

Moisture Relations and Physical Properties of Wood

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Wood, like many natural materials, is hygroscopic; it takes on moisture from the surrounding environment. Moisture exchange between wood and air depends on the relative humidity and temperature of the air and the current amount of water in the wood. This moisture relationship has an important influence on wood properties and performance. Many of the challenges of using wood as an engineering material arise from changes in moisture content or an abundance of moisture within the wood.

This chapter discusses the macroscopic physical properties of wood with emphasis given to their relationship with moisture content. Some properties are species-dependent; in such cases, data from the literature are tabulated according to species. The chapter begins with a broad overview of wood–water relations, defining key concepts needed to understand the physical properties of wood.

Wood–Moisture Relationships

Moisture Content and Green Wood

Many physical and mechanical properties of wood depend upon the moisture content of wood. Moisture content (MC) is usually expressed as a percentage and can be calculated from

$$MC = \frac{m_{\text{water}}}{m_{\text{wood}}} (100\%) \quad (4-1)$$

where m_{water} is the mass of water in wood and m_{wood} is the mass of the oven-dry wood. Operationally, the moisture content of a given piece of wood can be calculated by

$$MC = \frac{m_{\text{wet}} - m_{\text{dry}}}{m_{\text{dry}}} (100\%) \quad (4-2)$$

where m_{wet} is the mass of the specimen at a given moisture content and m_{dry} is the mass of the oven-dry specimen.

Green wood is often defined as freshly sawn wood in which the cell walls are completely saturated with water and additional water may reside in the lumina. The moisture content of green wood can range from about 30% to more than 200%. In green softwoods, the moisture content of sapwood is usually greater than that of heartwood. In green

Table 4–1. Average moisture content of green wood, by species

Species	Moisture content (%)		Species	Moisture content (%)	
	Heartwood	Sapwood		Heartwood	Sapwood
Hardwoods			Softwoods		
Alder, red	—	97	Baldcypress	121	171
Apple	81	74	Cedar, eastern red	33	—
Ash, black	95	—	Cedar, incense	40	213
Ash, green	—	58	Cedar, Port-Orford	50	98
Ash, white	46	44	Cedar, western red	58	249
Aspen	95	113	Cedar, yellow	32	166
Basswood, American	81	133	Douglas-fir, coast type	37	115
Beech, American	55	72	Fir, balsam	88	173
Birch, paper	89	72	Fir, grand	91	136
Birch, sweet	75	70	Fir, noble	34	115
Birch, yellow	74	72	Fir, Pacific silver	55	164
Cherry, black	58	—	Fir, white	98	160
Chestnut, American	120	—	Hemlock, eastern	97	119
Cottonwood	162	146	Hemlock, western	85	170
Elm, American	95	92	Larch, western	54	119
Elm, cedar	66	61	Pine, loblolly	33	110
Elm, rock	44	57	Pine, lodgepole	41	120
Hackberry	61	65	Pine, longleaf	31	106
Hickory, bitternut	80	54	Pine, ponderosa	40	148
Hickory, mockernut	70	52	Pine, red	32	134
Hickory, pignut	71	49	Pine, shortleaf	32	122
Hickory, red	69	52	Pine, sugar	98	219
Hickory, sand	68	50	Pine, western white	62	148
Hickory, water	97	62	Redwood, old growth	86	210
Magnolia	80	104	Spruce, black	52	113
Maple, silver	58	97	Spruce, Engelmann	51	173
Maple, sugar	65	72	Spruce, Sitka	41	142
Oak, California black	76	75	Tamarack	49	—
Oak, northern red	80	69			
Oak, southern red	83	75			
Oak, water	81	81			
Oak, white	64	78			
Oak, willow	82	74			
Sweetgum	79	137			
Sycamore, American	114	130			
Tupelo, black	87	115			
Tupelo, swamp	101	108			
Tupelo, water	150	116			
Walnut, black	90	73			
Yellow-poplar	83	106			

hardwoods, the difference in moisture content between heartwood and sapwood depends on the species. The average moisture content of green heartwood and green sapwood of some domestic species is given in Table 4–1. These values are considered typical, but variation within and between trees is considerable. Variability of green moisture content exists even within individual boards cut from the same tree. Additional information on moisture in green lumber is given in Chapter 13.

Fiber Saturation and Maximum Moisture Content

Moisture can exist in wood as free water (liquid water or water vapor in cell lumina and cavities) or as bound water (held by intermolecular attraction within cell walls). The moisture content at which only the cell walls are completely saturated (all bound water) but no water exists in cell lumina is called the fiber saturation point (FSP), MC_{fs} . The fiber saturation point is conceptually simple; however, in practice the exact partition between “free” and “bound” water

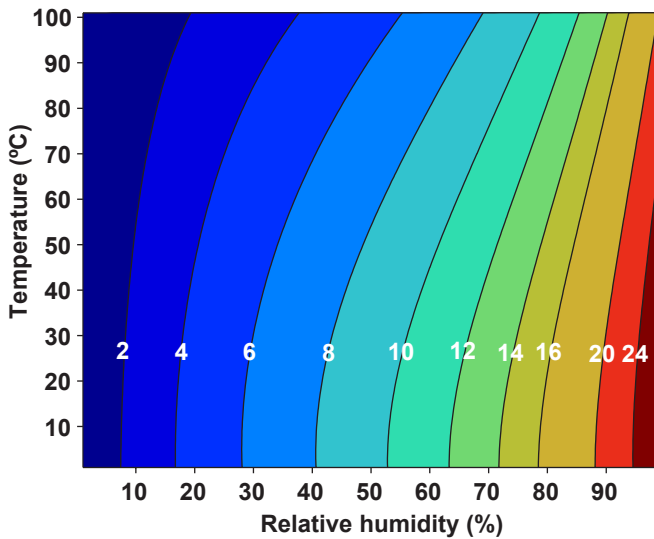


Figure 4–1. Equilibrium moisture content of wood (labeled contours) as a function of relative humidity and temperature.

is difficult to measure. As a result, a robust operational definition of the fiber saturation point is still a hotly debated topic in wood literature (Engelund and others 2013, Zelinka and others 2016b) even though the concept was introduced in the early 1900s (Tiemann 1906). From a practical standpoint, the fiber saturation point is considered as that moisture content above which the physical and mechanical properties of wood do not change as a function of moisture content. The point below which most wood properties start to change averages about 30% moisture content, but in individual species and individual pieces of wood it can vary by several percentage points from that value. The FSP value also varies depending on the method used to measure it.

The moisture content at which both cell lumina and cell walls are completely saturated with water is the maximum possible moisture content. Basic specific gravity G_b (based on oven-dry mass and green volume—see section below on Density and Specific Gravity) is the major determinant of maximum moisture content. As basic specific gravity increases, the volume of the lumina must decrease because the specific gravity of wood cell walls is constant among species. This decreases the maximum moisture content because less room is available for free water. Maximum moisture content $MC_{\max}$ for any basic specific gravity can be estimated from

$$MC_{\max} = 100(1.54 - G_b)/1.54G_b \quad (4-3)$$

where the specific gravity of wood cell walls is taken as 1.54. Maximum possible moisture content varies from 267% at $G_b = 0.30$ to 44% at $G_b = 0.90$. Maximum possible moisture content is seldom attained in living trees. The moisture content at which wood will sink in water can be calculated by

$$MC_{\text{sink}} = 100(1 - G_b)/G_b \quad (4-4)$$

Water Vapor Sorption

Water vapor sorption refers to the phase change between water vapor and water held within the wood. When wood is protected from contact with liquid water and heat sources, its moisture content is a function of both relative humidity (RH) and temperature of the surrounding air. Wood in service is exposed to both long-term (seasonal) and short-term (daily) changes in relative humidity and temperature of the surrounding air, which induce changes in wood moisture content. These changes usually are gradual, and short-term fluctuations tend to influence only the wood surface. Moisture content changes can be retarded, but not prevented, by protective coatings such as varnish, lacquer, or paint (Chap. 16). The objective of wood drying is to bring the moisture content close to the expected value that a finished product will have in service (Chap. 13).

Equilibrium Moisture Content

Equilibrium moisture content (EMC) is defined as that moisture content at which the wood is neither gaining nor losing moisture. The relationship between EMC, relative humidity, and temperature has been presented in various forms in Forest Products Laboratory literature since prior to 1920 (Glass and others 2014). EMC values at various levels of RH and temperature, suitable for most practical applications, are shown in Figure 4–1 and Table 4–2. These values have been calculated from the following equation:

$$EMC(\%) = \frac{1,800}{W} \left[\frac{Kh}{1 - Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2} \right] \quad (4-5)$$

where h is relative humidity (decimal, $0 \leq h \leq 1$) and the parameters W , K , K_1 , and K_2 depend on temperature:

For temperature T in $^{\circ}\text{C}$,

$$\begin{aligned} W &= 349 + 1.29T + 0.0135T^2 \\ K &= 0.805 + 0.000736T - 0.00000273T^2 \\ K_1 &= 6.27 - 0.00938T - 0.000303T^2 \\ K_2 &= 1.91 + 0.0407T - 0.000293T^2 \end{aligned}$$

For temperature T in $^{\circ}\text{F}$,

$$\begin{aligned} W &= 330 + 0.452T + 0.00415T^2 \\ K &= 0.791 + 0.000463T - 0.000000844T^2 \\ K_1 &= 6.34 + 0.000775T - 0.0000935T^2 \\ K_2 &= 1.09 + 0.0284T - 0.0000904T^2 \end{aligned}$$

Simpson (1973) showed that this equation provides a good fit to the EMC data tabulated in the 1955 edition of the *Wood Handbook*. An alternative equation for calculating EMC was presented by Glass and others (2014):

$$EMC(\%) = 100 \left[AT \left(1 - \frac{T}{T_c} \right)^B \ln(1 - h) \right]^{CTD} \quad (4-6)$$

where h is relative humidity (decimal, $0 \leq h < 1$), T is temperature (see below), and the parameters A , B , C , D , and T_c are as follows:

Table 4–2. Moisture content of wood in equilibrium with stated temperature and relative humidity

