

PHYSICAL AND MECHANICAL PROPERTIES OF CLEAR WOOD

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Moisture Relations

Wood is a hygroscopic material which contains water in varying amounts, depending upon the relative humidity and temperature of the surrounding atmosphere. **Equilibrium conditions** are established as shown in Table 6.7.1. The standard reference condition for wood is oven-dry weight, which is determined by drying at 100 to 105°C until there is no significant change in weight.

Moisture content is the amount of water contained in the wood, usually expressed as a percentage of the mass of the oven-dry wood. Moisture can exist in wood as **free water** in the cell cavities as well as water **bound** chemically within the intermolecular regions of the cell wall. The moisture content at which cell walls are completely saturated but at which no water exists in the cell cavities is called the **fiber saturation point**. Below the fiber saturation point, the cell wall shrinks as moisture is removed, and the physical and mechanical properties begin to change as a function of moisture content. **Air-dry wood** has a moisture content of 12 to 15 percent. **Green wood** is wood with moisture content above the fiber saturation point. The moisture content of green wood typically ranges from 40 to 250 percent.

Dimensional Changes

Shrinkage or swelling is a result of change in water content within the cell wall. Wood is dimensionally stable when the moisture content is above the fiber saturation point (about 28 percent for shrinkage estimates). Shrinkage is expressed as a percentage of the dimensional change based on the green wood size. Wood is an anisotropic material with respect to shrinkage. **Longitudinal shrinkage** (along the grain) ranges from 0.1 to 0.3 percent as the wood dries from green to oven-dry and is usually neglected. Wood shrinks most in the direction of the annual growth rings (**tangential shrinkage**) and about one-half as much across the rings (**radial shrinkage**). Average shrinkage values for a number of commercially important species are shown in Table 6.7.2. Shrinkage to any moisture condition can be estimated by assuming that the change is linear from green to oven-dry and that about one-half occurs in drying to 12 percent.

Swelling in polar liquids other than water is inversely related to the size of the molecule of the liquid. It has been shown that the tendency

to hydrogen bonding on the dielectric constant is a close, direct indicator of the swelling power of water-free organic liquids. In general, the strength values for wood swollen in any polar liquid are similar when there is equal swelling in the wood.

Swelling in aqueous solutions of sulfuric and phosphoric acids, zinc chloride, and sodium hydroxide above pH 8 may be as much as 25 percent greater in the transverse direction than in water. The transverse swelling may be accompanied by longitudinal shrinkage up to 5 percent. The swelling reflects a chemical change in the cell walls, and the accompanying strength changes are related to the degradation of the cellulase.

Dimensional stabilization of wood cannot be completely attained. Two or three coats of varnish, enamel, or synthetic lacquer may be 50 to 85 percent efficient in preventing short-term dimensional changes. Metal foil embedded in multiple coats of varnish may be 90 to 95 percent efficient in short-term cycling. The best long-term stabilization results from internal bulking of the cell wall by the use of materials such as phenolic resins polymerized in situ or water solutions of polyethylene glycol (PEG) on green wood. The presence of the bulking agents alters the properties of the treated wood. Phenol increases electrical resistance, hardness, compression strength, weight, and decay resistance but lowers the impact strength. Polyethylene glycol maintains strength values at the green wood level, reduces electric resistance, and can be finished only with polyurethane resins.

Mechanical Properties

Average **mechanical properties** determined from tests on clear, straight-grained wood at 12 percent moisture content are given in Table 6.7.2. Approximate standard deviation(s) can be estimated from

$$s = CX$$

where X is average value for species and

$$C = \begin{cases} 0.10 & \text{for specific gravity} \\ 0.22 & \text{for modulus of elasticity} \\ 0.16 & \text{for modulus of rupture} \\ 0.18 & \text{for maximum crushing strength parallel to grain} \\ 0.14 & \text{for compression strength perpendicular to grain} \\ 0.25 & \text{for tensile strength perpendicular to grain} \\ 0.25 & \text{for impact bending strength} \\ 0.10 & \text{for shear strength parallel to grain} \end{cases}$$

Relatively few data are available on tensile strength parallel to the grain. The modulus of rupture is considered to be a conservative estimate for the tensile strength of clear wood.

