ultimate bending strength of a material. Thus, MOR describes the load required to cause a wood beam to fail and can be thought of as the ultimate resistance or strength that can be expected (Figure 11.2, Point B; Figure 11.6, Point B) from a wood beam exposed to bending-type stress. MOR is derived by using the flexure formula:

$$\text{MOR} = Mc/I \quad (11.2)$$

which assumes an elastic response, although that assumption is not exactly true, where  $M$  is the maximum bending moment,  $c$  is a measure of distance from the highly-stressed flanges of the beam to its neutral axis (i.e., the plane where internal stress becomes zero as those stresses change from tension on one flange to compression on the opposite), and  $I$  is the moment of inertia, which relates



**FIGURE 11.6** Examples of the relationship between a typical stress–strain diagram and some mechanical properties. Key A, proportional limit; B, ultimate strength;  $\sigma_B$ , MOR,  $\sigma_A$ , FSPL;  $\Delta\sigma/\Delta\epsilon$  (from origin to A), MOE;  $\int_0^A \sigma d\epsilon$ , WPL; and  $\int_0^B \sigma d\epsilon$ , WML.

the bending moment to the geometric shape of the beam. Engineers often simplify these geometric factors ( $c/I$ ) to a parameter known as  $S$ , the section modulus:

$$S = c/I \quad (11.3)$$

For a rectangular or square beam in bending under center point loading, the flexure formula is varied to reflect loading conditions and beam geometry:

$$\text{MOR} = 1.5 \cdot P \cdot L^2 / b \cdot h^2 \quad (11.4)$$

where  $P$  is the ultimate load,  $L$  is the span of beam,  $b$  is the width of beam, and  $h$  is the height of beam.

#### 11.2.4.2 Fiber Stress at Proportional Limit

The FSPL is the maximum bending stress a material can sustain under static conditions and still exhibit no permanent set or distortion. It is by definition the amount of unit stress on the  $y$ -coordinate at the proportional limit of the material (Figure 11.2, Point A; Figure 11.6, Point A). FSPL is also derived using the flexure formula, where  $M$  is the bending moment at the proportional limit and  $S$  is the section modulus.

#### 11.2.4.3 Modulus of Elasticity

The MOE quantifies a material's elastic (i.e., recoverable) resistance to deformation under load. The MOE corresponds to the slope of the linear portion of the stress–strain relationship from zero to the proportional limit (Figure 11.6). Stiffness ( $\text{MOE} \cdot I$ ) is often incorrectly thought to be synonymous with MOE. However, MOE is solely a material property and stiffness depends both on the material and the size of the beam. Large and small beams of similar material would have similar MOEs but different stiffnesses. The MOE can be calculated from the stress–strain curve as the change in stress causing a corresponding change in strain.

#### 11.2.4.4 Work to Proportional Limit

The WPL is the measure of work performed, i.e., energy used, in going from an unloaded state to the elastic or proportional limit of a material (Figure 11.6). For a beam of rectangular cross section under center point loading, WPL is calculated as the area under the stress–strain curve from zero to the proportional limit.

#### 11.2.4.5 Work to Maximum Load

WML is the amount of work needed to actually fracture or fail a material. It is a measure of the amount of energy required to fracture the material. Toughness and work to total load are analogous properties, but their final limit state also includes energy absorbed beyond the ultimate failure. WML is calculated as the area under the stress–strain curve from zero to the ultimate strength of the material (Figure 11.6). Because WML is a measure of work both below and beyond the proportional limit, it is derived by either graphical approximations or by means of calculus.

### 11.2.5 AXIAL LOADING PROPERTIES

Because of the anisotropic and heterogeneous nature of wood, there can be profound differences in the strength in various directions. Wood is stronger along the grain (parallel to the longitudinal axis of the log or longitudinal axis of the wood cell) than perpendicular to the grain (at right angles to the longitudinal axis). Axial loads describe forces that have the same line of action and are, thus, both parallel and concurrent. Because there is no eccentricity in the application of these forces, they do not induce flexure or bending moments.

Mechanical properties dealing with axial loading conditions are maximum crushing strength (compression parallel to the grain), compression perpendicular to the grain, tension parallel to the grain, and tension perpendicular to the grain.

#### 11.2.5.1 Compression Parallel to the Grain

If wood is considered a bundle of straws bound together, then a compression parallel to the grain ( $C_{\parallel}$ ) can be thought of as a force trying to compress the straws from end to end. The distance through which compressive stress is transmitted does not increase or magnify the stress, but the length over which the stresses are carried is important. If the length of the column is far greater than the width, the specimen may buckle. This stress is analogous to bending-type failure rather than axial-type failure. As long as specimen width is great enough to preclude buckling,  $C_{\parallel}$  is solely an axial property.

Examples of wood in compression parallel to the grain are wooden columns or the top chord of a roof truss. Compression-parallel-to-the-grain strength or the maximum crushing strength is derived at the ultimate limit value of a standard stress–strain curve. The strength of wood in  $C_{\parallel}$  is derived by the following:

$$C_{\parallel} = P/A \quad (11.5)$$

where  $C_{\parallel}$  is the stress in compression parallel to grain,  $P$  is the maximum axial compressive load, and  $A$  is the area over which load is applied.

#### 11.2.5.2 Compression Perpendicular to the Grain

Compression perpendicular to the grain ( $C_{\perp}$ ) can be thought of as stress applied perpendicular to the length of the wood cell. Therefore, in our straw example, the straws (or wood cells) are being

crushed at right angles to their length. Until the cell cavities are completely collapsed, wood is not as strong perpendicular to the grain as it is parallel to the grain. However, once the wood cell cavities collapse, wood can sustain a nearly immeasurable load in  $C_{\perp}$ . Because a true ultimate stress is nearly impossible to achieve, maximum  $C_{\perp}$  in the sense of ultimate load-carrying capacity is undefined and discussions of  $C_{\perp}$  are usually confined to stress at some predetermined limit state such as the proportional limit or 4% deflection.

Compression-perpendicular-to-the-grain stresses are found whenever one member is supported upon another member at right angles to the grain. Examples of compression perpendicular to the grain are the bearing areas of a beam, truss, or joist.

The  $C_{\perp}$  strength is derived by:

$$C_{\perp} = P/A \quad (11.6)$$

where  $C_{\perp}$  is the stress in compression perpendicular to the grain,  $P$  is the proportional limit load, and  $A$  is the area.

#### 11.2.5.3 Tension Parallel to the Grain

A tension parallel to the grain ( $T_{\parallel}$ ) stress is a force trying to elongate the wood cells, or straws in our straw example. Wood is extremely strong in  $T_{\parallel}$ . The distance through which tensile stress is transmitted does not increase the stress. The  $T_{\parallel}$  is difficult to measure because of the difficulty in securely gripping the tensile specimen in the testing machine, especially with clear straight-grained wood. Often  $T_{\parallel}$  of clear straight-grain wood is conservatively estimated by the MOR (ultimate strength in bending). This conversion is accepted because bending failure of clear wood often occurs on the lower face of a bending specimen where the lower face fibers are under tensile-type stresses. An example of tension parallel to the grain would be the bottom chord of a truss that is under tensile stress. The  $T_{\parallel}$  strength of wood is derived by the following formula:

$$T_{\parallel} = P/A \quad (11.7)$$

where  $T_{\parallel}$  is the stress in tension parallel to the grain,  $P$  is the maximum load, and  $A$  is the area.

#### 11.2.5.4 Tension Perpendicular to Grain

Tension perpendicular to the grain ( $T_{\perp}$ ) is induced by a tensile force applied perpendicular to the longitudinal axis of the wood cell. In this case, the straws (or wood cells) are being pulled apart at right angles to their length. The  $T_{\perp}$  is extremely variable and is often avoided in discussions on wood mechanics. However,  $T_{\perp}$  stresses often cause cleavage or splitting failures along the grain, which can dramatically reduce the structural integrity of large beams. Failures from  $T_{\perp}$  are sometimes found in large beams that dry while in service. For example, if a beam is secured by a top and a bottom bolt at one end, shrinkage may eventually cause cleavage or splitting failures between the top and bottom boltholes. Wood can be cleaved by  $T_{\perp}$  forces at a relatively light load. It is this weakness that is often exploited in karate and other demonstrations of human strength. The  $T_{\perp}$  strength of wood is derived by the following:

$$T_{\perp} = P/A \quad (11.8)$$

where  $T_{\perp}$  is the stress in tension perpendicular to the grain,  $P$  is the maximum load, and  $A$  is the area.

## 11.2.6 OTHER MECHANICAL PROPERTIES

### 11.2.6.1 Shear

Shear parallel to the grain ( $\gamma$ ) measures the ability of wood to resist the slipping or sliding of one plane past another parallel to the grain. Shear strength is derived in a manner similar to axial properties, by using the following equation:

$$\gamma = P/A \quad (11.9)$$

where  $\gamma$  is the shear stress parallel to grain,  $P$  is the shearing load, and  $A$  is the area of the shear plane through the material.

### 11.2.6.2 Hardness

Hardness is used to represent the resistance to indentation and/or marring. Hardness (ASTM 2003a) is measured by the load required to embed a 1.128-cm steel ball one-half its diameter into the wood. While a material may be softer or harder in common vernacular, hardness, in engineering terms, is a material property that is measured using specified methods detailing sizes, sources, and test speeds. Beyond those specific test conditions, the term hardness when used in common language may have widely differing meanings to different people.

### 11.2.6.3 Shock Resistance

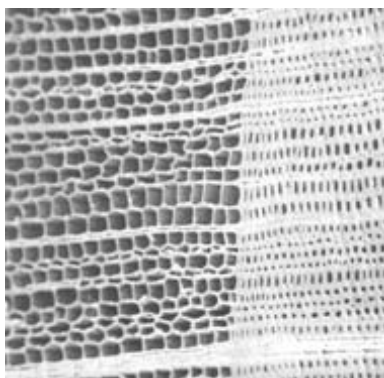
Shock resistance or energy absorption is a function of a material's ability to quickly absorb and then dissipate energy via deformation. This is an important property for baseball bats, tool handles, and other articles that are subjected to frequent shock loadings. High shock resistance on energy absorption properties requires both the ability to sustain high ultimate stress and the ability to deform greatly before failing.

Shock resistance can be measured by several methods. With wood, three of the most often used methods are work tests (to maximum load), impact bending tests, and toughness tests. Both of the later two test methods yield measures of strength and pliability, mutually referred to as energy absorption. These two measures of shock resistance are similar but are not particularly relative to one another. Impact bending is tested by dropping a weight onto a beam from successively increasing heights (ASTM 2003a). All that is recorded is the height of drop causing complete failure in a beam such that for a different sized beam or a different mass of weight the measured value would most certainly change. Toughness is the ability of a material to resist a single impact-type load from a pendulum device (ASTM 2003a). Thus, toughness is similar to impact bending in that both are measures of energy absorption or shock resistance. Yet critical differences exist. Toughness uses a single ultimate load and impact-type bending, whereas impact bending uses a series of progressively increasing, multiple loads in which the earlier load history can certainly alter the eventual result. Although each test method defines a material characteristic, each measured property should only be compared within the limited definitions of that method. They should not be compared on a method-to-method basis nor compared if tested on differing sized or conditioned materials.

## 11.3 CHEMICAL COMPONENTS OF STRENGTH

### 11.3.1 RELATIONSHIP OF STRUCTURE TO CHEMICAL COMPOSITION

The chemical components responsible for the strength properties of wood can be theoretically viewed from three distinct levels: the macroscopic (cellular) level, the microscopic (cell wall) level, and the molecular (polymeric) level.



**FIGURE 11.7** Scanning electron micrograph showing cellular structure with thin-walled earlywood (left) and thicker-walled latewood (right) at  $\times 120$  (A) and  $\times 400$  (B).