Temperature		Moisture content (%) at various relative humidity values																		
(°C)	(°F)	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
–1.1	(30)	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
4.4	(40)	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
10.0	(50)	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
15.6	(60)	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
21.1	(70)	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
26.7	(80)	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
32.2	(90)	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
37.8	(100)	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
43.3	(110)	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
48.9	(120)	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
54.4	(130)	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
60.0	(140)	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
65.6	(150)	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
71.1	(160)	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
76.7	(170)	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
82.2	(180)	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
87.8	(190)	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
93.3	(200)	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
98.9	(210)	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
104.4	(220)	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			
110.0	(230)	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						
115.6	(240)	0.3	0.6	0.9	1.3	1.7	2.1	2.6	3.1	3.5	4.1	4.6								
121.1	(250)	0.2	0.4	0.7	1.0	1.3	1.7	2.1	2.5	2.9										
126.7	(260)	0.2	0.3	0.5	0.7	0.9	1.1	1.4												
132.2	(270)	0.1	0.1	0.2	0.3	0.4	0.4													

For T in degrees Rankine ($[^{\circ}\text{R}] = [^{\circ}\text{F}] + 459.67$):

$$A = -0.000340$$

$$B = 2.43$$

$$C = 0.0448$$

$$D = 0.430$$

$$T_c = 1164.8$$

For T in kelvins ($[K] = [^{\circ}\text{C}] + 273.15$):

$$A = -0.000612$$

$$B = 2.43$$

$$C = 0.0577$$

$$D = 0.430$$

$$T_c = 647.1$$

Equilibrium relative humidity can be calculated from wood EMC using the inverted form of Equation (4–6) (Glass and others 2014):

$$h = 1 - \exp \left[\frac{1}{AT} \left(1 - \frac{T}{T_c} \right)^{-B} \left(\frac{\text{EMC}}{100} \right)^{(1/C)T^{-D}} \right] \quad (4-7)$$

where each symbol has the same meaning as in Equation (4–6).

The level of precision (0.1% MC) in Table 4–2 is provided only for the purpose of illustrating trends in EMC with temperature and RH. In reality, this level of precision is not meaningful. Actual EMC may vary considerably

among wood species and among different specimens of the same species. Multiple studies have indicated that at room temperature, differences in EMC among wood species generally are minor at low and moderate levels of relative humidity but become considerable at high RH levels (Glass and others 2014). Species with high extractive content generally have lower EMC at high RH levels than species with low extractive content. EMC also varies considerably as a result of sorption hysteresis (discussed below).

Although the EMC values listed in Table 4–2 or calculated using the equations above are suitable for practical applications, this data set is not reliable for scientific purposes such as thermodynamic analysis or evaluation of physical models for three reasons: (1) lack of proper documentation of methodology; (2) the unsolvable problem of knowing which values are determined from direct observations and which are interpolated; and (3) the absence of definitive measurement error analysis (Glass and others 2014).

Sorption Hysteresis

The relationship between EMC and relative humidity at constant temperature is referred to as a sorption isotherm. The history of a wood specimen also affects its EMC; this is called sorption hysteresis and is shown in Figure 4–2. A desorption isotherm is measured by bringing wood that was

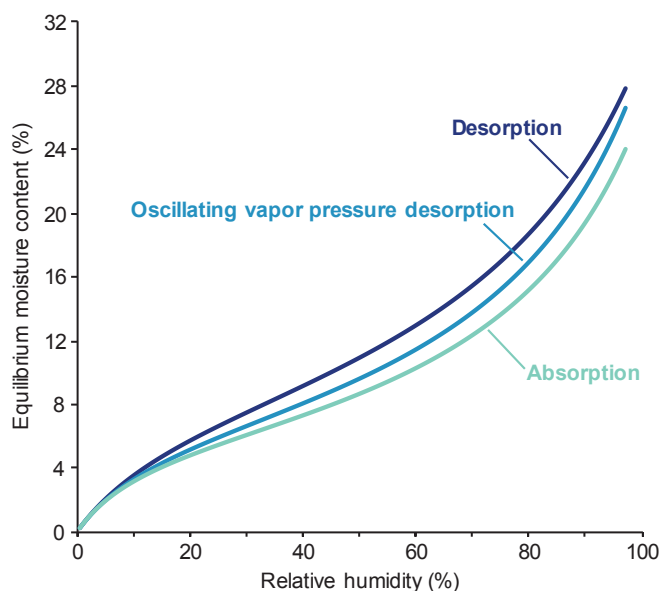


Figure 4–2. Moisture content–relative humidity relationship for wood under absorption and various desorption conditions.

initially wet to equilibrium with successively lower values of relative humidity. An absorption isotherm is measured in the opposite direction (from the dry state to successively higher RH values). In the literature, the absorption of water vapor is often referred to as “adsorption.” However, according to international consensus definitions for these terms, adsorption strictly refers to processes at a surface or interface, whereas absorption generally refers to the process of a material taking in moisture by any mechanism. “Absorption” is preferred because the vapor sorption process in wood involves water molecules being taken up within the cell walls and the capillary structure. At a given relative humidity level, the EMC for desorption is greater than the EMC for absorption. Strictly speaking, desorption isotherms should be taken from full saturation (Fredriksson and Thybring 2018). However, in practice, “scanning” desorption isotherms are commonly taken from samples initially equilibrated between 95% and 98% RH in absorption (Fredriksson and Thybring 2018). The ratio of absorption EMC to desorption EMC varies with species, RH, temperature, and the way in which the desorption isotherm is measured (Stamm 1964, Skaar 1988, Fredriksson and Thybring 2018).

EMC values in Table 4–2 were derived primarily for Sitka spruce under conditions described as oscillating vapor pressure desorption (Stamm and Loughborough 1935), which was shown to represent a condition midway between absorption and desorption. The tabulated EMC values thus provide a suitable and practical compromise for use when the direction of sorption is not always known.

Formerly it was thought that the initial desorption isotherm, as wood is dried from the green condition below the fiber

saturation point, yields a greater EMC than in subsequent desorption isotherms (Spalt 1958). However, this result was shown to be an artifact of incomplete saturation prior to subsequent desorption; full resaturation gave a desorption isotherm similar to the initial desorption isotherm from the green condition (Hoffmeyer and others 2011).

Dynamic Vapor Sorption Measurements

Water vapor sorption in wood has been studied for over a century using a variety of methods (Glass and others 2014). Most commonly, specimens were equilibrated in an environment at constant temperature where the RH was regulated by an aqueous solution in a closed container or by mechanical humidification and dehumidification in a conditioning chamber. Such methods have been standardized for building materials in general (ASTM 2016).

In the past decade, automated sorption balances, also known as dynamic vapor sorption (DVS) analyzers, have been widely adopted by wood laboratories worldwide. An automated sorption balance is a computer-controlled instrument featuring an electronic microbalance from which a small specimen (typically on the order of 10–100 mg) is suspended. Specimen mass is continuously recorded. The specimen chamber is maintained at constant temperature, and water vapor mixed with an inert carrier gas (such as dry air or nitrogen) is continuously flowed past the specimen. The relative humidity is controlled by combining vapor-saturated and dry gas streams using mass flow controllers. Automated sorption balances allow for high sensitivity in the measurement of moisture content with time under well-controlled temperature and relative humidity conditions.

The accuracy of EMC measurements using automated sorption balances depends on how long the specimen is allowed to condition at a given relative humidity. In practice, measurements are usually interrupted prior to attaining a constant specimen mass; an often-reported criterion for stopping data collection (and starting the next RH step) is when the rate of change in moisture content is less than $0.002\% \text{ min}^{-1}$, or 20 micrograms of moisture per gram of dry material per minute ($20 \mu\text{g g}^{-1} \text{ min}^{-1}$) over a 10-min period. Moisture contents reached when this criterion is met are claimed to be within 0.1% MC of the equilibrium value measured at extended time (Hill and others 2009), although no supporting data have been presented to verify this claim.

Recent work has more closely examined the accuracy of EMC values acquired with an automated sorption balance (Glass and others 2018). Equilibrium was defined operationally as the point at which the change in mass over 24 h was within the inherent mass stability of the instrument. The difference between EMC determined this way and the moisture content determined when the $20 \mu\text{g g}^{-1} \text{ min}^{-1}$ criterion was reached was as large as 1.25%

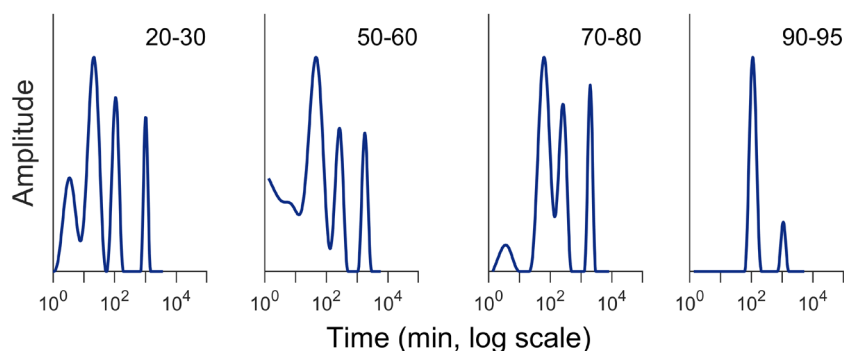


Figure 4–3. Spectra of characteristic time constants found by multi-exponential decay analysis of absorption data for loblolly pine (*Pinus taeda*) acquired using an automated sorption balance (Thybring and others 2019a). The numbers above each spectrum indicate the relative humidity step (“20–30” denotes the step from 20% RH to 30% RH).

MC at high RH levels, indicating much larger errors than previously thought. In contrast, a criterion of $3 \mu\text{g g}^{-1} \text{min}^{-1}$ over a 2-h period reduced the maximum error in EMC to less than 0.75% MC, with an average error of less than 0.3% MC. In addition, Glass and others (2018) presented a correction method to account for systematic error that required less data collection time and yielded EMC values with smaller errors. This method achieved an average error of 0.1% MC and a maximum error of only 0.23% MC with a criterion of $5 \mu\text{g g}^{-1} \text{min}^{-1}$ over a 1-h period. Further development of this correction method may provide high-quality data with less strict stop criteria.