Mechanical properties remain constant as long as the moisture content is above the fiber saturation point. Below the fiber saturation point properties generally increase with decreasing moisture content down to about 8 percent. Below about 8 percent moisture content, some properties, principally tensile strength parallel to the grain and shear strength, may decrease with further drying. An approximate adjustment for clear wood properties between about 8 percent moisture and green can be obtained by using an annual compound-interest type of formula

$$P_2 = P_1 \left(1 + \frac{C}{100} \right)^{-(M_2 - M_1)}$$

where P_1 is the known property at moisture content M_1 , P_2 is the property to be calculated at moisture content M_2 , and C is the assumed percentage change in property per percentage change in moisture content. Values of P_1 at 12 percent moisture content are given in Table 6.7.2, and values of C are given in Table 6.7.3. For the purposes of property adjustment, green is assumed to be 23 percent moisture content. The formula should not be used with redwood and cedars. A more accurate adjustment formula is given in "Wood Handbook." Additional data and tests on green wood can be found in "Wood Handbook" and on the Web at www.fpl.fs.fed.us. Data on foreign species are given in "Tropical Timbers of the World."

Table 6.7.1 Moisture Content of Wood in Equilibrium with Stated Dry-Bulb Temperature and Relative Humidity

Temperature (dry-bulb)		Moisture content, % at various relative-humidity levels																			
°F	(°C)	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	98
30	-1.3	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3	26.9
40	4.2	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3	26.9
50	9.8	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3	26.9
60	15	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1	26.8
70	21	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9	26.6
80	26	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6	26.3
90	32	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3	26.0
100	38	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	15.1	17.0	19.5	22.9	25.6
110	43	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4	25.2
120	49	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0	24.7
130	54	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5	24.2
140	60	0.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0	23.7
150	65	0.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4	23.1
160	71	0.8	1.6	2.4	3.2	3.9	4.6	5.2	5.8	6.4	7.1	7.8	8.5	9.3	10.3	11.4	12.7	14.4	16.7	19.9	22.5
170	76	0.7	1.5	2.3	3.0	3.7	4.3	4.9	5.6	6.2	6.8	7.4	8.2	9.0	9.9	11.0	12.3	14.0	16.2	19.3	21.9
180	81	0.7	1.4	2.1	2.8	3.5	4.1	4.7	5.3	5.9	6.5	7.1	7.8	8.6	9.5	10.5	11.8	13.5	15.7	18.7	21.3
190	88	0.6	1.3	1.9	2.6	3.2	3.8	4.4	5.0	5.5	6.1	6.8	7.5	8.2	9.1	10.1	11.4	13.0	15.1	18.1	20.7
200	93	0.5	1.1	1.7	2.4	3.0	3.5	4.1	4.6	5.2	5.8	6.4	7.1	7.8	8.7	9.7	10.9	12.5	14.6	17.5	20.0
210	99	0.5	1.0	1.6	2.1	2.7	3.2	3.8	4.3	4.9	5.4	6.0	6.7	7.4	8.3	9.2	10.4	12.0	14.0	16.9	19.3
220	104	0.4	0.9	1.4	1.9	2.4	2.9	3.4	3.9	4.5	5.0	5.6	6.3	7.0	7.8	8.8	9.9	*	*	*	*
230	110	0.3	0.8	1.2	1.6	2.1	2.6	3.1	3.6	4.2	4.7	5.3	6.0	6.7	*	*	*	*	*	*	*
240	115	0.3	0.6	0.9	1.3	1.7	2.1	2.6	3.1	3.5	4.1	4.6	*	*	*	*	*	*	*	*	*
250	121	0.2	0.4	0.7	1.0	1.3	1.7	2.1	2.5	2.9	*	*	*	*	*	*	*	*	*	*	*
260	126	0.2	0.3	0.5	0.7	0.9	1.1	1.4	*	*	*	*	*	*	*	*	*	*	*	*	*
270	132	0.1	0.1	0.2	0.3	0.4	0.4	*	*	*	*	*	*	*	*	*	*	*	*	*	*

*Conditions not possible at atmospheric pressure.
SOURCE: "Wood Handbook," Forest Products Laboratory, 1999.