### 11.3.1.1 Macroscopic Level

Wood with its inherent strength is a product of growing trees. The primary function of the woody trunk of the living tree is to provide support for the phototropic energy factory (i.e., leaves or needles) at the top and to provide a conduit for moving water and nutrients moving up to those leaves or needles. The phototropic sugars produced by the leaves or needles mostly move down the stem via the bark tissues. Woody tissues, interior to the bark, exist as concentric bands of cells oriented for specific functions (Figure 11.7). Thin-walled earlywood cells act both as conductive tissue and support; thick-walled latewood cells provide support. Each of these cells is a single fiber. Softwood fibers average about 3.5 mm in length and 0.035 mm in diameter. Hardwood fibers are generally shorter (1–1.5 mm) and smaller in diameter (0.015 mm). The earlywood and latewood fibers comprise large composite bands, bonded together by a phenolic adhesive, lignin. Each band is anisotropic in character but is reinforced in two of the three axial directions by longitudinal parenchyma and ray parenchyma cells. These parenchyma cells function as a means of either longitudinal or radial nutrient conduction and as a means of providing lateral support by increased stress distribution (Figure 11.8a,b). Because wood is a reinforced composite material, its structural performance at the cellular level has been likened to reinforced concrete (Freudenberg 1932, Mark 1967).

The macroscopic level of consideration takes into account fiber length and differences in cell growth, such as earlywood, latewood, reaction wood, sapwood, heartwood, mineral content, extractive chemicals, resin content, etc. Differences in cellular anatomy, environmental-controlled growth patterns, and chemistry can cause significant differences in the strength of wood.

### 11.3.1.2 Microscopic Level

At the microscopic level, wood has been compared to multipart systems, such as filament-wound fiber products (Mark 1967). Each component complements the other in such a manner that, when considering the overall range of physical performance, the components together outperform the components separately.

### 11.3.1.3 Composition

Within the cell wall are distinct regions (see Figure 3.12), each of which has distinct composition and attributes. For typical softwood the middle lamella and primary wall are mostly lignin (8.4% of the total weight) and hemicellulose (1.4%), with very little cellulose (0.7%). The  $S_1$  layer consists of cellulose (6.1%), hemicellulose (3.7%), and lignin (10.5%). The  $S_2$  layer is the thickest layer

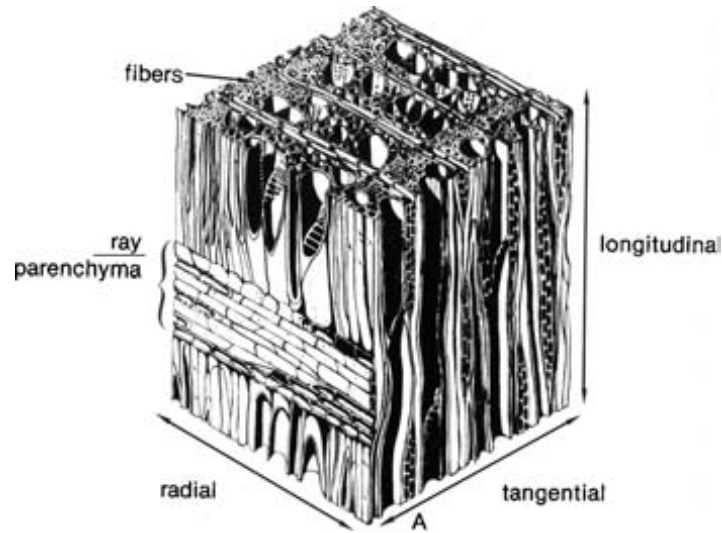


FIGURE 11.8A Cube of hardwood.

and has the highest carbohydrate content; it is mostly cellulose (32.7%) with lesser quantities of hemicelluloses (18.4%) and lignin (9.1%). The  $S_3$  layer, the innermost layer, consists of cellulose (0.8%), hemicelluloses (5.2%), and very little lignin. One interesting caveat is that although the relative lignin ratio is low within the  $S_2$  layer, the largest amount of lignin exists within this layer because of its large overall mass.

The large number of hydrogen bonds existing between cellulose molecules results in such strong lateral associations that certain areas of the cellulose chains are considered crystalline. More than 60% of the cellulose (Stamm 1964) exists in this crystalline form, which is stiffer and stronger than the less crystalline or amorphous regions. The crystalline areas are approximately 60 nm long (Thomas 1981) and are distributed throughout the cell wall.

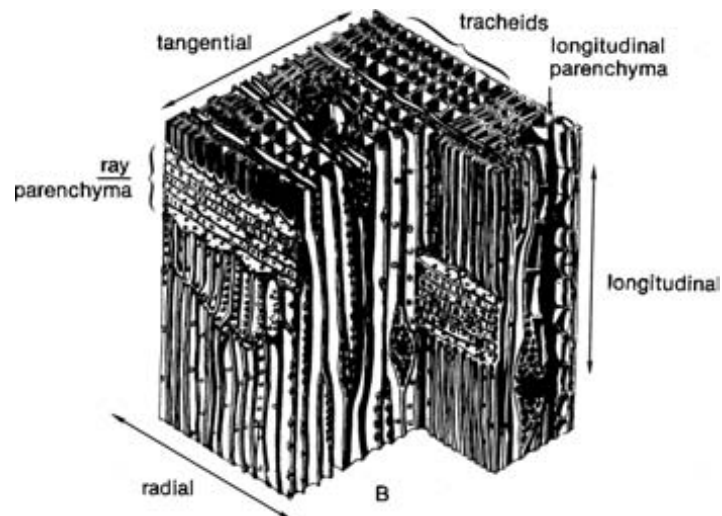


FIGURE 11.8B Cube of softwood.





**FIGURE 11.9** Scanning electron micrograph of softwood fibers embedded in lignin ( $\times 400$ ).

#### 11.3.1.4 Microfibril Orientation

Microfibrils are highly ordered groupings of cellulose that may also contain small quantities of hemicellulose and lignin. The exact composition of the microfibril and its relative niche between the polymeric chain and the layered cell wall are subjects of great discussion (Mark 1967). The microfibril orientation (fibril angle) is different and distinct for each cell wall layer (see Figure 3.12). The entire microfibril system is a grouping of rigid cellulose chains analogous to the steel reinforcing bars in reinforced concrete or the glass or graphite fibers in filament-wound reinforced plastics. Most composite materials use an adhesive of some type to bond the entire material into a system. In wood, lignin fulfills the function of a matrix material. Yet, it is not truly or solely an adhesive and by itself adds little to strength (Lagergren et al. 1957). Lignin is a hydrophobic phenolic material that surrounds and encrusts the carbohydrate complexes (Figures 11.9 and 11.10). It aids in holding the cell components together at the microscopic level. Lignin also seems to be responsible for part of the stiffness of wood and it most certainly is primarily responsible for the exclusion of water from the moisture-sensitive carbohydrates. Rubbery wood, a viral disease of certain varieties of apple (*Malus* spp.), is characterized by extremely flexible wood. The affected wood has been shown (Prentice 1949) to have cells rich in cellulose but low in lignin.

#### 11.3.1.5 Molecular Level

At the molecular level the relationship of strength and chemical composition deals with the individual polymeric components that make up the cell wall. The physical and chemical properties of cellulose, hemicelluloses, and lignin play a major role in the chemistry of strength. However, our perceptions of wood polymeric properties are based on isolated polymers that have been removed from the wood system and, therefore, possibly altered. The three individual polymeric components (cellulose, hemicelluloses, and lignin) may be far more closely associated and interspersed with one another than has heretofore been believed (Attalla 2002). Recent theories speculate

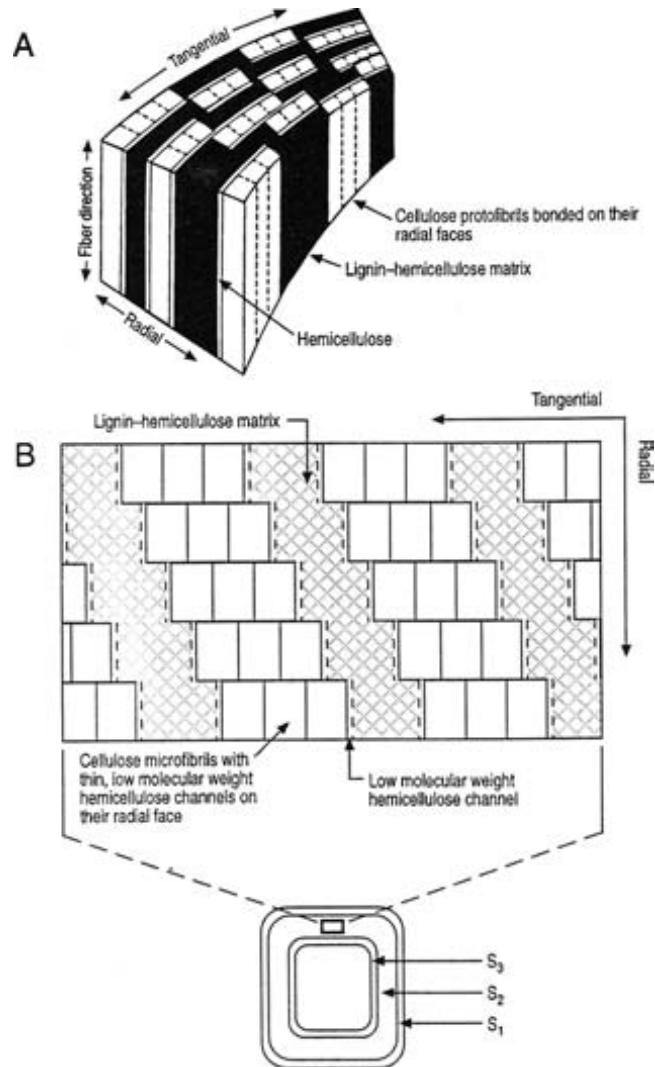


**FIGURE 11.10** Scanning electron micrograph of delignified softwood fiber wall ( $\times 16,000$ ).

that the crystalline and amorphous regions of the cellulose chains are more diffuse and less segregated between themselves than may have earlier been believed (Attalla 2002).

Cellulose is anhydro-D-glucopyranose ring units bonded together by  $\beta$ -1-4-glycosidic linkages. The greater the length of the polymeric chain and the higher the degree of polymerization, the greater the strength of the unit cell (Mark 1967, Ifju 1964) and, thus, the greater the strength of the wood. The cellulose chain may be 5000–10,000 units long. Cellulose is extremely resistant to tensile stress because of the covalent bonding within the pyranose ring and between the individual units. Hydrogen bonds within the cellulose provide rigidity to the cellulose molecule via stress transfer and allow the molecule to absorb shock by subsequently breaking and reforming. Past theories have speculated that the cellulose is the predominate factor in wood strength, but recent work has clearly shown that the hydrolytic or enzymatic action upon the hemicelluloses seem to always manifest themselves in the earliest levels of strength loss in woody materials.

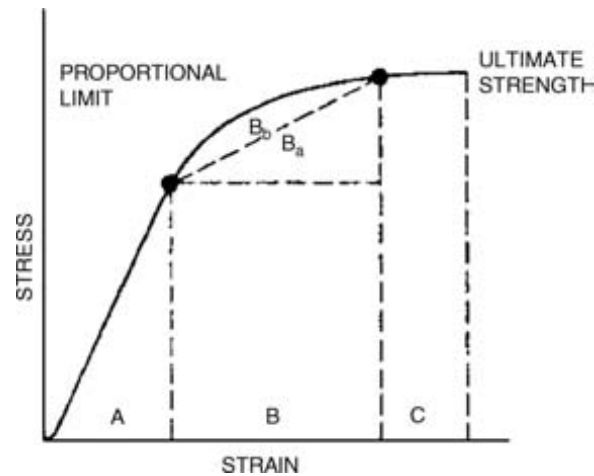
The hemicelluloses are a series of carbohydrate molecules that consist of various elementary sugar units, primarily the six-carbon sugars, D-glucose, D-galactose, and D-mannose, and the five-carbon sugars, L-arabinose and D-xylose. Hemicelluloses have linear chain backbones (primarily glucomannans and xylan chains) that are highly branched and have a lower degree of polymerization than cellulose. The sugars in the hemicellulose structure exhibit hydrogen bonding both within the hemicellulose chain as well as between other hemicellulose and amorphous cellulose regions. Most hemicelluloses are found interspersed within or on the boundaries of the amorphous regions of the cellulose chains and in close association with the lignin. Hemicellulose may be the connecting material between cellulose and lignin. The precise role of hemicellulose as a contributor to strength has long been a subject of conjecture. Recent work on hydrolytic chemical agents and enzymatic decay has indicated that early degradation of hemicellulose(s), especially degradation of the shorter branched monomers of D-galactose and L-arabinose along the hemicellulose main chains, seem primarily responsible for the earliest portions of strength loss in wood exposed to severe thermal, chemical, or biological exposures (Winandy and Lebow 2001, Curling et al. 2002, Winandy and Morrell 1993). Other work has speculated that the actions of hydrolytic agents at the aforementioned sheath of hemicellulose along the boundary areas of the cellulose microfibrils (Figure 11.11) may



**FIGURE 11.11** Representation of proposed ultrastructural models of the arrangement of lignin, cellulose, and hemicellulose in S<sub>2</sub> layer of the wood cell wall. Models proposed by Kerr and Goring 1975 (A) and Larsen et al. 1995 (B).

account for the radial degradation fissures (i.e., interwall cracks of the S<sub>2</sub> layer often seen during chemical or biological decay (Larsen et al. 1995)).