Rate of Sorption

Diffusion models have long been used for describing changes in moisture content with time in practical applications such as wood drying or predicting moisture content in wood structures. At the scale of wood cell walls, however, diffusion models cannot explain measurements of the rate of sorption, or sorption kinetics. The recent emergence of automated sorption balances has led to an increase in the study of sorption kinetics because moisture content data are automatically acquired as the wood moisture content approaches equilibrium. Researchers have sought to better understand wood–moisture relations by studying sorption kinetic data. Thybring and others (2019b) recently reviewed this topic and concluded that none of the existing models used for fitting and explaining sorption kinetic data adequately describes the physics of the sorption process.

The most widely adopted model to describe water vapor sorption kinetics in wood is the parallel exponential kinetics (PEK) model. This model was first applied to cellulosic materials by Kohler and others (2003) and increased in popularity after it was applied to wood by Hill and others (2010). Mathematically, the PEK model can be described as the sum of two exponentially decaying processes, which are referred to as “fast” and “slow” sorption processes,

each having a characteristic time constant. Several physical explanations have been proposed for these processes, including different sorption sites, different binding energies, or viscoelastic material responses to swelling. Although the PEK model has been shown to provide good curve-fitting statistics, Thybring and others (2019a) have shown that the PEK model parameters cannot be physically meaningful. The good fitting statistics published in previous papers were found to be an artifact of interrupting the measurements prior to equilibrium. When the data collection period was lengthened, the model parameters changed considerably, the residuals exhibited nonrandom patterns, and the fitting statistics became worse. Thybring and others (2019a) introduced a new approach for the analysis of sorption data, known as multi-exponential decay analysis (MEDEA). Moisture content data are first transformed, using the initial MC and the final MC values for a given RH step, into a normalized function having an initial value of unity and final value of zero. The MEDEA technique fits a series of hundreds of exponentially decaying functions to the normalized data. This approach yields spectra indicating the number of characteristic time constants for kinetic data after a given change in RH until equilibrium is reached (see Thybring and others (2019a) for further details). The MEDEA analysis identified between two and five distinct time constants in the kinetic data. Selected MEDEA spectra are depicted in Figure 4–3. This analysis explained why the PEK model parameters vary with data collection time and confirmed that the model is physically incorrect because the data clearly exhibited more than two time constants in nearly every case.

In summary, automated sorption balances have facilitated the collection of water vapor sorption kinetic data, but caution is needed when interpreting the data. Measurements interrupted prior to equilibrium do not provide a reliable basis for developing a better understanding of sorption kinetics.

Liquid Water Absorption

Wood products in service may be exposed to liquid water through a variety of mechanisms. Contact with liquid water can induce rapid changes in the moisture content of wood, in contrast to the slow changes that occur due to water vapor sorption. In addition, liquid water absorption can bring the moisture content of wood above fiber saturation (in most cases water vapor sorption alone cannot). As wood absorbs water above its fiber saturation point, air in the cell lumina is replaced by water. Absorption of liquid water may continue until the maximum moisture content is reached.

The mechanism of water absorption is called capillary action or wicking. Water interacts strongly with the wood cell wall and forms a concave meniscus (curved surface) within the lumen. This interaction combined with the water–air surface tension creates a pressure that draws water up the lumina.

The rate of liquid water absorption in wood depends on several factors. The rate of absorption is most rapid in the longitudinal direction (that is, when the transverse section or end grain is exposed to water). The rate at which air can escape from wood affects water absorption, as water displaces air in the lumina. Chapter 16 discusses the ability of surface finishes such as water repellents to inhibit water absorption.

Methods for measuring the rate of water absorption are described by international standards (ASTM C1794-15 (ASTM 2015); ISO 15148:2002 (ISO 2002)). One surface of a specimen is partially immersed in water. To limit absorption to this one surface and restrict moisture transport to one dimension, the sides of the specimen are coated with a water- and vapor-tight sealant. The specimen is periodically removed, surfaces are blotted, and the specimen is weighed and again partially immersed in the water. The mass of water absorbed per unit area of specimen surface is plotted against the square root of time. The initial part of the curve is usually linear, and the slope of this linear portion is the water absorption coefficient A_w ($\text{kg m}^{-2} \text{s}^{-1/2}$). Measured values of A_w for softwoods are in the range $10\text{--}16 \text{ g m}^{-2} \text{s}^{-1/2}$ in the longitudinal direction and $1\text{--}7 \text{ g m}^{-2} \text{s}^{-1/2}$ in the transverse directions (IEA 1991; Kumaran 1996, 1999; Kumaran and others 2002; Alsayegh and others 2013). Wood that has been colonized by blue stain fungus may have considerably higher A_w values (for example, on the order of $87 \text{ g m}^{-2} \text{s}^{-1/2}$ in the longitudinal direction and $9\text{--}23 \text{ g m}^{-2} \text{s}^{-1/2}$ in the transverse directions) (Zelinka and others 2016a).

The liquid water diffusivity D_w ($\text{m}^2 \text{s}^{-1}$) is a measure of the rate of moisture flow ($\text{kg m}^{-2} \text{s}^{-1}$) through a material subjected to unit difference in moisture concentration (kg m^{-3}) across unit thickness (m). An order-of-magnitude estimate of D_w can be made using the value of A_w as

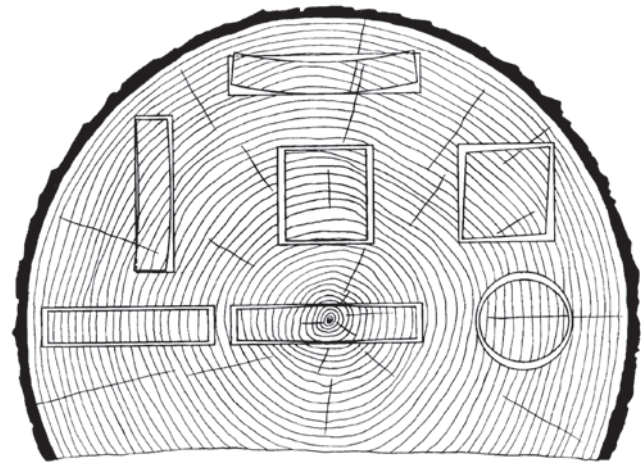


Figure 4-4. Characteristic shrinkage and distortion of flat, square, and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial.

$$D_w \approx \left(\frac{A_w}{c_{\text{sat}}} \right)^2 \quad (4-8)$$

where c_{sat} is the moisture concentration (kg m^{-3}) in water-saturated wood (Kumaran 1999).

Dimensional Stability

Wood is dimensionally stable when the equilibrium moisture content is greater than the fiber saturation point. Below MC_{fs} , wood changes dimension as it gains moisture (swells) or loses moisture (shrinks) because the volume of the cell wall depends on the amount of bound water. This shrinking and swelling can result in warping, checking, and splitting of the wood, which in turn can lead to decreased utility of wood products, such as loosening of tool handles, gaps in flooring, or other performance problems. Therefore, it is important that the dimensional stability be understood and considered when a wood product will be exposed to large moisture fluctuations in service.

With respect to dimensional stability, wood is an anisotropic material. It shrinks (swells) most in the direction of the annual growth rings (tangentially), about half as much across the rings (radially), and only slightly along the grain (longitudinally). The combined effects of radial and tangential shrinkage can distort the shape of wood pieces because of the difference in shrinkage and the curvature of annual rings. The major types of distortion resulting from these effects are illustrated in Figure 4-4.

Transverse and Volumetric Shrinkage

Data have been collected to represent the average radial, tangential, and volumetric shrinkage of numerous domestic species by methods described in American Society for Testing and Materials (ASTM) D143—Standard Test Methods for Small Clear Specimens of Timber (ASTM 2014). Shrinkage values, expressed as a percentage of the