Table 6.7.2 Strength and Related Properties of Wood at 12% Moisture Content (Average Values from Tests on Clear Pieces of 2 in x 2 in Cross Section per ASTM D 143)

Kind of wood	Specific gravity, oven-dry volume	Density at 12% m.c. lb/ft ³	Shrinkage, % from green to oven-dry condition based on dimension when green		Static bending		Max crushing strength parallel to grain, lb/in ²	Compression perpendicular to grain at proportional limit, lb/in ²	Tensile strength perpendicular to grain, lb/in ²	Impact bending, height of drop in inches for failure with 50-lb hammer	Shear strength parallel to grain, lb/in ² , avg of R and T	Hardness perpendicular to grain, lb, avg of R and T
			Rad.	Tan.	Modulus of rupture, lb/in ²	Modulus of elasticity, ×10 ³ lb/in ²						
Hardwoods												
Ash, white	0.60	42	4.9	7.8	15,400	1,740	7,410	1,160	940	43	1,910	1,320
Basswood	0.37	26	6.6	9.3	8,700	1,460	4,730	370	350	16	990	410
Beech	0.64	45	5.5	11.9	14,900	1,720	7,300	1,010	1,010	41	2,010	1,300
Birch, yellow	0.62	43	7.3	9.5	16,600	2,010	8,170	970	920	55	1,880	1,260
Cherry, black	0.50	35	3.7	7.1	12,300	1,490	7,110	690	560	29	1,700	950
Cottonwood, eastern	0.40	28	3.9	9.2	8,500	1,370	4,910	380	580	20	930	430
Elm, American	0.50	35	4.2	9.5	11,800	1,340	5,520	690	660	39	1,510	830
Elm, rock	0.63	44	4.8	8.1	14,800	1,540	7,050	1,230		56	1,920	1,320
Sweetgum	0.52	36	5.4	10.2	12,500	1,640	6,320	620	760	32	1,600	850
Hickory, shagbark	0.72	50	7.0	10.5	20,200	2,160	9,210	1,760		67	2,430	
Maple, sugar	0.63	44	4.8	9.9	15,800	1,830	7,830	1,470		39	2,330	1,450
Oak, red, northern	0.63	44	4.0	8.6	14,300	1,820	6,760	1,010	800	43	1,780	1,290
Oak, white	0.60	48	5.6	10.5	15,200	1,780	7,440	1,070	800	37	2,000	1,360
Poplar, yellow	0.42	29	4.6	8.2	10,100	1,580	5,540	500	540	24	1,190	540
Tupelo, black	0.50	35	4.2	7.6	9,600	1,200	5,520	930	500	22	1,340	810
Walnut, black	0.35	38	5.5	7.8	14,600	1,680	7,580	1,010	690	34	1,370	1,010
Softwoods												
Cedar, western red	0.32	23	2.4	5.0	7,500	1,110	4,560	460	220	17	990	350
Cypress, bald	0.46	32	3.8	6.2	10,600	1,440	6,360	730	300	24	1,900	510
Douglas-fir, coast	0.48	34	4.8	7.6	12,400	1,950	7,230	800	340	31	1,130	710
Hemlock, eastern	0.40	28	3.0	6.8	8,900	1,200	5,410	650		21	1,060	500
Hemlock, western	0.45	29	4.2	7.8	11,300	1,630	7,200	550	340	26	1,290	540
Larch, western	0.52	38	4.5	9.1	13,000	1,870	7,620	930	430	35	1,360	830
Pine, red	0.46	31	3.8	7.2	11,000	1,630	6,070	600	460	26	1,210	560
Pine, ponderosa	0.40	28	3.9	6.2	9,400	1,290	5,320	580	420	19	1,130	460
Pine, eastern white	0.35	24	2.1	6.1	8,600	1,240	4,800	440	310	18	900	380
Pine, western white	0.38	27	4.1	7.4	9,700	1,460	5,040	470		23	1,040	420
Pine, shortleaf	0.51	36	4.6	7.7	13,100	1,750	7,270	820	470	33	1,390	690
Redwood	0.40	28	2.6	4.4	10,000	1,340	6,150	700	240	19	940	480
Spruce, sitka	0.40	28	4.3	7.5	10,200	1,570	5,610	580	370	25	1,150	510
spruce, black	0.42	29	4.1	6.8	10,800	1,610	5,960	550		20	1,230	520

SOURCE: Tabulated from "Wood Handbook," Tropical Woods no. 95, and unpublished data from the USDA Forest Service, Forest Products Laboratory.