Lignin is often considered nature's adhesive. It is the least understood and most chemically complex polymer of the wood-structure triad. Its composition is based on highly organized three-dimensional phenolic polymers rather than linear or branched carbohydrate chains. Lignin is the most hydrophobic (water-repelling) component of the wood cell. Its ability to act as an encrusting agent on and around the carbohydrate fraction, and thereby limit water's influence on that carbohydrate fraction, is the cornerstone of wood's ability to retain its strength and stiffness as moisture is introduced to the system. Dry delignified wood has nearly the same strength as normal dry wood, but wet delignified wood has only approximately 10% of the strength of wet normal wood (Lagergren et al. 1957). Thus, wood strength is due in part to lignin's ability to limit the access of water to the carbohydrate moiety and thereby lessen the influence of water on wood's hydrogen-bonded structure.



**FIGURE 11.12** Typical stress-strain curve showing the three theoretically identifiable regions of mechanical behavior. Key: A, elastic region; B, viscoelastic, partially viscoelastic  $B_A$  and partially viscoplastic  $B_b$ ; and C, plastic region.

#### 11.4 RELATIONSHIP OF CHEMICAL COMPOSITION TO STRENGTH

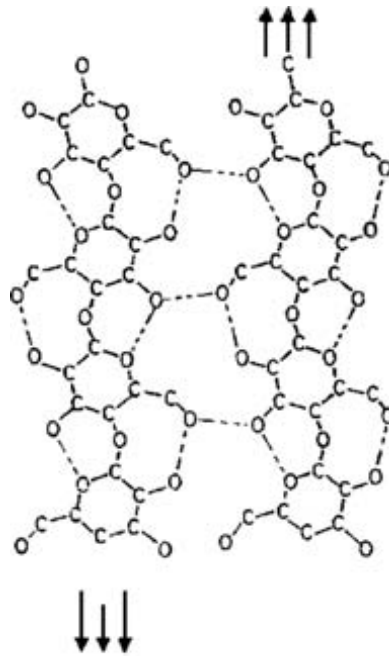
To relate chemical composition to strength properties, to work and toughness properties, and eventually to elastic parameters, a preliminary model or hypothesis must be developed to aid in conceptualizing the relationship between strength and wood composition. The theoretical relationship of stress to strain can be graphically represented by a diagram (Figure 11.12). If wood is assumed to be an elastic material, a linear region, A, represents the constant relationship below the proportional limit, and the nonlinear regions, B and C, represent nonconstant relationship beyond the proportional limit. If each region of the stress-strain relationship is examined at each of the three distinct levels of wood structure (macroscopic, microscopic, and molecular), the relationship between strength and composition may be hypothetically explained.

As loads are applied to a wood system, stresses are immediately introduced and distributed throughout the material. The stresses cause two types of strain or distortion: immediate, under which wood can be described as an elastic material, and time dependent. Even at low stress levels, permanent set or distortion will eventually be induced in a wood member. This phenomenon, known as creep, explains why wood is considered viscoelastic. But for purposes of simplification, the ensuing discussion will be confined to immediate strain or distortion and will consider wood as an elastic material. Immediate strain or distortion can be conceptualized at each of the three distinct levels of wood structure.

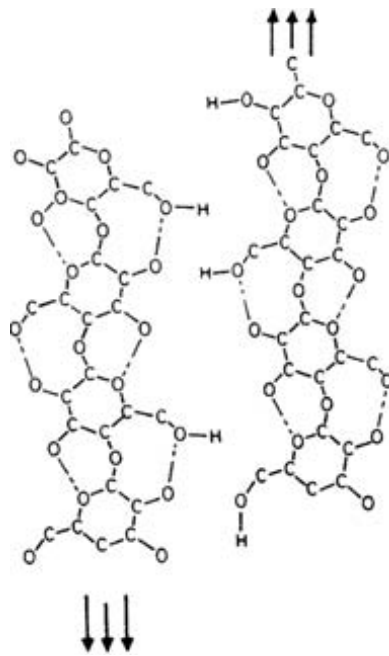
##### 11.4.1 BELOW PROPORTIONAL LIMIT (ELASTIC STRENGTH)

When a load is applied to a piece of wood, at the molecular level, hydrogen bonds between and within individual polymer chains are breaking, sliding (uncoiling), and subsequently reforming (Figure 11.13a, b, c, respectively); C-C and C-O bonds are distorting within the ring structures (Figure 11.14).

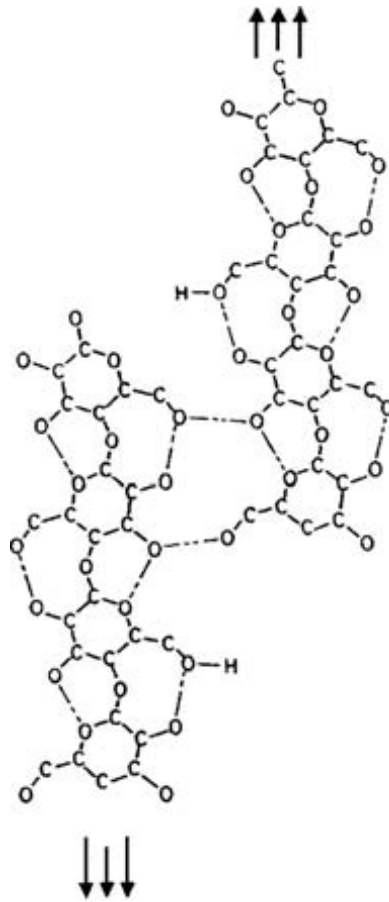
At the microscopic level, hydrogen bonds between adjacent microfibrils are breaking and reforming (Figure 11.13a, b, c) to allow the microfibrils to slide by one another with only the disruption of the hydrogen bonds that are subsequently reformed. Additionally, the individual cell wall layers are distorting in relation to each other, but no permanent set or distortion is occurring between these individual cell wall layers.



**FIGURE 11.13A** Hydrogen bonding (bonded) between polysaccharide chains under shear forces.



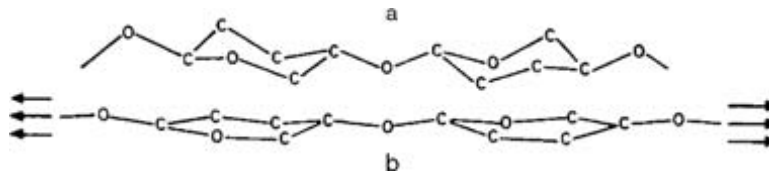
**FIGURE 11.13B** Hydrogen bonding (sliding, unbounded) between polysaccharide chains under shear forces.



**FIGURE 11.13C** Hydrogen bonding (rebounced) between polysaccharide chains under shear forces.

At the macroscopic level, there is distortion between the individual cells, but it is not permanent because the stresses are being distributed between the individual cells such that no permanent translocation or set is introduced.

Within the limits of the elastic model, all strain or distortion resulting from the accumulation of stress in this material has been recoverable up to this point. As the proportional limit is approached, the wood material can no longer distribute the stress in a linear elastic manner.



**FIGURE 11.14** Flexing and elongation of polysaccharide molecules under tensile force. Key: a, no tensile force, no elongation; and b, tensile force, elongation.

### 11.4.2 BEYOND PROPORTIONAL LIMIT (PLASTIC STRENGTH)

As the proportional limit is exceeded (Figure 11.12, Region B), the stress–strain relationship is no longer linear. Stresses are now great enough to induce covalent bond rupture and permanent distortion at all three structural levels.

At the molecular level, the limit of reversible or recoverable hydrogen bonding has been exceeded. Covalent C–C and C–O bonds are breaking, thus reducing larger molecules to smaller ones. This reduction in degree of polymerization by covalent bond scission is nonrecoverable.

At the microscopic level, stresses develop within the crystalline region of the carbohydrate microfibrils. Failure of the microfibril from stress overload causes actual covalent bond rupture and excessive microfibril disorientation. Additionally, the cell wall layers distort such that permanent micro cracks occur between the various cell wall layers. Separation of the cell wall layers is soon noticeable.

At the macroscopic level, entire fibers actually distort in relation to one another, such that recovery of the original position is now impossible. The wood cells or wood fibers are actually failing either by scission of the cell, in which the cell actually fails by tearing into two parts to give a brash type of failure, or by cell-to-cell withdrawal (middle lamella failure), where the cells actually pull away from one another to give a splintering type of failure.

Permanent set is now evident at all levels of consideration, and eventual failure is imminent. In approaching the ultimate strength (Figure 11.12, Region C), molecular level failures occur by C–C and C–O bond cleavage. Stress redistribution within the individual polymers is now impossible. At the microscopic level, the cell walls are distorting without additional stress. These walls are actually deforming at such an exaggerated rate that they can be thought of as being completely viscous or plastic, and they continue to deform and absorb strain energy but they can no longer handle additional stress. The cell wall is being sheared or torn apart. At the macroscopic level, failure is related to cell wall scission or cell-to-cell withdrawal.

## 11.5 RELATIONSHIP OF STRUCTURE TO STRENGTH

The mechanism of strength, as it relates to wood composition, has been discussed as a theoretical elastic model. To better understand this proposed model, we will look at what may be happening at each of the three structural levels.

### 11.5.1 MOLECULAR LEVEL

At the molecular level, strength is elastic or recoverable because the polymeric structure can flex and, thus, absorb energy without fracturing the important covalent bonds (Figure 11.12, Region A). The second region of the stress–strain diagram (Figure 11.12, Region B) consists of Region B<sub>a</sub>, which is indicative of residual elastic strength such as represented in Region A, and Region B<sub>b</sub>, which represents plastic strength or, more appropriately, strength associated with initial permanent set or distortion.

Section B<sub>b</sub> is representative of C–C and C–O cleavage at the intrapolymer level, which cannot be recovered. Examples of C–C bond breakage are lignin-hemicellulose copolymer separation, hemicellulose depolymerization, and amorphous cellulose depolymerization.

In Region C (Figure 11.12), elastic deformation essentially ends; there is now nearly pure plastic flow in the stress–strain relationship. Strain is continuing with little additional increase in stress and ultimate failure is imminent. This region is characterized by all the same mechanisms as in B<sub>b</sub>, but a new and terminal intrapolymeric factor is introduced—the crystalline cellulose failure. As crystalline cellulose failure occurs, the main framework of the wood material at the molecular level is disintegrating.