Table 4–3. Shrinkage values of domestic woods

Species	Shrinkage ^a (%) from green to oven-dry moisture content			Species	Shrinkage ^a (%) from green to oven-dry moisture content		
	Radial	Tangential	Volumetric		Radial	Tangential	Volumetric
Hardwoods				Oak, white—con.			
Alder, red	4.4	7.3	12.6	Chestnut	5.3	10.8	16.4
Ash				Live	6.6	9.5	14.7
Black	5.0	7.8	15.2	Overcup	5.3	12.7	16.0
Blue	3.9	6.5	11.7	Post	5.4	9.8	16.2
Green	4.6	7.1	12.5	Swamp, chestnut	5.2	10.8	16.4
Oregon	4.1	8.1	13.2	White	5.6	10.5	16.3
Pumpkin	3.7	6.3	12.0	Persimmon, common	7.9	11.2	19.1
White	4.9	7.8	13.3	Sassafras	4.0	6.2	10.3
Aspen				Sweetgum	5.3	10.2	15.8
Bigtooth	3.3	7.9	11.8	Sycamore, American	5.0	8.4	14.1
Quaking	3.5	6.7	11.5	Tanoak	4.9	11.7	17.3
Basswood, American	6.6	9.3	15.8	Tupelo			
Beech, American	5.5	11.9	17.2	Black	5.1	8.7	14.4
Birch				Water	4.2	7.6	12.5
Alaska paper	6.5	9.9	16.7	Walnut, black	5.5	7.8	12.8
Gray	5.2	—	14.7	Willow, black	3.3	8.7	13.9
Paper	6.3	8.6	16.2	Yellow-poplar	4.6	8.2	12.7
River	4.7	9.2	13.5	Softwoods			
Sweet	6.5	9.0	15.6	Cedar			
Yellow	7.3	9.5	16.8	Yellow	2.8	6.0	9.2
Buckeye, yellow	3.6	8.1	12.5	Atlantic white	2.9	5.4	8.8
Butternut	3.4	6.4	10.6	Eastern redcedar	3.1	4.7	7.8
Cherry, black	3.7	7.1	11.5	Incense	3.3	5.2	7.7
Chestnut, American	3.4	6.7	11.6	Northern white	2.2	4.9	7.2
Cottonwood				Port-Orford	4.6	6.9	10.1
Balsam poplar	3.0	7.1	10.5	Western redcedar	2.4	5.0	6.8
Black	3.6	8.6	12.4	Douglas-fir			
Eastern	3.9	9.2	13.9	Coast ^b	4.8	7.6	12.4
Elm				Interior north ^b	3.8	6.9	10.7
American	4.2	9.5	14.6	Interior west ^b	4.8	7.5	11.8
Cedar	4.7	10.2	15.4	Fir			
Rock	4.8	8.1	14.9	Balsam	2.9	6.9	11.2
Slippery	4.9	8.9	13.8	California red	4.5	7.9	11.4
Winged	5.3	11.6	17.7	Grand	3.4	7.5	11.0
Hackberry	4.8	8.9	13.8	Noble	4.3	8.3	12.4
Hickory, pecan	4.9	8.9	13.6	Pacific silver	4.4	9.2	13.0
Hickory, true				Subalpine	2.6	7.4	9.4
Mockernut	7.7	11.0	17.8	White	3.3	7.0	9.8
Pignut	7.2	11.5	17.9	Hemlock			
Shagbark	7.0	10.5	16.7	Eastern	3.0	6.8	9.7
Shellbark	7.6	12.6	19.2	Mountain	4.4	7.1	11.1
Holly, American	4.8	9.9	16.9	Western	4.2	7.8	12.4
Honeylocust	4.2	6.6	10.8	Larch, western	4.5	9.1	14.0
Locust, black	4.6	7.2	10.2	Pine			
Madrone, Pacific	5.6	12.4	18.1	Eastern white	2.1	6.1	8.2
Magnolia				Jack	3.7	6.6	10.3
Cucumbertree	5.2	8.8	13.6	Loblolly	4.8	7.4	12.3
Southern	5.4	6.6	12.3	Lodgepole	4.3	6.7	11.1
Sweetbay	4.7	8.3	12.9	Longleaf	5.1	7.5	12.2
Maple				Pitch	4.0	7.1	10.9
Bigleaf	3.7	7.1	11.6	Pond	5.1	7.1	11.2
Black	4.8	9.3	14.0	Ponderosa	3.9	6.2	9.7
Red	4.0	8.2	12.6	Red	3.8	7.2	11.3
Silver	3.0	7.2	12.0	Shortleaf	4.6	7.7	12.3
Striped	3.2	8.6	12.3	Slash	5.4	7.6	12.1
Sugar	4.8	9.9	14.7	Sugar	2.9	5.6	7.9
Oak, red				Virginia	4.2	7.2	11.9
Black	4.4	11.1	15.1	Western white	4.1	7.4	11.8
Laurel	4.0	9.9	19.0	Redwood			
Northern red	4.0	8.6	13.7	Old growth	2.6	4.4	6.8
Pin	4.3	9.5	14.5	Young growth	2.2	4.9	7.0
Scarlet	4.4	10.8	14.7	Spruce			
Southern red	4.7	11.3	16.1	Black	4.1	6.8	11.3
Water	4.4	9.8	16.1	Engelmann	3.8	7.1	11.0
Willow	5.0	9.6	18.9	Red	3.8	7.8	11.8
Oak, white				Sitka	4.3	7.5	11.5
Bur	4.4	8.8	12.7	Tamarack	3.7	7.4	13.6

^aExpressed as a percentage of the green dimension.^bCoast type Douglas-fir is defined as Douglas-fir growing in the States of Oregon and Washington west of the summit of the Cascade Mountains. Interior West includes the State of California and all counties in Oregon and Washington east of but adjacent to the Cascade summit. Interior North includes the remainder of Oregon and Washington and the States of Idaho, Montana, and Wyoming.

CHAPTER 4 | Moisture Relations and Physical Properties of Wood

Table 4–4. Shrinkage values of some woods imported into the United States^a

Species	Shrinkage ^b from green to oven-dry moisture content (%)			Location ^c	Species	Shrinkage ^b from green to oven-dry moisture content (%)			Location ^c
	Radial	Tan-gential	Volu-metric			Radial	Tan-gential	Volu-metric	
Afromosia (<i>Pericopsis elata</i>)	3.0	6.4	10.7	AF	Lauan, white (<i>Pentacme contorta</i>)	4.0	7.7	11.7	AS
Albarco (<i>Cariniana</i> spp.)	2.8	5.4	9.0	AM	Limba (<i>Terminalia superba</i>)	4.5	6.2	10.8	AF
Andiroba (<i>Carapa guianensis</i>)	3.1	7.6	10.4	AM	Macawood (<i>Platymiscium</i> spp.)	2.7	3.5	6.5	AM
Angelin (<i>Andira inermis</i>)	4.6	9.8	12.5	AM	Mahogany, African (<i>Khaya</i> spp.)	2.5	4.5	8.8	AF
Angelique (<i>Dicorynia guianensis</i>)	5.2	8.8	14.0	AM	Mahogany, true (<i>Swietenia macrophylla</i>)	3.0	4.1	7.8	AM
Apitong (<i>Dipterocarpus</i> spp.)	5.2	10.9	16.1	AS	Manbarklak (<i>Eschweilera</i> spp.)	5.8	10.3	15.9	AM
Avodire (<i>Turreanthus africanus</i>)	4.6	6.7	12.0	AF	Manni (<i>Symphonia globulifera</i>)	5.7	9.7	15.6	AM
Azobe (<i>Lophira alata</i>)	8.4	11.0	17.0	AM	Marishballi (<i>Licania</i> spp.)	7.5	11.7	17.2	AM
Balata (<i>Manilkara bidentata</i>)	6.3	9.4	16.9	AM	Meranti, white (<i>Shorea</i> spp.)	3.0	6.6	7.7	AS
Balsa (<i>Ochroma pyramidale</i>)	3.0	7.6	10.8	AM	Meranti, yellow (<i>Shorea</i> spp.)	3.4	8.0	10.4	AS
Banak (<i>Virola</i> spp.)	4.6	8.8	13.7	AM	Merbau (<i>Intsia bijuga</i> and <i>I. palembanica</i>)	2.7	4.6	7.8	AS
Benge (<i>Guibourtia arnoldiana</i>)	5.2	8.6	13.8	AF	Mersawa (<i>Anisoptera</i> spp.)	4.0	9.0	14.6	AS
Bubinga (<i>Guibourtia</i> spp.)	5.8	8.4	14.2	AF	Mora (<i>Mora</i> spp.)	6.9	9.8	18.8	AM
Bulletwood (<i>Manilkara bidentata</i>)	6.3	9.4	16.9	AM	Obeche (<i>Triplochiton scleroxylon</i>)	3.0	5.4	9.2	AF
Caribbean pine (<i>Pinus caribaea</i>)	6.3	7.8	12.9	AM	Ocota pine (<i>Pinus oocarpa</i>)	4.6	7.5	12.3	AM
Cativo (<i>Prioria copaifera</i>)	2.4	5.3	8.9	AM	Okoume (<i>Aucoumea klaineana</i>)	4.1	6.1	11.3	AF
Ceiba (<i>Ceiba pentandra</i>)	2.1	4.1	10.4	AM	Opepe (<i>Nauclea</i> spp.)	4.5	8.4	12.6	AF
Cocobolo (<i>Dalbergia retusa</i>)	2.7	4.3	7.0	AM	Ovangkol (<i>Guibourta ehie</i>)	4.5	8.2	12	AF
Courbaril (<i>Hymenaea courbaril</i>)	4.5	8.5	12.7	AM	Para-angelium (<i>Hymenolobium excelsum</i>)	4.4	7.1	10.2	AM
Cuangare (<i>Dialyanthera</i> spp.)	4.2	9.4	12.0	AM	Parana pine (<i>Araucaria angustifolia</i>)	4.0	7.9	11.6	AS
Degame (<i>Calycophyllum candidissimum</i>)	4.8	8.6	13.2	AM	Pau Marfim (<i>Balfourodendron riedelianum</i>)	4.6	8.8	13.4	AM
Determa (<i>Ocotea rubra</i>)	3.7	7.6	10.4	AM	Peroba de campos (<i>Paratecoma peroba</i>)	3.8	6.6	10.5	AM
Ebony, East Indian (<i>Diospyros</i> spp.)	5.4	8.8	14.2	AS	Peroba Rosa (<i>Aspidosperma</i> spp.)	3.8	6.4	11.6	AM
Ebony, African (<i>Diospyros</i> spp.)	9.2	10.8	20.0	AF	Piquia (<i>Caryocar</i> spp.)	5.0	8.0	13.0	AM
Ekop (<i>Tetraberlinia tubmaniana</i>)	5.6	10.2	15.8	AF	Pilon (<i>Hyeronima</i> spp.)	5.4	11.7	17.0	AM
Gmelina (<i>Gmelina arborea</i>)	2.4	4.9	8.8	AS	Primavera (<i>Cybistax donnell-smithii</i>)	3.1	5.1	9.1	AM
Goncalo alves (<i>Astronium graveolens</i>)	4.0	7.6	10.0	AM	Purpleheart (<i>Peltogyne</i> spp.)	3.2	6.1	9.9	AM
Greenheart (<i>Ocotea rodiaei</i>)	8.8	9.6	17.1	AM	Ramin (<i>Gonystylus</i> spp.)	4.3	8.7	13.4	AS
Hura (<i>Hura crepitans</i>)	2.7	4.5	7.3	AM	Roble (<i>Quercus</i> spp.)	6.4	11.7	18.5	AM
Ilomba (<i>Pycnanthus angolensis</i>)	4.6	8.4	12.8	AF	Roble (<i>Tabebuia</i> spp. Roble group)	3.6	6.1	9.5	AM
Imbuia (<i>Phoebe porosa</i>)	2.7	6.0	9.0	AM	Rosewood, Brazilian (<i>Dalbergia nigra</i>)	2.9	4.6	8.5	AM
Ipe (<i>Tabebuia</i> spp.)	6.6	8.0	13.2	AM	Rosewood, Indian (<i>Dalbergia latifolia</i>)	2.7	5.8	8.5	AS
Iroko (<i>Chlorophora excelsa</i> and <i>C. regia</i>)	2.8	3.8	8.8	AF	Rubberwood (<i>Hevea brasiliensis</i>)	2.3	5.1	7.4	AM
Jarrah (<i>Eucalyptus marginata</i>)	7.7	11.0	18.7	AS	Sande (<i>Brosimum</i> spp. Utile group)	4.6	8.0	13.6	AM
Jelutong (<i>Dyera costulata</i>)	2.3	5.5	7.8	AS	Sapele (<i>Entandrophragma cylindricum</i>)	4.6	7.4	14.0	AF
Kaneelhart (<i>Licaria</i> spp.)	5.4	7.9	12.5	AM	Sepetir (<i>Pseudosindora</i> spp. and <i>Sindora</i> spp.)	3.7	7.0	10.5	AS
Kapur (<i>Dryobalanops</i> spp.)	4.6	10.2	14.8	AS	Spanish-cedar (<i>Cedrela</i> spp.)	4.2	6.3	10.3	AM
Karri (<i>Eucalyptus diversicolor</i>)	7.8	12.4	20.2	AS	Sucupira (<i>Diplotropis purpurea</i>)	4.6	7.0	11.8	AM
Kempas (<i>Koompassia malaccensis</i>)	6.0	7.4	14.5	AS	Teak (<i>Tectona grandis</i>)	2.5	5.8	7.0	AS
Keruing (<i>Dipterocarpus</i> spp.)	5.2	10.9	16.1	AS	Wallaba (<i>Eperua</i> spp.)	3.6	6.9	10.0	AM
Lauan, light red and red (<i>Shorea</i> spp.)	4.6	8.5	14.3	AS					
Lauan, dark red (<i>Shorea</i> spp.)	3.8	7.9	13.1	AS					

^aShrinkage values were obtained from world literature and may not represent a true species average.