Table 6.7.3 Functions Relating Mechanical Properties to Specific Gravity and Moisture Content of Clear, Straight-Grained Wood

Property	Specific gravity–strength relation*				Change for 1% change in moisture content, %
	Green wood		Wood at 12% moisture content		
	Softwood	Hardwood	Softwood	Hardwood	
Static bending					
Modulus of elasticity (10 ⁶ lb/in ²)	2.331G ^{0.76}	2.02G ^{0.72}	2.966G ^{0.84}	2.39G ^{0.70}	2.0
Modulus of rupture (lb/in ²)	15,889G ^{1.01}	17,209G ^{1.16}	24,763G ^{1.03}	24,850G ^{1.13}	4.0
Maximum crushing strength parallel to grain (lb/in ²)	7,207G ^{0.94}	7,111G ^{1.11}	13,592G ^{0.97}	11,033G ^{0.89}	6.0
Shear parallel to grain (lb/in ²)	1,585G ^{0.73}	2,576G ^{1.24}	2,414G ^{0.85}	3,174G ^{1.13}	3.0
Compression perpendicular to grain at proportional limit (lb/in ²)	1,360G ^{1.60}	2,678G ^{2.48}	2,393G ^{1.57}	3,128G ^{2.09}	5.5
Hardness perpendicular to grain (lb)	1,399G ^{1.41}	3,721G ^{2.31}	1,931G ^{1.50}	3,438G ^{2.10}	2.5

*The properties and values should be read as equations; e.g., modulus of rupture for green wood of softwoods = 15,889G^{1.01}, where G represents the specific gravity of wood, based on the oven-dry weight and the volume at the moisture condition indicated.

Specific Gravity and Density

Specific gravity G_m of wood at a given moisture condition m is the ratio of the weight of the oven-dry wood W_o to the weight of water displaced by the sample at the given moisture condition w_m :

$$G_m = \frac{W_o}{w_m}$$

This definition is required because volume and weight are constant only under special conditions. The weight density of wood D (unit weight) at my given moisture content is the oven-dry weight plus the contained water divided by the volume of the piece at that same moisture content. Average values for specific gravity oven-dry and weight density at 12 percent moisture content in given in Table 6.7.2. Specific gravity at solid, dry wood substance based on helium displacement is 1.46, or about 91 lb/ft³.

Conversion of weight density from one moisture condition to another can be accomplished by the following equation (“Standard Handbook for Mechanical Engineers,” 9th ed., McGraw-Hill):

$$D_2 = D_1 \frac{100 + M_2}{100 + M_1 + 0.0135D_1(M_2 - M_1)}$$

where D_1 is the weight density, lb/ft³, which is known for some moisture condition M_1 ; D_2 is desired weight density at moisture content M_2 . moisture contents M_1 and M_2 are expressed in percentage.

Specific gravity and strength properties vary directly in an exponential relationship $S = KG^N$ Table 6.1.3 gives values for K and the exponent N for various strength properties. The equation is based on more than 160 kinds of wood and yields estimated average values for wood in general. This relationship is the best general index to the quality of defect-free wood.

Load Direction and Relation to Grain of Wood

All strength properties vary with the orthotropic axes of the wood in a manner approximated by Hankinson’s formula (“Wood Handbook”)

$$N = \frac{PQ}{P \sin^2 \theta + Q \cos^2 \theta}$$

where N is allowable stress induced by a load acting at M angle to the grain direction. lb/in²; P is allowable stress parallel to the grain. lb/in²; Q is allowable stress perpendicular to the grain, lb/in²; and θ is angle between the direction of load and the direction of grain.

The deviation of the grain from the long axis of the member to which the load is applied is known as the slope of grain and is determined by measuring the length of run in inches along the axis for a 1-in deviation of the grain from the axis. The effect of grain slope on the important strength properties is shown in Table 6.7.4

Rheological Properties

Wood exhibits viscoelastic characteristics. When first loaded, a wood member deforms elastically. If the load is maintained, additional time-dependent deformation occurs. Because of this time-dependent relation, the rate of loading is an important factor to consider in the testing and use of wood. For example, the load required to produce failure in 1 s is approximately 10 percent higher than that obtained in a standard 5-min strength test. Impact and dynamic measures of elasticity of small specimens are about 10 percent higher than those for static measures. Impact strengths are also affected by this relationship. In the impact bending test, a 50-lb (23-kg) hammer is dropped upon a beam from increasing heights until complete rupture occurs. The maximum height, as shown in Table 6.7.2. is for comparative purposes only.