### 11.5.2 MICROSCOPIC LEVEL

At the microscopic level, the strength of the phenolic matrix is usually great enough that the cell wall stress reaches failure level in the carbohydrate framework. The  $S_1$  layer microfibrils are oriented in both a right-hand (S helix) and a left-hand (Z helix) arrangement, whereas the  $S_2$  and  $S_3$  have only the S-helix arrangement (Figure 11.9). The  $S_3$  layer can be bihelical or monohelical, but, for the purpose of simplification, it has been assumed to be monohelical in this example. Because of the different linear elongation of the bihelical  $S_1$  layer as compared to the monohelical arrangement of the  $S_2$  and  $S_3$  layers, the cell wall initially fails by  $S_1$ - $S_2$  separation (Siau 1969). As  $S_1$ - $S_2$  separate, the  $S_2$ - $S_3$  layers assume the transferred stresses, and sustained stress increases, which will eventually cause either a brash-type failure (carbohydrate covalent bond failure) or a slow buildup to ultimate stress yielding a fibrous-type failure (phenolic covalent bond failure).

Below the proportional limit (Figure 11.12, Region A), there is elastic transfer of stresses between the  $S_1$ - $S_2$ - $S_3$  cell wall layers. As Region B is entered, stress is still transferred between the  $S_1$ - $S_2$ - $S_3$  cell wall layers as characterized by Section  $B_a$ . But  $S_1$ - $S_2$  separation is initiating, causing a sizeable transfer of stresses to the  $S_2$ - $S_3$  layers characterized by Section  $B_b$ . In Region C, ultimate strength is now dictated by the  $S_2$ - $S_3$  cell wall layer's ability to sustain additional stress until eventual failure of the substantial  $S_2$  layer.

### 11.5.3 MACROSCOPIC LEVEL

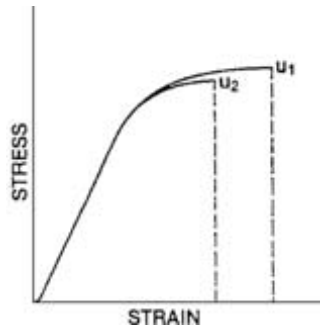
At the macroscopic level, it is necessary to consider wood a viscoelastic material. As stress is applied to a wooden member, minute cracks initiate, propagate, and terminate throughout the collective cellular system in all directions. They develop in all regions of the stress-strain relationship at the macroscopic level, but only in the elastic region (Figure 11.12, Regions A and  $B_a$ ) is crack propagation controlled and eventually terminated. In the tangential direction, the concentric ring structure of thin-walled earlywood and thick-walled latewood in softwoods, and porous early-season vessels and dense late-season fibers in hardwoods act as the elements of elastic stress transfer. In the radial direction, the ray structures and the linear arrangement of fibers and vessels are the elements of elastic stress transfer. Every cell in the radial direction is aligned closely with the next cell because each cell in the radial direction has originated from the same cambial mother cell. Thus, the material can transfer stress elastically until an induced crack or a natural growth defect interrupts this orderly cellular arrangement. As stresses are built up within the material, cracks are initiated in the areas where elastic stress transfer is interrupted. These cracks continue to propagate until they are terminated either via dispersion of the energy away from the crack by the structural elements of stress transfer, or by eventual terminal failures as graphically characterized by Regions  $B_b$ , and C (Figure 11.12).

## 11.6 ENVIRONMENTAL EFFECTS

When wood is exposed to environmental agents of deterioration, such as chemical treatments or elevated temperatures, each mechanical property reacts differently. Most commonly, ultimate strength properties are reduced and properties dealing with the proportional limit show little or no effect. However, the strain-to-failure (strain rate) is often considerably reduced, which, due to embrittlement of the fibers, is reflected as a reduction in pliability and energy-related properties such as work, toughness, etc.

As individual wood components are altered in size, stature, or composition, the strength of the wood material is dramatically affected. Hypothetically, when ultimate stress is reduced 5% (Figure 11.15,  $U_1$ - $U_2$ ) and the proportional limit is not affected, the properties dealing with proportional limit (FSPL, MOE, WPL) reflect this in that they too are unaffected. The mechanical properties dealing with the point of ultimate stress (MOR in bending tests, C in axial-type compression tests,



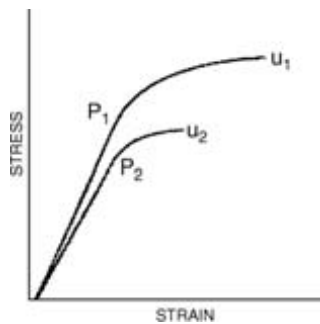


**FIGURE 11.15** Hypothetical example of the effect of no change in proportional limit and a 5% reduction in ultimate bending strength on a few mechanical properties: MOE is not affected, MOR is reduced 5%, but WML is reduced by 33% because it is a dual function of stress and strain.

and  $T$  and  $T_{\perp}$  in axial-type tensile tests) are reduced 5%. Work to maximum load can be reduced 33% because it is a function of both stress and strain. If the stress level at the proportional limit is reduced, and both the ultimate stress and strain levels are significantly reduced (Figure 11.16), larger decreases will occur in proportional limit properties (MOE, and FSPL, WPL), ultimate strength properties (MOR, C, T,  $T_{\perp}$ ), and work to maximum load. The examples in both Figures 11.15 and 11.16 show evidence that WML and related properties, such as toughness and impact bending, are usually affected long before the other properties dealing with ultimate strength and the proportional limit are significantly affected.

What causes the phenomenon of stress and strain reduction and why is the reduction in impact and work properties so visible at small or negligible changes in elastic modulus and ultimate strengths? As discussed previously, mechanical properties deal with stress and strain relationships that are simply functions of chemical bond strength. At the molecular level, strength is related to both covalent and hydrogen intrapolymer bonds. At the microscopic level, strength is related to both covalent and hydrogen interpolymer bonds and cell wall layer bonds ( $S_1$ - $S_2$  and  $S_2$ - $S_3$ ). At the macroscopic level, strength is related to fiber-to-fiber bonding with the middle lamella acting as the adhesive. Thus, any chemical or environmental agent that affects those bonds also affects strength.

In considering the structural performance of the polysaccharide and phenolic polymers in wood fiber, the chemical environment of the fiber is of great importance. Chemicals can swell, hydrolyze, pyrolyze, oxidize, and, in general, depolymerize wood polymers, causing a loss in strength properties



**FIGURE 11.16** Hypothetical example of the effect of a 20% reduction in proportional limit and a 30% reduction in ultimate bending strength on a few mechanical properties: MOE is reduced 20%; MOR is reduced 30%, and WML is reduced 50%, because it is a dual function of stress and strain.

due to wood fiber network degradation. Other environmental agents, such as UV light, heat, and biological organisms, have a similar influence in changing strength properties.

### 11.6.1 ACIDS AND BASES

The average pH of wood is between 3 and 5.5 (Stamm 1964) due to the acetyl content, the presence of acid extractives, and the adsorption of cations that comprise the ash. Even after several hundred years, this naturally mild acidic state does not induce any appreciable strength losses as long as the wood is protected from biological attack (USDA 1999).

If the pH of the environment substantially changes or if temperatures increases to a point where the pH of the environment changes, strength properties can be reduced. These effects are further compounded by time and moisture. In general, the longer the time or the higher the temperature at which wood is exposed to an acid or a base, the greater is the degradative effect on strength (USDA 1999, Wangaard 1950, Stamm 1964). Heartwood is generally more resistant to acid than is sapwood, probably because of heartwood's lower permeability and higher extractives content. Hardwoods are usually more susceptible to degradation by either acids or alkali's than are softwoods. This may be due to hardwood's lower lignin content and higher proportion of pentosan hemicelluloses. Oxidizing acids, such as  $\text{HNO}_3$ , have a greater degradative action on wood fiber than do nonoxidizing acids. Alkaline solutions are more destructive to wood fibers than are acidic solutions because wood adsorbs alkaline solutions more readily than acidic solutions. Acids with pH values above 2 and bases with pH values below 10 do not degrade the wood fiber greatly over short periods of time at low temperatures (Kollman and Cote 1968). Mild acids, such as acetic acid, have little effect on strength, whereas strong acids, such as  $\text{H}_2\text{SO}_4$ , cause extensive strength losses (Alliot 1926).

### 11.6.2 ADSORPTION OF ELEMENTS

Chemicals other than acids and bases can also be adsorbed and can cause degradation of the wood fiber. For example, fibers of southern pine exposed to the ocean air can be degraded badly (Figure 11.17). Salt crystals deposited in the void structure (Figure 11.18) can cause extensive

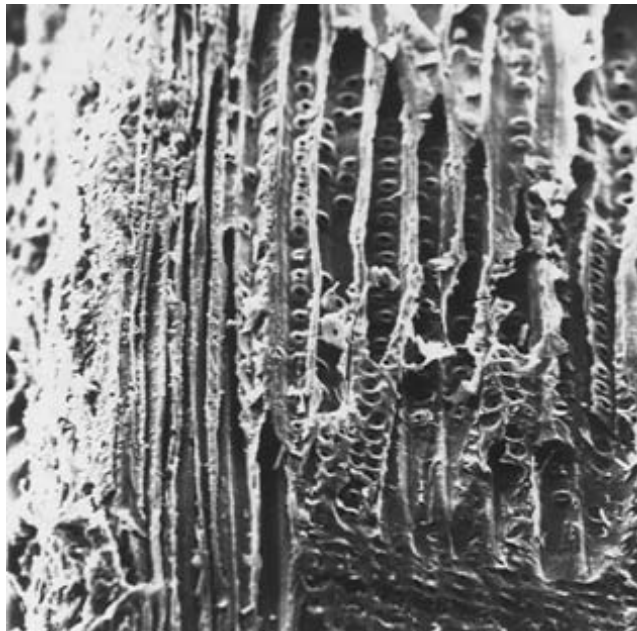
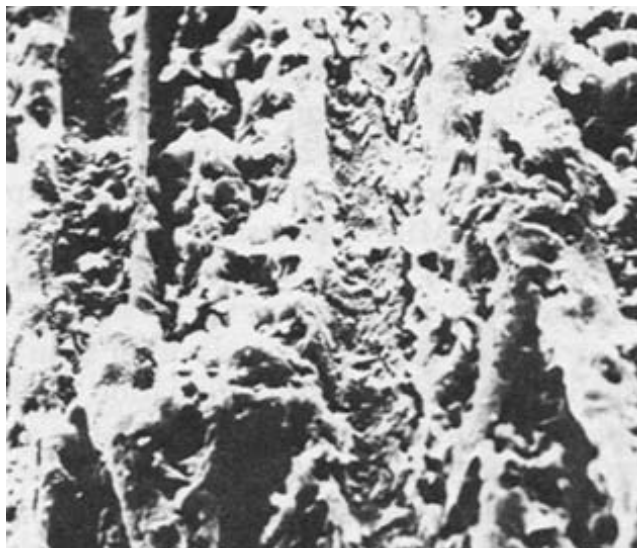


FIGURE 11.17 Scanning electron micrograph of sodium chloride in southern pine cell ( $\times 40$ ).



**FIGURE 11.18** Scanning electron micrograph of sodium chloride in southern pine cell ( $\times 400$ ).

chemical and physical damage. This chemical damage is due, in part, to the salt catalyzing hydrolysis reactions, whereas mechanical damage is related to the hygroscopic salts promoting greater shrinkage and swelling.

Other materials can be adsorbed from the environment if a hydrolytic solvent (e.g., water) is available. When water is available, wood will adsorb iron from oxidized metal (rust) and cause decomposition of the cellulose (Koenigs 1974). This is also true for copper, chromium, tin, zinc, and other similar reactive metals.

### 11.6.3 SWELLING SOLVENTS

Solutions that swell wood tend to plasticize it and reduce its strength properties. Water, for example, swells the intrapolymeric spaces, reduces cross-linking and, thus, reduces strength. In general, the greater the swelling, the greater the strength loss. Nonswelling liquids generally do not decrease strength properties. For example, oven-dry wood and wood saturated with water-free benzene have virtually the same strength (Erickson and Rees 1940, Siau 1969).