^bExpressed as a percentage of the green dimension.

^cAF is Africa; AM is Tropical America; AS is Asia and Oceania.

green dimension, are listed in Table 4–3. Shrinkage values collected from the world literature for selected imported species are listed in Table 4–4.

The shrinkage of wood is affected by a number of variables. In general, greater shrinkage is associated with greater density. The size and shape of a piece of wood can affect shrinkage, and the rate of drying for some species can affect shrinkage. Transverse and volumetric shrinkage variability can be expressed by a coefficient of variation of approximately 15% (Markwardt and Wilson 1935).

Longitudinal Shrinkage

Longitudinal shrinkage of wood (shrinkage parallel to the grain) is generally quite small. Average values for shrinkage from green to oven-dry are between 0.1% and 0.2% for most species of wood. However, certain types of wood exhibit excessive longitudinal shrinkage, and these should be avoided in uses where longitudinal stability is important. Additionally, reaction wood, whether compression wood in softwoods or tension wood in hardwoods, tends to shrink excessively parallel to the grain. Wood from near the center of trees (juvenile wood) of some species also shrinks excessively lengthwise. Reaction wood and juvenile wood can shrink 2% from green to oven-dry. Wood with cross grain exhibits increased shrinkage along the longitudinal axis of the piece.

Reaction wood exhibiting excessive longitudinal shrinkage can occur in the same board with normal wood. The presence of this type of wood, as well as cross grain, can cause serious warping, such as bow, crook, or twist, and cross breaks can develop in the zones of high shrinkage.

Relationship between Moisture Content and Shrinkage

For a sufficiently small piece of wood without significant moisture gradients, shrinkage normally begins at about the fiber saturation point and continues in a fairly linear manner until the wood is completely dry. However, in the normal drying of lumber or other large pieces, the surface of the wood dries first, causing a moisture gradient. When the surface MC drops below the fiber saturation point, it begins to shrink even though the interior can still be quite wet and not shrink. Because of moisture gradients, shrinkage of lumber can occur even when the average moisture content of the entire piece of lumber is above fiber saturation. With moisture gradients, the moisture content–shrinkage relationship is not linear but rather looks similar to the one in Figure 4–5. The exact form of the shrinkage curve with moisture gradients depends on several variables, principally size and shape of the piece, species of wood, and drying conditions used.

Considerable variation in shrinkage occurs for any species. Tangential shrinkage data for Douglas-fir boards, 22 by 140 mm (7/8 by 5-1/2 in.) in cross section, are given in Figure 4–6 (Comstock 1965). The material was grown in

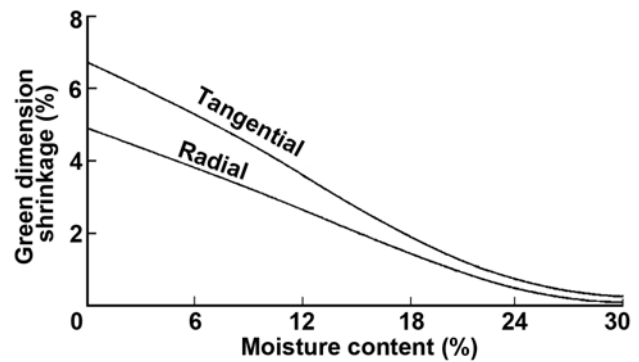


Figure 4–5. Typical moisture content–shrinkage curves.

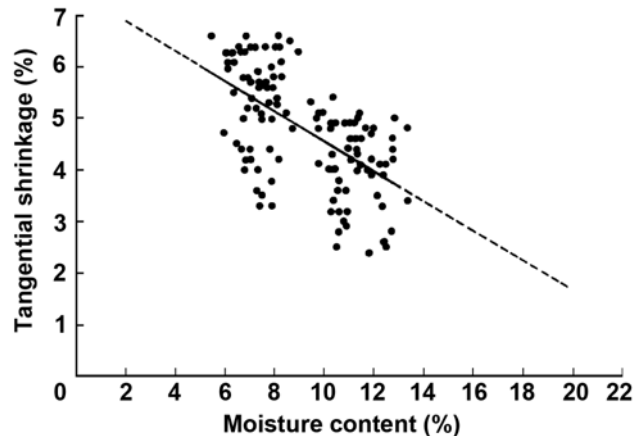


Figure 4–6. Variation in individual tangential shrinkage values of several Douglas-fir boards from one locality, dried from green condition.

one locality and dried under mild conditions from green to near equilibrium at 32 °C (90 °F) and two different humidity conditions: (1) 60–65% RH and (2) 30% RH. The figure shows that accurately predicting the shrinkage of an individual piece of wood is impossible; however, the relationship between average shrinkage and moisture content of a sufficient quantity of pieces can be predicted accurately by linear regression.

Average shrinkage data in Tables 4–3 and 4–4 can be used to estimate shrinkage for a particular species if a great deal of accuracy is not required. The following assumptions are made: (1) shrinkage begins at the fiber saturation point MC_{fs} ; and (2) dimensions decrease linearly with decreasing moisture content. The percent shrinkage S_x from the green condition to final moisture content x can be calculated from

$$S_x = S_0 \left(1 - \frac{x}{MC_{fs}} \right) \quad (4-9)$$

where S_0 is percent shrinkage from the green condition to oven-dry (radial, tangential, or volumetric) from Table 4–3 or 4–4. If MC_{fs} is not known, 30% MC can be used as an approximation. Tangential values for S_0 should be used for estimating width shrinkage of plainsawn material and radial values for quartersawn material. For mixed or

unknown ring orientations, tangential values are suggested. Shrinkage values for individual pieces will vary from predicted shrinkage values. As noted previously, shrinkage variability is characterized by a coefficient of variation of approximately 15%. This applies to pure tangential or radial ring orientation and is probably somewhat greater in commercial lumber, where ring orientation is seldom aligned perfectly parallel or perpendicular to board faces. Chapter 13 contains additional discussion of shrinkage–moisture content relationships, including a method to estimate shrinkage for the relatively small moisture content changes of wood in service. Shrinkage assumptions for commercial lumber, which typically is not perfectly plainsawn or quartersawn, are discussed in Chapter 7.

Density and Specific Gravity

The density ρ of a substance is defined as the ratio of its mass to its volume and is expressed in the international system (SI) in units of kilograms per cubic meter (kg m^{-3}), in the inch–pound system (I–P) in units of pounds per cubic foot (lb ft^{-3}), or in the centimeter–gram–second system (CGS) in units of grams per cubic centimeter (g cm^{-3}). The CGS system is convenient because of its relationship to specific gravity (also known as relative density). Specific gravity G is defined as the ratio of the density of a substance to the density of water ρ_w at a specified reference temperature, typically 4 °C (39 °F), where ρ_w is 1.000 g cm^{-3} ($1,000 \text{ kg m}^{-3}$ or 62.43 lb ft^{-3}). Therefore, a material with a density of 5 g cm^{-3} has a specific gravity of 5.

At constant temperature, the density of materials that do not adsorb moisture is constant. For example, at room temperature the densities of steel, aluminum, and lead are 7.8, 2.7, and 11.3 g cm^{-3} , respectively. For materials that adsorb moisture but do not change volume, such as stone and brick, the density depends upon moisture content. For these materials, the density can be calculated at any moisture content as the ratio of its mass to its volume, and the relationship between density and moisture content is linear. Specific gravity has only one definition for these materials (because volume is constant): the ratio of oven-dry density to density of water.

In contrast to these materials, for wood, both mass and volume depend on moisture content. The remainder of this section explains the relationships between moisture content, volumetric shrinkage, specific gravity, and density.

The density of oven-dry wood ρ_0 varies significantly between species. Although the oven-dry density of most species falls between about 320 and 720 kg m^{-3} (20 and 45 lb ft^{-3}), the range actually extends from about 160 kg m^{-3} (10 lb ft^{-3}) for balsa to more than $1,040 \text{ kg m}^{-3}$ (65 lb ft^{-3}) for some other imported woods. Within a given species, ρ_0 varies because of anatomical characteristics such as the ratio of earlywood to latewood and heartwood to sapwood. For a limited

Table 4–5. Expressions for specific gravity and density of wood^a

Symbol	Mass basis	Volume basis
G_0	Ovendry	Ovendry
G_b (basic specific gravity)	Ovendry	Green
G_{12}	Ovendry	12% MC
G_x	Ovendry	$x\%$ MC
ρ_0	Ovendry	Ovendry
ρ_{12}	12% MC	12% MC
ρ_x	$x\%$ MC	$x\%$ MC

^a x is any chosen moisture content.

number of species, minerals and extractable substances may also affect density. A coefficient of variation of about 10% is considered suitable for describing the variability of oven-dry density within common domestic species.