Table 6.7.4 Strength of Wood Members with Various Grain Slopes as Percentages of Straight-Grained Members

Maximum slope of grain in member	Static bending		Impact bending: drop height to failure (50-lb hammer), %	Maximum crushing strength parallel to grain, %
	Modulus of rupture, %	Modulus of elasticity, %		
Straight-grained	100	100	100	100
1 in 25	96	97	95	100
1 in 20	93	96	90	100
1 in 15	89	91	81	100
1 in 10	81	89	62	99
1 in 5	55	61	36	93

SOURCE: “Wood Handbook.”

When solid material is strained, some mechanical energy is dissipated as heat. *Internal friction* is the term used to denote the mechanism that causes this energy dissipation. The **internal friction** of wood is a complex function of temperature and moisture content. The value of internal friction, expressed by logarithmic decrement, ranges from 0.1 for hat, moist wood to less than 0.02 for hot, dry wood. Cool wood, regardless of moisture content, has an intermediate value.

The term *fatigue* in engineering is defined as progressive damage that occurs in a material subjected to cyclic loading. *Fatigue life* is a term used to define the number of cycles sustained before failure. Researchers at the USDA Forest Service Forest Products Laboratory have found that small cantilever bending specimens subjected to fully reversed stresses, at 30 Hz with maximum stress equal to 30 percent of estimated Static strength and at 12 percent moisture content and 75°F (24°C), have a fatigue life of approximately 30 million cycles.

Thermal Properties

The coefficients of thermal expansion in wood vary with the structural axes. According to Weathewax and Stamm (*Trans. ASTM E 69, 1947, p. 421*), the longitudinal coefficient for the temperature range +150 to -50°C averages $3.39 \times 10^{-6}/^{\circ}\text{C}$ and is independent of specific gravity. Across the grain, for an average specific gravity oven-dry of 0.46, the radial coefficient α_r is $25.7 \times 10^{-6}/^{\circ}\text{C}$ and the tangential α_t is $34.8 \times 10^{-6}/^{\circ}\text{C}$. Both α_r and α_t vary with specific gravity approximately to the first power. Thermal expansions are usually overshadowed by the larger dimensional changes due to moisture.

Thermal conductivity of wood varies principally with the direction of heat with respect to the grain. **Approximate transverse conductivity** can be calculated with a linear equation of the form

$$k = G(B + CM) + A$$

where G is specific gravity, based on oven-dry weight and volume at a given moisture content M percent; for specific gravities above 0.3, temperatures around 75°F (24°C), and moisture contents below 25 percent, the values of constants A , B , and C are $A = 0.129$, $B = 1.34$, and $C = 0.028$ in English units, with k in $\text{Btu} \cdot \text{in}/(\text{h} \cdot \text{ft}^2 \cdot ^{\circ}\text{F})$ (TenWolde et al., 1988). Conductivity in watts per meter per kelvin is obtained by multiplying the result by 0.144. The effect of temperature on thermal conductivity is relatively minor and increases about 1 to 2 percent per 10°F (2 to 3 percent per 10°C). Longitudinal conductivity is considerably greater than transverse conductivity, but reported values vary widely. It has been reported as 1.5 to 2.8 times larger than transverse conductivity, with an average of about 1.8.

Specific heat of wood is virtually independent of specific gravity and varies principally with temperature and moisture content. Wilkes found that the approximate specific heat of dry wood can be calculated with

$$c_{p0} = a_0 + a_1 T$$

where $a_0 = 0.26$ and $a_1 = 0.000513$ for English units (specific heat in Btu per pound per degree Fahrenheit and temperature in degrees Fahrenheit) or $a_0 = 0.103$ and $a_1 = 0.00387$ for SI units [specific heat in $\text{kJ}/(\text{kg} \cdot ^{\circ}\text{K})$ and temperature in kelvins]. The specific heat of moist wood can be derived from

$$c_p = \frac{c_{p0} + 0.01M c_{p,w}}{1 + 0.01M} + A$$

where $c_{p,w}$ is the specific heat of water [1 Btu/(lb · °F)], or 4.186 kJ/(kg · K), M is the moisture content (percent), and A is a correction factor, given by

$$A = M(b_1 + b_2 T + b_3 M)$$

with $b_1 = -4.23 \times 10^{-4}$, $b_2 = 3.12 \times 10^{-5}$ in and $b_3 = -3.17 \times 10^{-5}$ in English units; and $b_1 = -0.6191$, $b_2 = 2.36 \times 10^{-4}$, and $b_3 = -1.33 \times 10^{-4}$ in SI units. These formulas are valid for wood below fiber saturation at temperatures between 45°F (7°C) and 297°F (147°C). And T is the temperature at which c_{p0} is desired.