### 11.6.4 ULTRA VIOLET DEGRADATION

Wood exposed to the outdoors undergoes chemical reactions due to UV radiation. UV radiation causes photochemical degradation primarily in the lignin component, which gives rise to characteristic color changes (see Chapter 7). Southern pine, for example, changes from a light-yellow natural color to brown and evenly to gray. As the lignin degrades, the wood surface becomes richer in cellulose content. Although the cellulose is much less susceptible to UV degradation (Kalnins 1966), it is eventually washed off the surface with water during rain, which exposes new lignin-rich surfaces that then start to degrade. As this process continues, the wood surface is said to weather.

Because UV radiation does not penetrate wood more than a few cells deep, weathering is considered a surface phenomenon. Over time it can account for a significant loss in surface fiber (see Figure 7.1). As the degradative process continues, the loss in fiber may eventually cause a reduction in the material's load-carrying capacity.

### 11.6.5 THERMAL DEGRADATION

Wood strength is inversely related to temperature (see Chapter 6). A nearly linear decrease in strength is observed on increasing the temperature from  $-200$  to  $+160^{\circ}\text{C}$  (Figure 11.4; a corresponding loss in strength from two- to threefold (Gerhards 1982, Kollman and Cote 1968, Green 1999). Heat has two types of effects on wood, immediate effects that occur only as long as the increased temperature is maintained and permanent effects that result from thermal degradation of wood polymers. The immediate effects of heat are recoverable, but permanent effects are not. The combination of immediate and permanent effects is multiplicative rather than additive.

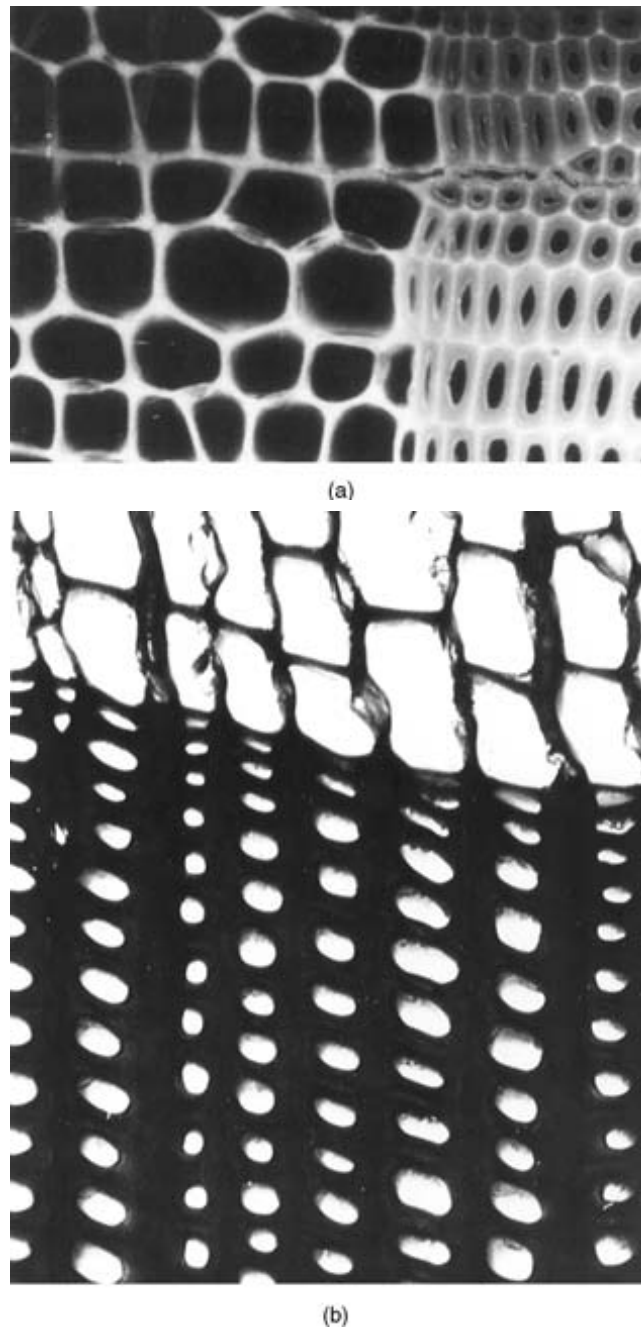
In an environment without adequate humidity, the initial effect of heating wood is dehydration. As temperatures approach  $55$ – $65^{\circ}\text{C}$  for extended periods (2–3 months), hemicellulose and cellulose depolymerization slowly begins (Feist et al. 1973, LeVan et al. 1990). This progressively escalates to pyrolysis and volatilization of cell wall polymers, which rapidly occurs at about  $250^{\circ}\text{C}$ , followed by char formation in the absence of air and combustion in the presence of air.

Heating dry Douglas fir in an oven at  $102^{\circ}\text{C}$  for 335 days reduced MOE by 17%, MOR by 45%, and fiber stress at proportional limit by 33% (MacLean 1945,1953, Millett and Gerhards 1972). The same losses might be observed in 7 days at  $160^{\circ}\text{C}$ . In the absence of air, heating softwood at  $210^{\circ}\text{C}$  for 10 min reduced MOR by 2%, hardness by 5%, and toughness by 5% (Stamm et al. 1946). Under the same conditions at  $280^{\circ}\text{C}$  MOR was reduced 17%, hardness was reduced 21%, and toughness was reduced 40%. Both examples illustrate the compound effect of heat, air, and time.

Comparison of photomicrographs of southern pine at  $25^{\circ}\text{C}$  (Figure 11.19 top) and the same sample after heating from 20 to  $295^{\circ}\text{C}$  under nitrogen over a period of 15 min (Figure 11.19 bottom) shows the cell structure still intact, but the cell wall components have been darkened by pyrolysis. LeVan et al. (1990) noted an ongoing darkening of pinewood exposed at  $82^{\circ}\text{C}$ , which corresponded to a loss in arabinose and to a lesser degree xylose. They then attributed the darkening brown color at  $82^{\circ}\text{C}$  to hydrolysis of furan-ringed arabinose and xylose to chocolate-brown colored furfural. Over the last 20 years, the permanent effect of extended high-temperature and cyclic exposure on wood strength has been extensively studied (LeVan et al. 1991, Winandy et al. 1991, Winandy 1995a, LeVan et al. 1996, Green et al. 2003) and fairly thoroughly reviewed (Winandy 2001). Predictive kinetic-based models have also been developed (Woo 1981, Pasek and McIntyre 1990, Winandy and Lebow 1996, Lebow and Winandy 1999, Green et al. 2003). The reasons for these permanent thermal effects on strength relate to changes in the wood polymeric substance and structure and predictive models have been developed (Winandy and Lebow 2001). The comprehensive analyses of almost 10,000 specimens systematically exposed to various high-temperature regimes, followed by their development of kinetic models, debunked one long-held misconception that a thermal threshold existed below which permanent effects did not occur (Lebow and Winandy 1999). That work concluded that thermal degradation of wood was a continuum, but at most ambient temperature exposures below  $40$ – $50^{\circ}\text{C}$ , the rate of degrade was so slow as to be negligible.

Tables 11.5–11.9 show loss in mechanical properties as a function of sugar analysis when southern pine is heated at different temperatures for different times either untreated or treated with various fire retardant chemicals. Table 11.5 shows the effects of these variables on untreated wood, and it can be seen that heat alone results in a decrease in MOR and WML as the time and temperature increase. Along with the loss of mechanical properties, there is an accompanying loss of xylose, galactose, and arabinose. The greatest loss is in arabinose, which may be the causative event leading to initial strength losses.

Table 11.6 shows the effects of these variables on wood that has been treated with phosphoric acid. MOE, MOR, and WML all decrease with increasing temperature and time. Significant losses in glucose, xylose, galactose, arabinose, and mannose also occur as the time and temperature increase. Table 11.7 shows a similar trend for southern pine treated with monoammonium phosphate, Table 11.8 for guanylurea phosphate/boric acid, and Table 11.9 for borax/boric acid. The most sensitive and consistent hemicellulose sugar lost in untreated and fire retardant treated wood is



**FIGURE 11.19** Southern pine at 25°C ( $\times 400$ ) (top) and southern pine after heating in a nitrogen environment from 20 to 295°C over 15 minutes ( $\times 400$ ).

arabinose. The loss of arabinose can be used as an approximate indication of strength loss without having to do a bending test to determine strength properties.

These results indicate that strength losses from external exposure of untreated or FRT wood to elevated temperatures are a result of loss of hemicelluloses or cell wall matrix structure, not a loss in the degree of polymerization of cellulose (Sweet and Winandy 1999).

**TABLE 11.5**  
**Relationship between Loss of Strength and Sugar Analysis of Fire Retardant Treated Southern Pine—Control**

Temp (°C)	Time (days)	MOE (Gpa)	MOR (Mpa)	WML (kJ/m <sup>3</sup> )	Lig (%)	Glu (%)	Xyl (%)	Gal (%)	Arab (%)	Mann (%)
23	3	13.9	117.4	101.2	29.4	48.1	8.0	3.0	1.3	12.9
23	16	14.5	127.9	116.6	27.6	44.9	6.1	2.1	1.2	11.2
54	3	13.9	124.1	110.2	29.6	47.0	7.5	3.4	1.2	12.6
54	7	13.8	116.9	98.5	28.4	48.0	7.0	2.4	1.3	13.2
54	21	13.5	119.5	101.2	29.6	47.1	7.1	2.6	1.2	12.4
54	60	13.8	121.3	101.5	29.4	45.9	6.6	2.5	1.0	12.0
54	160	13.9	120.1	99.3	27.8	52.9	7.1	2.2	1.3	13.6
54	7	14.6	115.9	95.8	28.6	42.9	6.1	1.9	1.0	10.8
66	21	14.0	113.8	96.7	28.5	42.7	5.9	1.8	1.0	11.1
66	60	14.8	122.2	97.3	28.6	42.8	5.9	1.9	0.9	11.1
66	160	13.5	116.0	79.7	28.2	43.1	5.9	2.0	0.8	11.0
66	290	14.3	113.4	74.5	29.3	43.4	5.9	2.2	0.5	10.8
66	560	14.7	96.5	51.3	29.4	42.9	5.7	2.2	0.4	11.0
66	1095	14.6	81.3	32.7	29.7	43.0	5.4	1.7	0.2	10.9
66	1460	11.2	42.5	10.8	32.8	43.0	3.8	0.7	0.1	8.3
82	3	13.5	119.0	112.0	29.2	46.7	7.3	2.6	1.2	12.4
82	7	14.0	125.0	105.3	29.3	46.5	6.9	2.5	1.2	12.3
82	21	14.7	124.2	101.4	29.7	48.0	6.8	2.4	0.9	12.7
82	60	14.0	118.7	84.4	29.1	46.9	6.8	2.6	0.7	12.7
82	160	13.8	104.7	58.0	27.6	53.1	6.9	2.3	0.6	13.4

Lig, Klason lignin; Glu, glucose; Xyl, xylose; Gal; galactose; Arab, arabinose; Mann, mannose.

### 11.6.6 MICROBIAL DEGRADATION

When certain organisms come into contact with wood, several types of degradation occur (see Chapter 5). The mechanical damage caused by metabolic action can result in significant losses in strength. Microbial activity via enzymatic pathways induces wood fiber degradation by chemical reactions such as hydrolysis, dehydration, and oxidation. Brown-rot fungi preferentially metabolize holocellulose, especially the strength-critical cellulose fraction (Cowling 1961). White-rot fungi metabolize nearly all fractions of the wood, but strength is not affected to the same degree as with a brown-rot fungus. An initial 10% weight loss for sweetgum (*Liquidambar styraciflua L.*) attacked by a brown-rot fungus reduced the degree of polymerization of the holocellulose from 1500 to 300 (Figure 11.20) (Cowling 1961). As the side-chains of the hemicellulose (e.g., arabinose, galactose) in the wood fiber are degraded, mechanical properties begin to decrease (Winandy and Morrell 1993, Curling et al. 2002). This work has shown that the initial 5–20% of strength loss seems to be directly related to this initial hemicellulose degradation. Later, as the main-chain backbones of the hemicellulose (e.g., xylose, mannose) are degraded, additional strength loss occurs. Finally, after strength has been reduced about 40–60% from the virgin strength level, noticeable degradation of glucose and lignin becomes evident (Winandy and Lebow 2001).