Wood is used in a wide range of conditions and thus has a wide range of moisture content values in service. Determining the density of wood (including water) at a given moisture content, ρ_x , is often necessary for applications such as estimating structural loads or shipping weights. Several methods can be used for determining ρ_x , as discussed in the following sections. The resulting value should be considered an approximation because of the inherent variability in the properties used in calculating ρ_x .

To make comparisons between species or products, a standard reference basis is desirable. Several valid choices are possible for wood, including oven-dry density ρ_0 and specific gravity G referenced to a particular volume basis. As shown in Table 4–5, the specific gravity of wood may be referenced to its volume at any moisture content, but in all cases G is based on oven-dry mass. Commonly used bases for volume are (a) oven-dry, (b) green, and (c) 12% moisture content. The combination of oven-dry mass and oven-dry volume is used in design specifications for wood, such as contained in the *National Design Specification (NDS) for Wood Construction* (AWC 2018). The combination of oven-dry mass and green volume is referred to as basic specific gravity G_b . Some specific gravity data are reported in Tables 5–3, 5–4, and 5–5 (Chap. 5) on both the green (basic) and 12% MC volume basis.

Converting between Different Specific Gravity Bases

In general, we use the symbol G_x to denote specific gravity based on the volume at a given moisture content x . If the value of G_x is known for a particular moisture content, the value at any other moisture content can be approximated using expressions for volumetric shrinkage. Explicitly, if the specific gravity is known at moisture content x' , the value at x'' is

$$G_{x''} = G_{x'} \left(\frac{100 - S_{x'}}{100 - S_{x''}} \right) \quad (4-10)$$

where S_x is the percent volumetric shrinkage from the green condition to moisture content x . In the case where basic specific gravity G_b is known, the value at any moisture content x below the fiber saturation point is

$$G_x = G_b / (1 - S_x / 100) \quad (4-11)$$

The shrinkage–moisture content relationship can be reasonably approximated using Table 4–3 or 4–4 and Equation (4–9). However, if the total volumetric shrinkage S_0 is not known for the species of interest, it can be estimated from the basic specific gravity (Stamm 1964):

$$S_0 = 26.5 G_b \quad (4-12)$$

Using this relation, Equation (4–11) then becomes

$$G_x = G_b / [1 - 0.265 G_b (1 - x / MC_{fs})] \quad (4-13)$$

Methods for Calculating Density

The density of wood (including water) at a given moisture content, ρ_x , may be determined by any of three methods given below.

Method 1—Equations Using Basic Specific Gravity

The specific gravity G_x based on volume at the moisture content of interest may be calculated from Equation (4–11) or (4–13) with basic specific gravity taken from Table 5–3, 5–4, or 5–5 (Chap. 5). Density is then calculated by

$$\rho_x = \rho_w G_x (1 + x / 100) \quad (4-14)$$

Method 2—Equations Using Ovendry Density

Density is given by

$$\rho_x = \rho_0 (1 + x / 100) \left(\frac{100 - S_0}{100 - S_x} \right) \quad (4-15)$$

where S_x is calculated using Equation (4–9) and S_0 is taken from Table 4–3 or 4–4. If S_0 is not known for the particular species of interest, it can be estimated using the same relation as in Equation (4–12), which in terms of ovendry density is

$$S_0 = 26.5 \rho_0 / (\rho_w + 0.265 \rho_0) \quad (4-16)$$

Method 3—Using Figure 4–7 and Table 4–6

Figure 4–7 depicts the relationship between specific gravity G_x and moisture content for different values of basic specific gravity. This figure adjusts for average dimensional changes that occur below the fiber saturation point (assumed to be 30% MC) and incorporates the assumptions in Equations (4–9), (4–12), and (4–13). The specific gravity of wood does not change at moisture content values above approximately 30%, because the volume does not change.

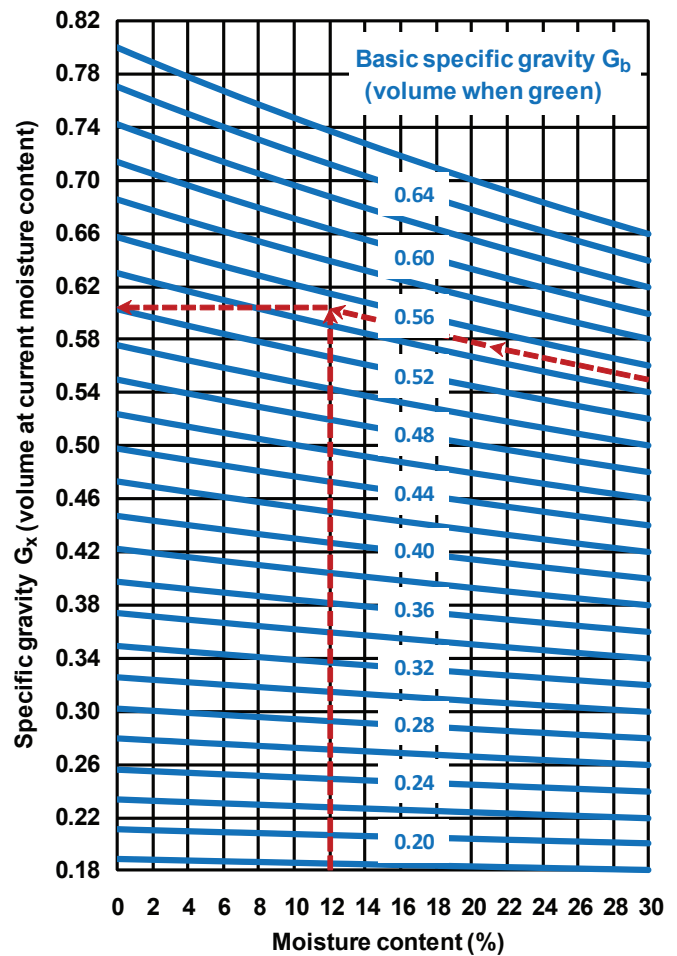


Figure 4–7. Relationship of specific gravity and moisture content.

To use Figure 4–7, locate the inclined line corresponding to the known basic specific gravity (volume when green). From this point, move left parallel to the inclined lines until vertically above the target moisture content. Then read the specific gravity G_x corresponding to this point at the left-hand side of the graph.

For example, to estimate the density of white ash at 12% moisture content, consult Table 5–3a in Chapter 5. The average basic specific gravity G_b for this species is 0.55 (volume when green). Using Figure 4–7, the dashed curve for $G_b = 0.55$ is found to intersect with the vertical 12% moisture content dashed line at a point corresponding to $G_{12} = 0.605$. The density of wood (including water) at this moisture content can then be obtained from Table 4–6 (these values are based on Eq. (4–14)). By interpolation, the specific gravity of 0.605 corresponds to a density at 12% MC of 678 kg m^{-3} (42.2 lb ft^{-3}).

Thermal Properties

Four important thermal properties of wood are thermal conductivity, heat capacity, thermal diffusivity, and coefficient of thermal expansion.

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Table 4–6a. Density of wood as a function of specific gravity and moisture content (SI)

Moisture content of wood (%)	Density (kg m ⁻³) when the specific gravity G_x is																				
	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70
0	300	320	340	360	380	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700
4	312	333	354	374	395	416	437	458	478	499	520	541	562	582	603	624	645	666	686	707	728
8	324	346	367	389	410	432	454	475	497	518	540	562	583	605	626	648	670	691	713	734	756
12	336	358	381	403	426	448	470	493	515	538	560	582	605	627	650	672	694	717	739	762	784
16	348	371	394	418	441	464	487	510	534	557	580	603	626	650	673	696	719	742	766	789	812
20	360	384	408	432	456	480	504	528	552	576	600	624	648	672	696	720	744	768	792	816	840
24	372	397	422	446	471	496	521	546	570	595	620	645	670	694	719	744	769	794	818	843	868
28	384	410	435	461	486	512	538	563	589	614	640	666	691	717	742	768	794	819	845	870	896
32	396	422	449	475	502	528	554	581	607	634	660	686	713	739	766	792	818	845	871	898	924
36	408	435	462	490	517	544	571	598	626	653	680	707	734	762	789	816	843	870	898	925	952
40	420	448	476	504	532	560	588	616	644	672	700	728	756	784	812	840	868	896	924	952	980
44	432	461	490	518	547	576	605	634	662	691	720	749	778	806	835	864	893	922	950	979	1,008
48	444	474	503	533	562	592	622	651	681	710	740	770	799	829	858	888	918	947	977	1,006	1,036
52	456	486	517	547	578	608	638	669	699	730	760	790	821	851	882	912	942	973	1,003	1,034	1,064
56	468	499	530	562	593	624	655	686	718	749	780	811	842	874	905	936	967	998	1,030	1,061	1,092
60	480	512	544	576	608	640	672	704	736	768	800	832	864	896	928	960	992	1,024	1,056	1,088	1,120
64	492	525	558	590	623	656	689	722	754	787	820	853	886	918	951	984	1,017	1,050	1,082	1,115	1,148
68	504	538	571	605	638	672	706	739	773	806	840	874	907	941	974	1,008	1,042	1,075	1,109	1,142	1,176
72	516	550	585	619	654	688	722	757	791	826	860	894	929	963	998	1,032	1,066	1,101	1,135	1,170	1,204
76	528	563	598	634	669	704	739	774	810	845	880	915	950	986	1,021	1,056	1,091	1,126	1,162	1,197	
80	540	576	612	648	684	720	756	792	828	864	900	936	972	1,008	1,044	1,080	1,116	1,152	1,188		
84	552	589	626	662	699	736	773	810	846	883	920	957	994	1,030	1,067	1,104	1,141	1,178			
88	564	602	639	677	714	752	790	827	865	902	940	978	1,015	1,053	1,090	1,128	1,166				
92	576	614	653	691	730	768	806	845	883	922	960	998	1,037	1,075	1,114	1,152	1,190				
96	588	627	666	706	745	784	823	862	902	941	980	1,019	1,058	1,098	1,137	1,176					
100	600	640	680	720	760	800	840	880	920	960	1,000	1,040	1,080	1,120	1,160	1,200					
110	630	672	714	756	798	840	882	924	966	1,008	1,050	1,092	1,134	1,176	1,218						
120	660	704	748	792	836	880	924	968	1,012	1,056	1,100	1,144	1,188	1,232							
130	690	736	782	828	874	920	966	1,012	1,058	1,104	1,150	1,196	1,242	1,288							
140	720	768	816	864	912	960	1,008	1,056	1,104	1,152	1,200	1,248	1,296								
150	750	800	850	900	950	1,000	1,050	1,100	1,150	1,200	1,250	1,300	1,350								

Thermal Conductivity

Thermal conductivity k is a measure of the rate of heat flow (W m⁻² or Btu h⁻¹ ft⁻²) through a material subjected to unit temperature difference (K or °F) across unit thickness (m or in.). The thermal conductivity of common structural woods is much less than the conductivity of metals with which wood often is mated in construction. It is about two to four times that of common insulating materials. For example, the conductivity of structural softwood lumber at 12% moisture content is in the range of 0.10 to 0.14 W m⁻¹ K⁻¹ (0.7 to 1.0 Btu in. h⁻¹ ft⁻² °F⁻¹) compared with 216 (1,500) for aluminum, 45 (310) for steel, 0.9 (6) for concrete, 1 (7) for glass, 0.7 (5) for plaster, and 0.036 (0.25) for mineral wool. Thermal resistivity is simply the reciprocal of the thermal conductivity. Insulating materials are commonly compared by their “R-value,” which is simply the thermal resistivity times the thickness when expressed in I–P units.