The **fuel value** of wood depends primarily upon its dry density, moisture content, and chemical composition. Moisture in wood decreases

the fuel value as a result of latent heat absorption of water vaporization. An approximate relation for the fuel value of moist wood (Btu per pound on wet weight basis) (2.326 Btu/lb = 1 J/kg) is

$$H_w = H_d \left(\frac{100 - u/T}{100 + u} \right)$$

where H_d is higher fuel value of dry wood, averaging 8,500 Btu/lb for hardwoods and 9,000 Btu/lb for conifers, and u is the moisture content in percent. The actual fuel value of moist wood in a furnace will be less since water vapor interferes with the combustion process and prevents the combustion of pyrolytic gases. (See Sec. 7 for fuel values and Sec. 4 for combustion.)

Wood undergoes thermal degradation to volatile gases and char when it is exposed to elevated temperature. When wood is directly exposed to the standard fire exposure of ASTM E 119, the **char rate** is generally considered to be 1½ in/h (38 mm/h). The temperature at the base of the char layer is approximately 550°F (300°C). A procedure for calculating the fire resistance rating of an exposed wood member can be found in recent editions of "National Design Specification" (American Forest & Paper Association, 2005 and later). Among other factors, the ignition of wood depends on the intensity and duration of exposure to elevated temperatures. Typical values for rapid ignition are 570 to 750°F (300 to 400°C). In terms of heat flux, a surface exposure to 1.1 Btu/ft² (13 kW/m²) per second is considered sufficient to obtain piloted ignition. Recommended "maximum safe working temperatures" for wood exposed for prolonged periods range from 150 to 212°F (65 to 100°C). **Flame spread** values as determined by ASTM E 84 generally range from 65 to 200 for nominal 1-in- (25-mm-) thick lumber. Lists of flame spread index values for different species can be found in "Wood Handbook" and the Website of the American Wood Council. Flame spread can be reduced by impregnating the wood with fire-retardant chemicals or applying a fire-retardant coating.

The **reversible effect or temperature** on the properties of wood is a function of the change in temperature, moisture content of the wood, duration of heating, and property being considered. In general, the mechanical properties of wood decrease when the wood is heated above normal temperatures and increase when it is cooled. The magnitude of the change is greater for green wood than for dry. When wood is frozen, the change in property is reversible; i.e., the property will return to the value at the initial temperature. At constant moisture content and below about 150°F (65°C), mechanical properties are approximately linearly related to temperature. The change in property is also reversible if the wood is heated for a short time at temperatures below about 150°F. Table 6.7.5 lists the changes in properties at -58°F (-50°C) and 122°F (50°C) relative to those at 68°F (20°C).

Permanent loss in properties occurs when wood is exposed to higher temperatures for prolonged periods and then is cooled and tested at normal temperatures. If the wood is tested at a higher temperature after prolonged exposure, the actual strength loss is the sum of the reversible and permanent losses in properties. Permanent losses are higher for heating in steam than in water, and higher when heated in water than when heated in air. Repeated exposure to elevated temperatures is assumed to have a cumulative effect on wood properties. For example, at a given temperature the property loss will be about the same after six exposure of 1-year duration as it would be after a single exposure of 6 years. Figure 6.7.1 illustrates the effect of heating at 150°F (65°C) at 12 percent moisture content on the modulus of rupture relative to the strength at normal temperatures for spruce-pine-fir, Douglas-fir, and southern pine 2 × 4 s. Over the 6-year period, there was little or no change in the modulus of elasticity. Increasing the temperature would be expected to increase the permanent loss in strength; reducing the relative humidity would decrease the loss (see Green et al., 2003).

Electrical Properties

The important electrical properties of wood are conductivity (or its reciprocal, **resistivity**), dielectric constant, and dielectric power factor (see James, 1988).