Using isolated polymers derived from wood, previous research has indicated a large drop in degree of polymerization, which was then related to the large drop in wood strength properties without corresponding weight loss (Ifju 1964, Cowling 1961, Kennedy 1958). This work indicated that, in the initial stages of biological attack, hydrolytic chemical reactions play an important part. Yet, more recent work that carefully approached this same subject using less invasive isolation techniques to study the polymers, found that hydrolytic hemicellulose depolymerization preceded

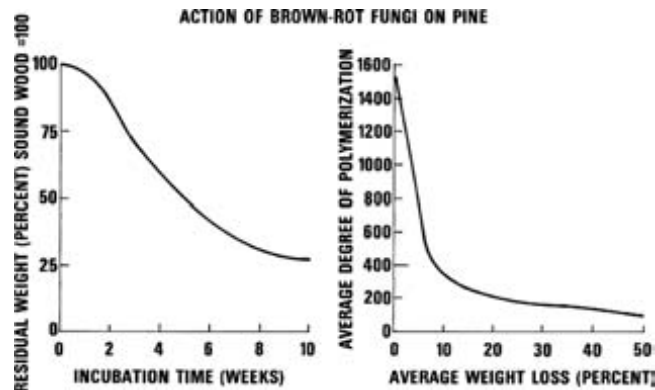
**TABLE 11.6**  
**Relationship between Loss of Strength and Sugar Analysis of Fire Retardant Treated Southern Pine—Phosphoric Acid 58.2 kg/m<sup>3</sup>**

Temp (°C)	Time (days)	MOE (Gpa)	MOR (Mpa)	WML (kj/m <sup>3</sup> )	Lig (%)	Glu (%)	Xyl (%)	Gal (%)	Arab (%)	Mann (%)
23	3	11.5	58.3	22.5	26.7	40.9	5.9	2.6	0.7	10.8
23	160	11.4	56.9	21.6	24.8	44.3	5.8	1.8	1.2	11.3
54	3	11.8	55.8	18.5	27.1	41.5	5.9	2.4	0.8	11.9
54	7	11.2	52.9	17.7	27.0	41.6	5.9	2.7	1.1	10.7
54	21	13.2	55.4	19.1	26.8	43.6	6.1	2.7	1.1	12.2
54	60	10.7	50.8	19.0	27.4	43.2	5.7	2.8	0.8	10.8
54	160	11.3	52.4	17.7	26.7	44.1	6.4	1.5	0.6	10.3
66	7	11.3	49.1	17.2	26.2	41.8	5.6	1.8	0.9	10.9
66	21	10.2	41.1	13.9	27.2	40.2	4.7	1.7	0.7	9.6
66	60	10.5	43.8	13.0	29.3	41.2	3.5	0.9	0.3	8.4
66	160	8.2	27.5	5.5	33.0	40.5	2.2	0.2	0.3	5.3
66	290	7.0	19.2	3.2	36.6	36.6	2.1	0.4	0.1	4.1
66	560	3.3	6.9	0.8	44.4	32.2	1.0	0.2	0.0	1.8
66	1095	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
66	1460	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
82	3	10.6	41.0	12.6	28.4	5.4	5.4	2.5	0.7	10.2
82	7	10.4	43.6	12.5	29.3	4.4	4.4	1.8	0.6	10.1
82	21	8.6	30.9	6.5	34.0	2.6	2.6	1.7	0.2	6.2
82	60	7.6	20.4	3.4	37.9	2.0	2.0	0.8	0.0	4.2

Lig, Klason lignin; Glu, glucose; Xyl, xylose; Gal, galactose; Arab, arabinose; Mann, mannose.

cellulose depolymerization (Sweet and Winandy 1999). In either case, in the initial phase(s) of degradation, large polymers are broken into smaller, more digestible units, but the initial degradation products are not actually consumed by the organisms. Hydrogen peroxide and iron have been proposed as being involved in initial depolymerization (Koenigs 1974). The initial enzymatic attack by microorganisms is probably not only hydrolytic but also oxidative in nature.

Curling et al. (2002) recently evaluated the effect of brown-rot decay on Southern pine (*Pinus* spp.) exposed in a laboratory test for periods ranging from 3 days to 12 weeks. The relative effects



**FIGURE 11.20** Action of brown rot fungus on holocellulose (Cowling 1961).

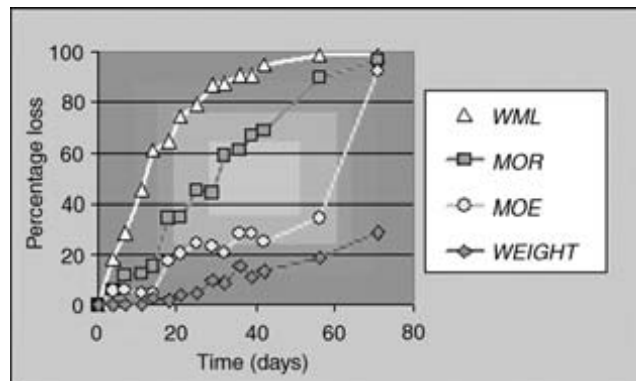
**TABLE 11.7**  
**Relationship between Loss of Strength and Sugar Analysis of Fire Retardant Treated Southern Pine—Monoammonium Phosphate 55.5 kg/m<sup>3</sup>**

Temp (°C)	Time (days)	MOE (Gpa)	MOR (Mpa)	WML (kj/m <sup>3</sup> )	Lig (%)	Glu (%)	Xyl (%)	Gal (%)	Arab (%)	Mann (%)
23	3	12.5	101.8	81.3	27.3	43.8	5.9	2.1	0.7	11.3
23	160	12.7	103.5	79.3	23.6	42.5	6.2	2.1	1.0	11.8
54	3	12.5	96.1	76.6	27.5	43.6	6.6	2.4	1.2	11.7
54	7	12.2	99.2	77.7	27.2	41.8	6.4	2.2	0.9	11.0
54	21	15.6	98.6	62.6	26.6	42.6	6.1	1.7	0.7	11.3
54	60	12.6	95.9	65.1	27.0	41.5	6.2	2.6	0.9	11.1
54	160	13.2	90.9	44.3	26.3	44.2	6.4	2.0	0.6	11.6
66	7	13.4	99.5	69.5	26.6	40.8	5.6	1.8	0.8	10.6
66	21	12.3	90.7	55.1	26.5	40.5	5.7	1.7	0.3	10.2
66	60	12.8	79.2	34.7	27.6	42.1	5.8	2.2	0.4	11.0
66	160	11.7	66.1	25.6	27.8	41.2	5.0	1.6	0.1	10.0
66	290	11.7	57.5	19.0	29.3	40.6	4.0	0.8	0.0	9.1
66	560	10.5	32.7	6.7	33.6	43.0	2.8	0.3	0.0	6.6
66	1095	7.6	18.8	2.6	39.7	41.2	2.2	0.2	0.0	3.7
66	1460	2.2	5.8	0.6	43.4	41.3	1.9	0.1	0.0	3.3
82	3	13.0	89.2	45.7	27.1	41.8	6.2	2.1	0.6	10.9
82	7	12.3	77.5	33.5	27.3	41.1	5.7	2.0	0.5	10.6
82	21	13.3	76.0	29.0	27.7	42.7	6.0	1.7	0.6	10.5
82	60	12.5	61.1	21.1	30.2	43.5	4.9	1.2	0.0	9.8
82	160	10.5	42.7	11.2	26.3	44.7	2.6	0.2	0.0	5.6

Lig, Klasson lignin; Glu, glucose; Xyl, xylose; Gal, galactose; Arab, arabinose; Mann, mannose.

of decay on strength, weight, and chemical composition can be seen by comparing the loss in bending strength (MOR), loss in work to maximum load (WML), and loss in stiffness (MOE) to loss in dry weight (Figure 11.21).

These results demonstrate that considerable bending strength loss occurs before measurable weight loss. At 10% weight loss, strength loss was approximately 40% and the loss in the energy properties, such as work to maximum load, was reduced by 70–80%. The decay–strength relationship



**FIGURE 11.21** Effect of decay by *G. trabeum* on weight loss and mechanical properties (Curling et al. 2002).



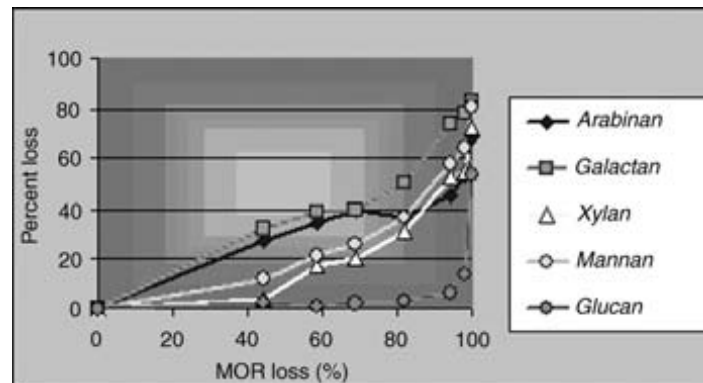
**TABLE 11.8**  
**Relationship between Loss of Strength and Sugar Analysis of Fire Retardant Treated Southern Pine—Guanylurea Phosphate/Boric Acid 55.5 kg/m<sup>3</sup>**

Temp (°C)	Time (days)	MOE (Gpa)	MOR (Mpa)	WML (kj/m <sup>3</sup> )	Lig (%)	Glu (%)	Xyl (%)	Gal (%)	Arab (%)	Mann (%)
23	3	12.2	108.1	82.8	28.3	41.4	5.7	2.3	1.2	11.2
23	160	12.6	107.8	80.7	25.9	44.1	6.0	2.4	1.1	12.4
54	3	12.6	107.4	84.4	27.9	43.0	6.2	1.9	1.1	11.4
54	7	13.4	108.5	77.6	27.5	43.1	5.9	1.8	1.1	11.4
54	21	12.5	107.6	75.6	28.1	42.6	6.3	2.3	1.2	11.6
54	60	12.9	104.2	72.0	27.9	42.4	5.8	1.9	1.3	11.3
54	160	13.0	104.6	65.1	25.6	46.2	6.2	2.3	0.8	12.0
66	7	14.1	105.9	73.8	26.9	40.5	5.9	1.7	1.0	10.6
66	21	13.3	104.9	72.5	28.1	40.3	5.4	1.8	0.8	10.3
66	60	13.3	98.8	57.5	28.2	40.8	5.7	1.6	0.6	10.4
66	160	12.2	78.3	33.6	29.1	—	5.7	1.7	0.4	10.7
66	290	13.3	69.8	24.6	28.9	41.7	5.6	1.4	0.1	10.4
66	560	12.7	56.2	16.8	30.3	42.8	5.2	1.1	0.1	9.9
66	1095	11.7	38.5	7.6	32.8	41.0	3.7	0.7	0.1	7.3
66	1460	8.0	17.9	3.3	37.6	42.1	2.8	0.4	0.1	5.8
82	3	13.5	111.1	70.1	27.9	42.2	5.7	2.1	1.5	10.9
82	7	12.8	110.3	69.3	28.1	42.3	6.2	2.3	1.4	10.9
82	21	13.3	105.0	55.1	29.5	44.2	6.6	2.4	1.2	11.1
82	60	13.4	83.7	37.2	29.3	44.2	6.5	2.6	0.9	10.4
82	160	12.5	66.3	25.2	26.9	48.4	5.3	1.6	0.3	9.8

Lig, Klasson lignin; Glu, glucose; Xyl, xylose; Gal, galactose; Arab, arabinose; Mann, mannose.

appears very consistent as decay initiates and progresses. It seems not only qualitative but may also be quantitative.

Curling et al. (2002) also found that changes in chemical composition were directly related to strength loss (Figure 11.22). As decay progressed it sequentially affected different chemical components. A virtually similar effect was previously noted by Winandy and Morrell (1993). Initial loss in the mannan and xylan components correlated with the start of measurable weight loss; both



**FIGURE 11.22** Comparison of loss of carbohydrate components with loss in bending strength (MOR) caused by *G. trabeum* (Curling et al. 2002).