The thermal conductivity of wood is affected by a number of basic factors: density, moisture content, extractive content, grain direction, structural irregularities such as checks and knots, fibril angle, and temperature. Thermal conductivity increases as density, moisture content, temperature, or extractive content of the wood increases. Thermal conductivity is nearly the same in the radial and tangential directions. However, conductivity along the grain

has been reported as greater than conductivity across the grain by a factor of 1.5 to 2.8, with an average of about 1.8 (TenWolde and others 1988).

For moisture contents below 25%, approximate thermal conductivity k across the grain can be calculated with a linear equation of the form

$$k = G_x(B + Cx) + A \quad (4-17)$$

where G_x is specific gravity based on oven-dry mass and volume at moisture content x (%) and A , B , and C are constants. For $G_x > 0.3$, temperatures around 24 °C (75 °F), and $x < 25\%$ MC, the values of the constants are as follows:

$$A = 0.01864, B = 0.1941, C = 0.004064 \quad (k \text{ in } \text{W m}^{-1} \text{K}^{-1})$$

$$A = 0.129, B = 1.34, C = 0.028 \quad (k \text{ in } \text{Btu in. h}^{-1} \text{ft}^{-2} \text{°F}^{-1})$$

Equation (4–17) was derived from measurements made by several researchers on a variety of species. Table 4–7 provides average approximate conductivity values for selected wood species, based on Equation (4–17). However, actual conductivity may vary as much as 20% from the tabulated values.

Although thermal conductivity measurements have been made at moisture content values above 25%, measurements have been few in number and generally lacking in accuracy.

Table 4–6b. Density of wood as a function of specific gravity and moisture content (I–P)

Moisture content of wood (%)	Density (lb ft ⁻³) when the specific gravity G_x is																				
	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70
0	18.7	20.0	21.2	22.5	23.7	25.0	26.2	27.5	28.7	30.0	31.2	32.4	33.7	34.9	36.2	37.4	38.7	39.9	41.2	42.4	43.7
4	19.5	20.8	22.1	23.4	24.7	26.0	27.2	28.6	29.8	31.2	32.4	33.7	35.0	36.6	37.6	38.9	40.2	41.5	42.8	44.1	45.4
8	20.2	21.6	22.9	24.3	25.6	27.0	28.3	29.6	31.0	32.3	33.7	35.0	36.4	37.7	39.1	40.4	41.8	43.1	44.5	45.8	47.2
12	21.0	22.4	23.8	25.2	26.6	28.0	29.4	30.8	32.2	33.5	34.9	36.3	37.7	39.1	40.5	41.9	43.3	44.7	46.1	47.5	48.9
16	21.7	23.2	24.6	26.0	27.5	29.0	30.4	31.8	33.3	34.7	36.2	37.6	39.1	40.5	42.0	43.4	44.9	46.3	47.8	49.2	50.7
20	22.5	24.0	25.5	27.0	28.4	30.0	31.4	32.9	34.4	35.9	37.4	38.9	40.4	41.9	43.4	44.9	46.4	47.9	49.4	50.9	52.4
24	23.2	24.8	26.3	27.8	29.4	31.0	32.5	34.0	35.6	37.1	38.7	40.2	41.8	43.3	44.9	46.4	48.0	49.5	51.1	52.6	54.2
28	24.0	25.6	27.2	28.8	30.4	31.9	33.5	35.1	36.7	38.3	39.9	41.5	43.1	44.7	46.3	47.9	49.5	51.1	52.7	54.3	55.9
32	24.7	26.4	28.0	29.7	31.3	32.9	34.6	36.2	37.9	39.5	41.2	42.8	44.5	46.1	47.8	49.4	51.1	52.7	54.4	56.0	57.7
36	25.5	27.2	28.9	30.6	32.2	33.9	35.6	37.3	39.0	40.7	42.4	44.1	45.8	47.5	49.2	50.9	52.6	54.3	56.0	57.7	59.4
40	26.2	28.0	29.7	31.4	33.2	34.9	36.7	38.4	40.2	41.9	43.7	45.4	47.2	48.9	50.7	52.4	54.2	55.9	57.7	59.4	61.2
44	27.0	28.8	30.6	32.3	34.1	35.9	37.7	39.5	41.3	43.1	44.9	46.7	48.5	50.3	52.1	53.9	55.7	57.5	59.3	61.1	62.9
48	27.7	29.6	31.4	33.2	35.1	36.9	38.8	40.6	42.5	44.3	46.2	48.0	49.9	51.7	53.6	55.4	57.3	59.1	61.0	62.8	64.6
52	28.5	30.4	32.2	34.1	36.0	37.9	39.8	41.7	43.6	45.5	47.4	49.3	51.2	53.1	55.0	56.9	58.8	60.7	62.6	64.5	66.4
56	29.2	31.2	33.1	35.0	37.0	38.9	40.9	42.8	44.8	46.7	48.7	50.6	52.6	54.5	56.5	58.4	60.4	62.3	64.2	66.2	68.1
60	30.0	31.9	33.9	35.9	37.9	39.9	41.9	43.9	45.9	47.9	49.9	51.9	53.9	55.9	57.9	59.9	61.9	63.9	65.9	67.9	69.9
64	30.7	32.7	34.8	36.8	38.9	40.9	43.0	45.0	47.1	49.1	51.2	53.2	55.3	57.3	59.4	61.4	63.4	65.5	67.5	69.6	71.6
68	31.4	33.5	35.6	37.7	39.8	41.9	44.0	46.1	48.2	50.3	52.4	54.5	56.6	58.7	60.8	62.9	65.0	67.1	69.2	71.3	73.4
72	32.2	34.3	36.5	38.6	40.8	42.9	45.1	47.2	49.4	51.5	53.7	55.8	58.0	60.1	62.3	64.4	66.5	68.7	70.8	73.0	75.1
76	32.9	35.1	37.3	39.5	41.7	43.9	46.1	48.3	50.5	52.7	54.9	57.1	59.3	61.5	63.7	65.9	68.1	70.3	72.5		
80	33.7	35.9	38.2	40.4	42.7	44.9	47.2	49.4	51.7	53.9	56.2	58.4	60.7	62.9	65.1	67.4	69.6	71.9	74.1		
84	34.4	36.7	39.0	41.3	43.6	45.9	48.2	50.5	52.8	55.1	57.4	59.7	62.0	64.3	66.6	68.9	71.2	73.5			
88	35.2	37.5	39.9	42.2	44.6	46.9	49.3	51.6	54.0	56.3	58.7	61.0	63.3	65.7	68.0	70.4	72.7				
92	35.9	38.3	40.7	43.1	45.5	47.9	50.3	52.7	55.1	57.5	59.9	62.3	64.7	67.1	69.5	71.9	74.3				
96	36.7	39.1	41.6	44.0	46.5	48.9	51.4	53.8	56.3	58.7	61.2	63.6	66.0	68.5	70.9	73.4					
100	37.4	39.9	42.4	44.9	47.4	49.9	52.4	54.9	57.4	59.9	62.4	64.9	67.4	69.9	72.4	74.9					
110	39.3	41.9	44.6	47.2	49.8	52.4	55.0	57.7	60.3	62.9	65.5	68.1	70.8	73.4	76.0						
120	41.2	43.9	46.7	49.4	52.2	54.9	57.7	60.4	63.1	65.9	68.6	71.4	74.1	76.9							
130	43.1	45.9	48.8	51.7	54.5	57.4	60.3	63.1	66.0	68.9	71.8	74.6	77.5	80.4							
140	44.9	47.9	50.9	53.9	56.9	59.9	62.9	65.9	68.9	71.9	74.9	77.9	80.9								
150	46.8	49.9	53.0	56.2	59.3	62.4	65.5	68.6	71.8	74.9	78.0	81.1	84.2								

Therefore, we do not provide values for moisture content values above 25%.

The effect of temperature on thermal conductivity is relatively minor: conductivity increases about 2% to 3% per 10 °C (1% to 2% per 10 °F).

Heat Capacity

Heat capacity is defined as the amount of energy needed to increase one unit of mass (kg or lb) one unit in temperature (K or °F). The heat capacity of wood depends on the temperature and moisture content of the wood but is practically independent of density or species. Heat capacity of dry wood c_{p0} (kJ kg⁻¹ K⁻¹, Btu lb⁻¹ °F⁻¹) is approximately related to temperature T (K, °F) by

$$c_{p0} = 0.1031 + 0.003867T \text{ (SI)} \quad (4-18a)$$

$$c_{p0} = 0.2605 + 0.0005132T \text{ (I-P)} \quad (4-18b)$$

The heat capacity of wood that contains water is greater than that of dry wood. Below fiber saturation, it is the sum of the heat capacity of the dry wood and that of water (c_{pw}) and an additional adjustment factor A_c that accounts for the additional energy in the wood–water bond:

$$c_{p,x} = (c_{p0} + c_{pw} x/100)/(1 + x/100) + A_c \quad (4-19)$$

where x is moisture content (%). The heat capacity of water is about 4.18 kJ kg⁻¹ K⁻¹ (1.00 Btu lb⁻¹ °F⁻¹). The adjustment factor can be calculated from

$$A_c = x(b_1 + b_2T + b_3x) \quad (4-20)$$

with

$$b_1 = -0.06191, b_2 = 2.36 \times 10^{-4}, b_3 = -1.33 \times 10^{-4} \text{ (} T \text{ in K)}$$

$$b_1 = -4.23 \times 10^{-4}, b_2 = 3.12 \times 10^{-5}, b_3 = -3.17 \times 10^{-5} \text{ (} T \text{ in } ^\circ\text{F)}$$

These formulas are valid for wood below fiber saturation at temperatures between 280 K (45 °F) and 420 K (297 °F). Representative values for heat capacity can be found in Table 4–8. The moisture content above fiber saturation contributes to heat capacity according to the simple rule of mixtures.