Table 6.7.5 Approximate Middle-Trends for the Reversible Effect of Temperature on Mechanical Properties of Clear Wood at Various Moisture Conditions

Property	Moisture condition, %	Relative change in mechanical property from 68°F %	
		At -58°F	At +122°F
Modulus of elasticity parallel to grain	0	+11	-6
	12	+17	-7
	>FSP*	+50	—
Modulus of rupture	≤4	+18	-10
	11-15	+35	-70
	18-20	+60	-25
	>FSP*	+110	-25
Tensile strength parallel to grain	0-12	—	-4
Compressive strength parallel to grain	0	+20	-10
	12-45	+50	-25
Shear strength parallel to grain	>FSP*	—	-25
Compressive strength perpendicular to grain at proportional limit	0-16	—	-20
	≥10	—	-35

*Moisture content higher than the fibersaturation point (FSP).
 $T_c = (TF - 32)(0.55)$.

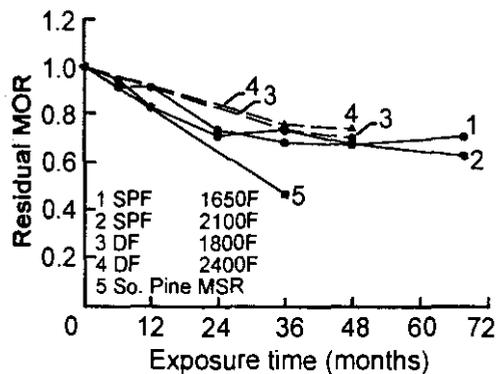


Fig. 6.7.1 Average residual MOR for solid-sawn 2 × 4 lumber exposed for various times at 66°C (150°F), 75 percent relative humidity and tested at 23°C (73°F), 67 percent relative humidity. DF, Douglas-fir; So. Pine, southern pine; SPF, spruce-pine-fir.

Resistivity approximately doubles for each 10°C decrease in temperature. As moisture content increases from zero to the fiber saturation point (FSP), the resistivity decreases by 10¹³ to 10¹³ times in an approximately linear relationship between the logarithm resistivity and moisture content. The resistivity is about 10¹⁴ to 10¹⁶ W · m for oven-dry wood and 10³ to 10⁴ W · m for wood at FSP. As the moisture content increases up to complete saturation, the decrease in resistivity is a factor of only about 50. Wood species also affect resistivity (see James), and the resistivity perpendicular to the grain is about twice that parallel to the grain. Water-soluble salts (some preservatives and fire retardants) reduce resistivity by only a minor amount when the wood has 8 percent moisture content or less, but they have a much larger effect when moisture content exceeds 10 to 12 percent.

The dielectric constant of oven-dry wood ranges from about 2 to 5 at room temperature, and it decreases slowly with increasing frequency. The dielectric constant increases as either temperature or moisture content increases. There is a negative interaction between moisture and frequency: At 20 Hz, the dielectric constant may range from 4 for dry wood to 106 for wet wood; at 1 kHz, from 4 dry to 5,000 wet; and at 1 MHz, from about 3 dry to 100 wet. The dielectric constant is about 30 percent greater parallel to the grain than perpendicular to it.

The power factor of wood varies from about 0.01 for dry, low-density woods to as great as 0.95 for wet, high-density woods. It is usually

greater parallel to the grain than perpendicular. The power factor is affected by complex interactions of frequency, moisture content, and temperature (James, 1975).

The change in electrical properties of wood with moisture content has led to the development of moisture meters for nondestructive estimation of moisture content. Resistance-type meters measure resistance between two pins driven into the wood. Dielectric-type meters depend on the correlation between moisture content and either dielectric constant or power factor, and they require only contact with the wood surface, not penetration.

Wood in Relation to Sound

Transmission of sound and the vibrational properties in wood are functions of a variety of factors. The speed of sound transmission is described by the expression $v = \sqrt{E/\rho}$, in which v is the speed of sound in wood, in/s; E is the dynamic Young's modulus, lb/in²; and ρ is the density of the wood, slugs/in³ (Pellerin and Ross, 2002). Various factors influence the speed of sound transmission: two of the most important factors are grain angle and the presence of degradation from decay. Hankinsan's formula, cited previously, adequately describes the relationship between speed of sound transmission and grain angle. The dynamic modulus is about 10 percent higher than the static value and varies inversely with moisture changes by approximately 1.3 percent for each percentage change in moisture content.

Degradation from biological agents can significantly alter the speed at which sound travels in wood. Speed of sound transmission values are greatly reduced in severely degraded wood members. Sound transmission characteristics of wood products are used in one form of nondestructive testing to assess the performance characteristics of wood products. Because speed of sound transmission is a function of the extent of degradation from decay, this technique is used to estimate the extent of severe degradation in large timbers.

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