**TABLE 11.9**  
**Relationship between Loss of Strength and Sugar Analysis of Fire Retardant Treated Southern Pine—Borax/Boric Acid 56.3 kg/m<sup>3</sup>**

Temp (°C)	Time (days)	MOE (Gpa)	MOR (Mpa)	WML (kj/m <sup>3</sup> )	Lig (%)	Glu (%)	Xyl (%)	Gal (%)	Arab (%)	Mann (%)
23	3	12.4	115.7	69.3	27.8	42.2	6.7	2.6	1.21	14.8
23	160	13.3	115.3	65.4	26.3	39.3	5.9	2.4	1.2	10.5
54	3	12.9	106.1	57.6	27.1	42.8	6.5	2.3	1.0	14.7
54	7	13.9	115.4	62.2	26.8	44.4	7.0	2.7	1.4	15.5
54	21	16.0	117.1	59.8	26.7	43.9	6.5	1.9	1.0	15.7
54	60	13.5	126.5	86.3	27.0	43.5	6.8	1.9	1.2	14.9
54	160	13.7	122.7	70.9	25.7	44.9	6.5	2.0	1.0	12.4
66	7	13.8	116.5	69.0	27.4	42.2	6.1	1.9	1.0	11.2
66	21	13.1	116.0	74.7	27.5	41.8	6.4	2.0	1.0	11.1
66	60	13.1	108.5	66.1	28.2	42.0	6.2	1.8	1.0	10.7
66	160	13.4	115.0	77.8	28.9	43.5	6.0	2.0	0.8	11.2
66	290	13.3	108.7	76.3	28.6	44.0	6.0	1.7	0.7	11.1
66	560	13.4	99.2	65.8	29.3	44.1	6.3	1.9	0.8	10.9
66	1095	12.8	73.5	32.3	27.4	42.7	5.4	1.4	0.3	9.7
66	1460	11.7	50.3	16.2	31.6	45.2	4.3	0.8	0.1	8.9
82	3	14.6	123.1	66.9	27.0	43.1	6.7	2.7	1.2	15.7
82	7	14.5	131.1	76.9	27.1	43.5	6.3	1.4	0.6	14.8
82	21	14.4	132.7	73.9	27.0	46.0	6.8	2.3	0.9	15.4
82	60	14.8	137.9	89.1	27.0	42.3	6.5	2.5	0.9	14.5
82	160	14.3	124.0	69.1	26.3	43.8	6.1	2.3	0.7	11.4

Lig, Klason lignin; Glu, glucose; Xyl, xylose; Gal, galactose; Arab, arabinose; Mann, mannose.

occurred at about 40% strength loss. Because mannan/xylan components make up approximately 18% of the wood, compared to 8% for galactan and arabinan, it is understandable why measurable weight loss is not evident in incipient decay. Final stage of brown-rot decay occurs once the glucan-rich cellulose is broken down, at a strength loss of about 80%. It is also at this stage (80% loss in MOR) that loss in stiffness (MOE) increases rapidly suggesting that the stiffness of the wood is related to the cellulose rather than the hemicellulose composition.

Table 11.10 shows the loss in MOE and maximum compression strength (MCS) in wood exposed to the brown-rot fungus *Postia placenta* in standard ASTM soil block and in ground tests. In the wood blocks, at 2 weeks into the standard 12-week test, there is only a 3% weight loss but already a 13% loss in MOE and a 21% loss in MCS. At five weeks, there is a 26% weight loss but a 53% loss in MOE and a 71% loss in MCS. In the wood stakes, the losses are less since the specimen size is larger and requires more time for the fungus to degrade the wood. Even so, the wood stakes at 5 weeks show a weight loss of 7% and a loss of 12% in MOE and 22% in MCS.

Table 11.11 shows the correlation between time in test and changes in sugar analysis that has occurred during that time. The greatest loss is in the arabinose sugar, which was also the case in FRT wood.

### 11.6.7 NATURALLY OCCURRING CHEMICALS

Some woods have a higher acidic extractives content that can cause greater strength loss due to hydrolysis. This may be a problem in some of the tropical species coming into the market. These

**TABLE 11.10**  
**Strength Loss in Decayed Wood**

Time (weeks)	Wood Blocks			Wood Stakes		
	Weight Loss (%)	MOE Reduction (%)	MCS Reduction (%)	Weight Loss (%)	MOE Reduction (%)	MCS Reduction (%)
1	0	3	6	0	5	2
2	3	13	21	0	8	2
3	9	22	37	1	7	8
4	18	34	53	3	9	19
5	26	53	71	7	12	22

Fungus used in test, *Postia placenta*; MOE, modulus of elasticity; MCS, maximum compression strength.

Source: Clausen and Kartal, 2003.

more acidic woods will not only be more susceptible to strength loss but will also increase the corrosion potential of iron fasteners used with the wood. It is not uncommon to find silica and calcium salt crystals in wood fiber (Figure 11.23), and they can lead to strength losses by abrasion of the fibers during machining. Naturally occurring chemicals may also cause increased hygroscopicity and hydrolysis when salts dissolve in water.

## 11.7 TREATMENT EFFECTS

From a quantitative viewpoint, the effects of preservatives have been investigated by many researchers. A recent review (Winandy 1996a) identified and then classified several treatment-related issues that controlled the treatment effect with waterborne preservatives. In that review, waterborne-preservative treatments were shown to generally reduce the mechanical properties

**TABLE 11.11**  
**Correlation between Strength Loss in Decayed Wood and Carbohydrate Analysis**

Sample	Time (weeks)	Carbohydrate Composition					
		Arabinan (%)	Galactan (%)	Rhamnan (%)	Glucan (%)	Xylan (%)	Mannan (%)
Blocks	0	1.01	1.37	0.07	42.82	5.88	11.32
	1	0.87	1.40	0.07	42.56	5.05	12.15
	2	0.78	1.10	0.06	42.46	5.60	10.32
	3	0.68	1.02	0.05	42.23	4.82	9.65
	4	0.55	1.07	0.04	41.89	3.91	10.73
Stakes	5	0.61	0.86	0.04	39.13	4.36	7.87
	0	1.02	2.63	0.09	41.97	6.44	9.84
	1	0.93	2.20	0.09	42.80	6.39	10.43
	2	0.94	2.13	0.09	42.07	6.61	10.53
	3	0.86	2.05	0.08	42.23	6.21	10.62
	4	0.82	1.69	0.07	41.25	6.13	9.84
	5	0.77	2.04	0.07	40.48	5.93	8.98

Source: Clausen and Kartal, 2003.



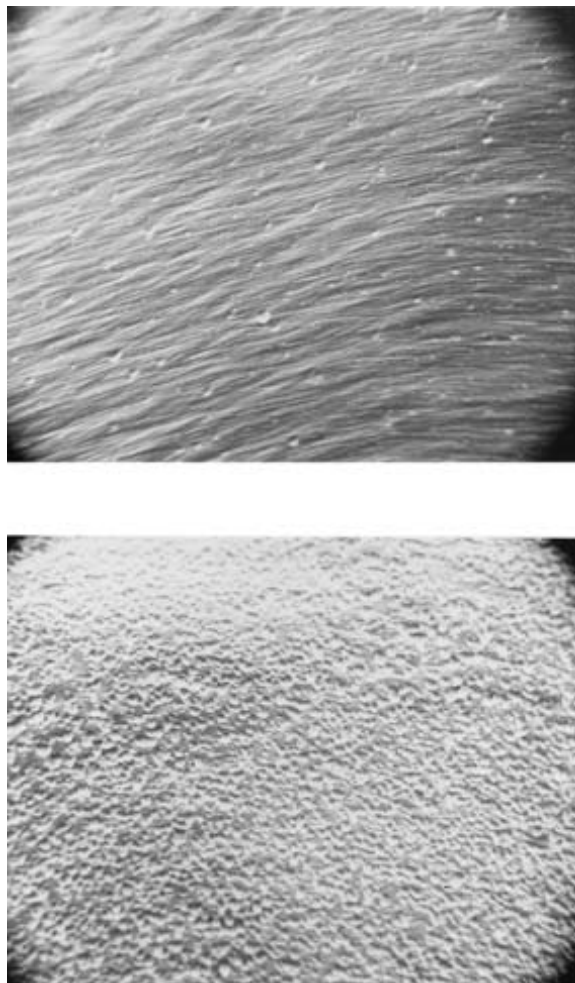
**FIGURE 11.23** Scanning electron micrograph of calcium carbonate crystals in lumens of southern pine ( $\times 800$ ).

of wood. The effects of waterborne preservatives on mechanical properties are related to several key wood material factors and pretreatment, treatment, and post-treatment processing factors. These key factors include preservative chemistry or chemical type (Wood et al. 1980, Bendtsen et al. 1983, Winandy et al. 1983), retention (Winandy et al. 1985, Winandy et al. 1989), post-treatment drying temperature (Winandy and Boone 1988, Winandy 1989), initial kiln-drying temperature (Winandy and Barnes 1991), grade of material (Winandy et al. 1988, Winandy 1989), and incising (if required) (Lam and Morris 1989, Morrell et al. 1998, Winandy and Morrell 1998). The effects of treatments on time-dependent relationships previously shown in Figure 11.5 have also been studied, but whereas they seemed to have little practical significance related to long-term duration-of-load (Soltis and Winandy 1989) they did have significant effects on short-term impact loading (Winandy 1995b).

In summary, each factor has the potential to influence the effects of the preservative treatment on mechanical properties. As might be expected, the interactive nature of the processing and chemical factors is critical, and these factors must always be considered when attempting to define the effects of waterborne preservatives on mechanical properties. A cumulative-damage model to predict these effects has also been developed (Winandy 1996b).

From a qualitative viewpoint, metallic salts such as chromated copper arsenate (CCA), amine- or ammoniacal-copper quat (ACQ), Copper Azol (CA), and other metallic salts of copper, arsenic, zinc, and tin are used to increase the service life of wood in use against biological attack. One major advantage of many waterborne preservatives is their resistance to leaching by water. Some organo-metallic salt preservatives (e.g., ACQ, CA) become insoluble as the treated wood dries, which dehydrates the preservative complex within the wood. In this process, known as immobilization, the cell wall is not directly affected and subsequently strength is virtually unaffected. Other metal salts (e.g., CCA) undergo hydrolytic reduction upon contact with the reducing sugars found in wood. In this process, known as fixation, the cell wall is oxidized and subsequently strength is affected. At most usable concentrations these preservatives are sufficiently acidic or alkaline to cause some cell wall hydrolysis (Betts and Newlin 1915, Hatt 1906, Wood et al. 1980). The effects on strength are greater in kiln-dried waterborne preservative-treated wood than in air-dried salt-treated wood (Bendtsen et al. 1983, Winandy et al. 1985). Most water-borne preservative salts increase the hygroscopicity of the wood (Bendtsen 1966, Bendtsen et al. 1983). This causes an increased EMC, which further influences strength.

After treatment and either immobilization or fixation, precipitated preservative salts can be seen in the wood structure. Comparison of photomicrographs of untreated southern pine (Figure 11.24 top) and southern pine treated with 2.5 lb CCA/ft<sup>3</sup> (Figure 11.24 bottom) reveals that the salts in



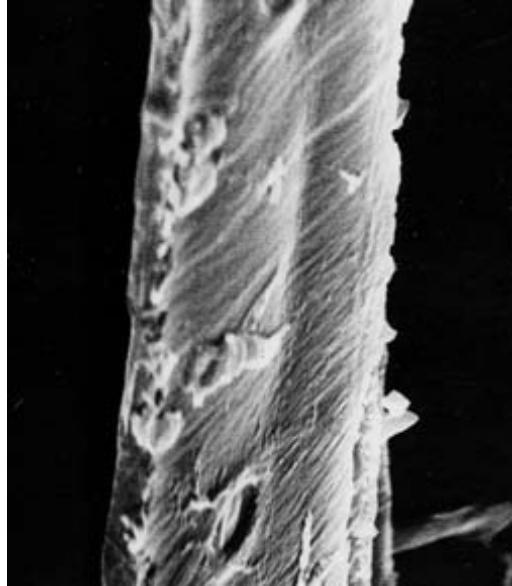
**FIGURE 11.24** Scanning electron micrograph of CCA in southern pine.

the treated wood form a rough coating on the lumen walls. The exact final location of these fixed salts is still subject to discussion. Undoubtedly, most of these injected hydrolytic preservatives remain in the cell lumen, but the extent to which these preservatives enter the cell wall and react with the cell wall substance dictates the preservative's effect on strength.

Preservative formulations that contain copper and chromium salts reportedly promote afterglow in treated wood subjected to fire. Once the treated wood starts to burn or glow, the wood may continue to glow until the entire member is consumed, even when no flame is present (Dale 1966, McCarthy et al. 1972). This characteristic can cause serious problems for utility poles, fence posts, and highway signs, structures that might be subjected to accidental fires or controlled ground fire, which is used as a forest or agricultural management tool.

Petroleum-based chemicals such as creosote and pentachlorophenol in oil are also used as wood preservatives. These organic preservatives are inert toward the cell wall substance and do not seem to cause any appreciable strength losses (MacLean 1951, Koukal et al. 1960, Gillwald 1961, USDOD 1979, Barnes and Winandy 1986).

Salts such as sodium tetraborate, diammonium phosphate, trisodium phosphate, diammonium sulfate, and salts of boric acid have long been used as fire retardants. Hygroscopicity, corrosion of fasteners, and increased acidity are also problems with these salts. Like the preservative salts, these



**FIGURE 11.25** Scanning electron micrograph of southern pine with FRT crystal deposition on surface.

salts also precipitate in the cell cavity and the cell wall (Figure 11.25). They appear on the fiber surface of pine treated with 4.2 lb of ammonium dihydrogen phosphate ( $\text{NH}_4\text{H}_2\text{PO}_4$ ) per cubic foot of wood. The initial effects of FR treatments on strength are greater in kiln-dried salt-treated wood than in air-dried salt-treated wood (Gerhards 1970, Brazier and Laidlaw 1974, Adams et al. 1979, Johnson 1967). Like the waterborne preservatives, this is due to hydrolytic degradation of the fiber, caused by the combination of high moisture content, high temperature, and acid salts or alkalis during the post-treatment redrying process.

Many fire-retardant salt treatments are very hygroscopic salts causing increased moisture sorption and irreversible swelling (Bendtsen 1966). Most interior FR formulations are not recommended for use where relative humidity is over 92% (AWPA 2003).

FRT plywood roof sheathing is often required by U.S. Building Codes in roof systems for multifamily dwellings having common property walls. In the mid-1980s, users of some FRT materials, especially plywood roof sheathing exposed to elevated in-service temperatures, were experiencing significant thermal degrade (Figure 11.26). From the late 1980s until about 2001, a major +10-year research program was carried on at the U.S. Forest Products Laboratory to identify the factors and mechanisms of FRT-induced strength loss. Qualitatively, the mechanism of thermal degrade in FRT plywood was acid hydrolysis. The magnitude of strength loss could be cumulatively related to FR chemistry, thermal exposure during pretreatment, treatment, and post-treatment processing and in-service exposure. The effects of FR chemistry could be mitigated by use of pH buffers. The strength effects were similar for many quality levels of plywood. Quantitatively, a kinetics-based approach could be used to predict strength loss based on its time-temperature history.

From a mechanistic approach to FR thermal degradation, the effects of FR treatments on strength properties were shown to depend on FR chemistry and thermal processing. The research confirmed that field problems with FRT plywood roof sheathing and roof-truss lumber resulted from thermal-induced acid degradation. In one comprehensive study, over 6000 specimens of density matched southern pine ( $16 \times 35 \times 250$ -mm) were systematically exposed at one of four temperatures: 25°, 54°, 66°, and 82°C for exposures up to 4 years (LeVan et al. 1990, Winandy 1995a, Lebow and Winandy 1999a). Data on the rates and magnitudes of thermal-induced strength loss at 27°, 54°, 66°, and 82°C were obtained for specimens treated with one of six FR-model chemicals or untreated.

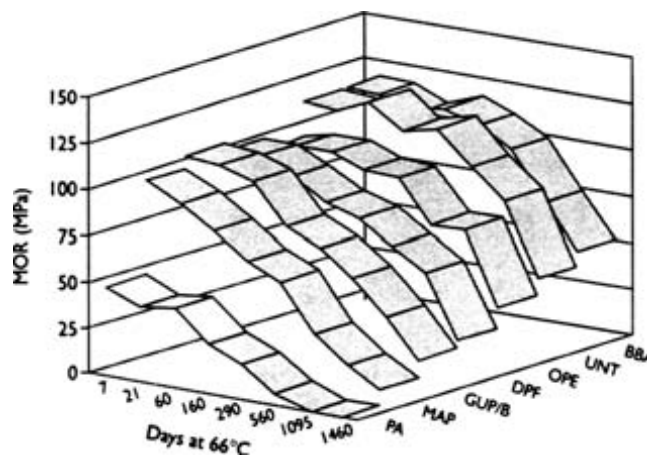


**FIGURE 11.26** Example of fully serviceable untreated plywood roof sheathing (top left) adjacent to thermally degraded FR-treated plywood sheathing (center) used next to a gypsum-sheathed 60-minute-rated fire wall (lower right).

The influence of temperature and treatment pH was progressive, as shown by this example at 66°C in which each treatment (going from left to right on z-axis) has a progressively higher pH (Figure 11.27).

Kinetic-based models for predicting strength loss as a function of exposure temperature and duration of exposure were then developed from this data obtained at four temperatures. These kinetic models can be used predict thermal degradation at other temperatures (Lebow and Winandy 1999a). A single-stage approach quantitatively based on time-temperature superposition was used to model reaction rates, such that

$$Y_{ij} = b_j * \exp(-X * A * (H_i/H_0) * e^{(-E_a/RT_{ij})}) \quad (11.10)$$



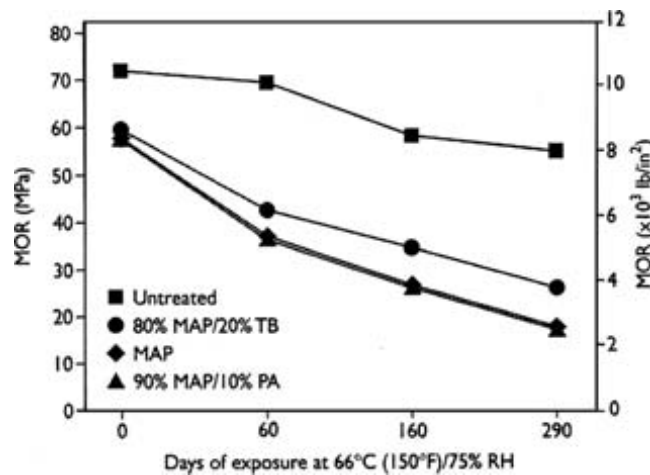
**FIGURE 11.27** Strength loss over time of exposed to 66°C. Key: PA, phosphoric acid; MAP, monoammonium phosphate; GUP/B, guanylurea phosphate/boric acid; DPF, dicyandiamide-PA-formaldehyde; OPE, organo-phosphonate ester; UNT, untreated; and BBA, borax/boric acid.

where

- $i$  = temperature of exposure,
- $j$  = FR chemical,
- $Y_{ij}$  = bending strength (MPa) at Temperature ( $T_i$ ) for  $FR_j$ ,
- $X$  = time (days) at Temperature ( $T_i$ ) for  $FR_j$ ,
- $b_{ij}$  = initial bending strength (MPa) at time ( $X_i = 0$ ),
- $H_i$  = relative humidity at test,
- $H_o$  = normalized relative humidity (67% R.H. (per ASTM D5516),
- $A$  = pre-exponential factor,
- $E_a$  = activation energy,
- $R$  = gas constant ( $J/^\circ K \cdot \text{mole}$ ), and
- $T_{ij}$  = temperature ( $^\circ K$ ) and for  $FR_j$ .

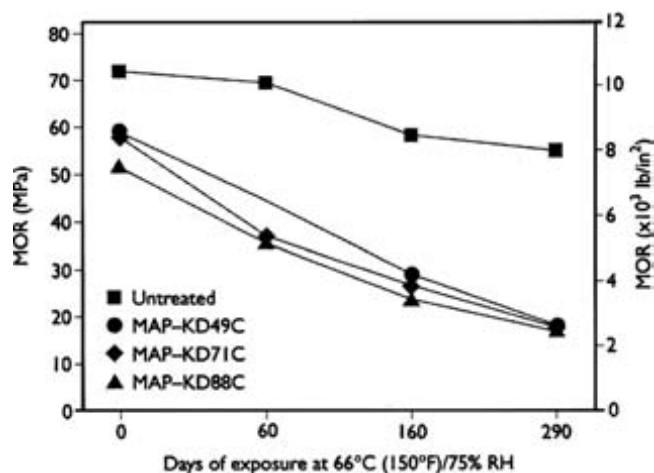
This research also proved that the use of pH buffers in FR chemicals, such as borates, can partially mitigate the initial effect of the FR treatment on strength and then significantly enhance resistance to subsequent thermal degradation. For modulus of elasticity there appeared to be few real benefits derived from adding borate-based pH buffers to the FR-mixture on the subsequent thermal degrade of FRT plywood exposed to high-temperatures (Winandy 1997). However, after 290 days of exposure at  $66^\circ C$  there were significant ( $P < 0.05$ ) benefits derived with respect to limiting strength loss and loss in energy-related properties, such as work to maximum load, by the addition of borate to the FR-chemical mixture (Figure 11.28). Remedial treatments based on surface application of pH-buffered borate/glycol solutions were also developed to protect against additional in-service strength loss (Winandy and Schmidt 1995).

Other work also found that the rate of strength loss was largely independent of plywood quality or grade (Lebow and Winandy 1998) and could be directly related to changes in treated wood pH (Lebow and Winandy 1999b). Further, variation in redrying temperatures from  $49^\circ C$  to  $88^\circ C$  had little differential effect on the subsequent rate of thermal degradation when the treated plywood was exposed at  $66^\circ C$  for up to 290 days (Winandy 1997, Figure 11.29). This was related to the shorter kiln-residence times required at higher temperatures yielding similar states of entropy via differing, but thermodynamically comparable, temperature-duration histories.



**FIGURE 11.28** Effect of pH buffers on the rate of thermal degrade (Winandy 1997). Key: MAP, monoammonium phosphate; PA, phosphoric acid; and TB, sodium tetraborate.





**FIGURE 11.29** Effects of kiln drying after MAP treatment at 49, 71, and 88°C on thermal degrade (Winandy 1997).

## 11.8 SUMMARY

Over the years the strength of wood has been, for the most part, studied by physical chemists and engineers, and the chemistry of wood has been studied by organic chemists and biochemists. In a materials science approach to wood research, these disciplines must work together to relate the physical properties to the chemistry of the wood material.

In this chapter an explanation is presented of certain engineering aspects that are important in understanding the mechanical properties of wood. Individual factors such as growth, environment, chemicals, and use can greatly affect the physical and mechanical properties of the wood material. A theoretical model is presented to explain the relationship between physical properties and chemistry of wood at three distinct levels: macroscopic or cellular, microscopic or cell wall, and molecular or polymeric. These three levels and their implications on material properties must be understood to relate both wood chemistry and wood engineering from a materials science standpoint. When this is accomplished, the treatment and processing of wood and wood products can be controlled to yield more desirable and uniform properties.

While considerable work has been undertaken in the last 20–30 years, many of the underlying governing principles are yet unknown. The theories presented in this paper are offered as a starting point for consideration and discussion. Hopefully they may some day become a point from which, through mutual cooperation between the fields of engineering and chemistry, the chemistry of wood strength may be truly explained.

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