Thermal Diffusivity

Thermal diffusivity is a measure of how quickly a material can absorb heat from its surroundings. It is defined as the ratio of thermal conductivity to the product of density and heat capacity. Therefore, conclusions regarding its variation with temperature and density are often based on calculating the effect of these variables on heat capacity and thermal conductivity. Because of the low thermal conductivity and

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Table 4–7. Thermal conductivity of selected hardwoods and softwoods^a

Species	Specific gravity	Conductivity (W m ⁻¹ K ⁻¹ (Btu in. h ⁻¹ ft ⁻² °F ⁻¹))		Resistivity (K m W ⁻¹ (h ft ² °F Btu ⁻¹ in. ⁻¹))	
		Ovendry	12% MC	Ovendry	12% MC
Hardwoods					
Ash					
Black	0.53	0.12 (0.84)	0.15 (1.0)	8.2 (1.2)	6.8 (0.98)
White	0.63	0.14 (0.98)	0.17 (1.2)	7.1 (1.0)	5.8 (0.84)
Aspen					
Big tooth	0.41	0.10 (0.68)	0.12 (0.82)	10 (1.5)	8.5 (1.2)
Quaking	0.40	0.10 (0.67)	0.12 (0.80)	10 (1.5)	8.6 (1.2)
Basswood, American	0.38	0.092 (0.64)	0.11 (0.77)	11 (1.6)	9.0 (1.3)
Beech, American	0.68	0.15 (1.0)	0.18 (1.3)	6.6 (0.96)	5.4 (0.78)
Birch					
Sweet	0.71	0.16 (1.1)	0.19 (1.3)	6.4 (0.92)	5.2 (0.76)
Yellow	0.66	0.15 (1.0)	0.18 (1.2)	6.8 (0.98)	5.6 (0.81)
Cherry, black	0.53	0.12 (0.84)	0.15 (1.0)	8.2 (1.2)	6.8 (0.98)
Chestnut, American	0.45	0.11 (0.73)	0.13 (0.89)	9.4 (1.4)	7.8 (1.1)
Cottonwood					
Black	0.35	0.087 (0.60)	0.10 (0.72)	12 (1.7)	9.6 (1.4)
Eastern	0.43	0.10 (0.71)	0.12 (0.85)	9.8 (1.4)	8.1 (1.2)
Elm					
American	0.54	0.12 (0.86)	0.15 (1.0)	8.1 (1.2)	6.7 (0.96)
Rock	0.67	0.15 (1.0)	0.18 (1.3)	6.7 (0.97)	5.5 (0.80)
Slippery	0.56	0.13 (0.88)	0.15 (1.1)	7.9 (1.1)	6.5 (0.93)
Hackberry	0.57	0.13 (0.90)	0.16 (1.1)	7.7 (1.1)	6.4 (0.92)
Hickory, pecan	0.69	0.15 (1.1)	0.19 (1.3)	6.6 (0.95)	5.4 (0.77)
Hickory, true					
Mockernut	0.78	0.17 (1.2)	0.21 (1.4)	5.9 (0.85)	4.8 (0.69)
Shagbark	0.77	0.17 (1.2)	0.21 (1.4)	5.9 (0.86)	4.9 (0.70)
Magnolia, southern	0.52	0.12 (0.83)	0.14 (1.0)	8.4 (1.2)	6.9 (1.0)
Maple					
Black	0.60	0.14 (0.94)	0.16 (1.1)	7.4 (1.1)	6.1 (0.88)
Red	0.56	0.13 (0.88)	0.15 (1.1)	7.9 (1.1)	6.5 (0.93)
Silver	0.50	0.12 (0.80)	0.14 (0.97)	8.6 (1.2)	7.1 (1.0)
Sugar	0.66	0.15 (1.0)	0.18 (1.2)	6.8 (0.98)	5.6 (0.81)
Oak, red					
Black	0.66	0.15 (1.0)	0.18 (1.2)	6.8 (0.98)	5.6 (0.81)
Northern red	0.65	0.14 (1.0)	0.18 (1.2)	6.9 (1.0)	5.7 (0.82)
Southern red	0.62	0.14 (0.96)	0.17 (1.2)	7.2 (1.0)	5.9 (0.85)
Oak, white					
Bur	0.66	0.15 (1.0)	0.18 (1.2)	6.8 (0.98)	5.6 (0.81)
White	0.72	0.16 (1.1)	0.19 (1.3)	6.3 (0.91)	5.2 (0.75)
Sweetgum	0.55	0.13 (0.87)	0.15 (1.1)	8.0 (1.2)	6.6 (0.95)
Sycamore, American	0.54	0.12 (0.86)	0.15 (1.0)	8.1 (1.2)	6.7 (0.96)
Tupelo					
Black	0.54	0.12 (0.86)	0.15 (1.0)	8.1 (1.2)	6.7 (0.96)
Water	0.53	0.12 (0.84)	0.15 (1.0)	8.2 (1.2)	6.8 (0.98)
Yellow poplar	0.46	0.11 (0.75)	0.13 (0.90)	9.3 (1.3)	7.7 (1.1)

Table 4–7. Thermal conductivity of selected hardwoods and softwoods^a—con.

Species	Specific gravity	Conductivity (W m ⁻¹ K ⁻¹ (Btu in. h ⁻¹ ft ⁻² °F ⁻¹))		Resistivity (K m W ⁻¹ (h ft ² °F Btu ⁻¹ in. ⁻¹))	
		Ovendry	12% MC	Ovendry	12% MC
Softwoods					
Baldcypress	0.47	0.11 (0.76)	0.13 (0.92)	9.1 (1.3)	7.5 (1.1)
Cedar					
Atlantic white	0.34	0.085 (0.59)	0.10 (0.70)	12 (1.7)	9.9 (1.4)
Eastern red	0.48	0.11 (0.77)	0.14 (0.94)	8.9 (1.3)	7.4 (1.1)
Northern white	0.31	0.079 (0.55)	0.094 (0.65)	13 (1.8)	11 (1.5)
Port-Orford	0.43	0.10 (0.71)	0.12 (0.85)	9.8 (1.4)	8.1 (1.2)
Western red	0.33	0.083 (0.57)	0.10 (0.68)	12 (1.7)	10 (1.5)
Yellow	0.46	0.11 (0.75)	0.13 (0.90)	9.3 (1.3)	7.7 (1.1)
Douglas fir					
Coast	0.51	0.12 (0.82)	0.14 (0.99)	8.5 (1.2)	7.0 (1.0)
Interior north	0.50	0.12 (0.80)	0.14 (0.97)	8.6 (1.2)	7.1 (1.0)
Interior west	0.52	0.12 (0.83)	0.14 (1.0)	8.4 (1.2)	6.9 (1.0)
Fir					
Balsam	0.37	0.090 (0.63)	0.11 (0.75)	11 (1.6)	9.2 (1.3)
White	0.41	0.10 (0.68)	0.12 (0.82)	10 (1.5)	8.5 (1.2)
Hemlock					
Eastern	0.42	0.10 (0.69)	0.12 (0.84)	10 (1.4)	8.3 (1.2)
Western	0.48	0.11 (0.77)	0.14 (0.94)	8.9 (1.3)	7.4 (1.1)
Larch, western	0.56	0.13 (0.88)	0.15 (1.1)	7.9 (1.1)	6.5 (0.93)
Pine					
Eastern white	0.37	0.090 (0.63)	0.11 (0.75)	11 (1.6)	9.2 (1.3)
Jack	0.45	0.11 (0.73)	0.13 (0.89)	9.4 (1.4)	7.8 (1.1)
Loblolly	0.54	0.12 (0.86)	0.15 (1.0)	8.1 (1.2)	6.7 (0.96)
Lodgepole	0.43	0.10 (0.71)	0.12 (0.85)	9.8 (1.4)	8.1 (1.2)
Longleaf	0.62	0.14 (0.96)	0.17 (1.2)	7.2 (1.0)	5.9 (0.85)
Pitch	0.53	0.12 (0.84)	0.15 (1.0)	8.2 (1.2)	6.8 (0.98)
Ponderosa	0.42	0.10 (0.69)	0.12 (0.84)	10 (1.4)	8.3 (1.2)
Red	0.46	0.11 (0.75)	0.13 (0.90)	9.3 (1.3)	7.7 (1.1)
Shortleaf	0.54	0.12 (0.86)	0.15 (1.0)	8.1 (1.2)	6.7 (0.96)
Slash	0.61	0.14 (0.95)	0.17 (1.2)	7.3 (1.1)	6.0 (0.86)
Sugar	0.37	0.090 (0.63)	0.11 (0.75)	11 (1.6)	9.2 (1.3)
Western white	0.40	0.10 (0.67)	0.12 (0.80)	10 (1.5)	8.6 (1.2)
Redwood					
Old growth	0.41	0.10 (0.68)	0.12 (0.82)	10 (1.5)	8.5 (1.2)
Young growth	0.37	0.090 (0.63)	0.11 (0.75)	11 (1.6)	9.2 (1.3)
Spruce					
Black	0.43	0.10 (0.71)	0.12 (0.85)	9.8 (1.4)	8.1 (1.2)
Engelmann	0.37	0.090 (0.63)	0.11 (0.75)	11 (1.6)	9.2 (1.3)
Red	0.42	0.10 (0.69)	0.12 (0.84)	10 (1.4)	8.3 (1.2)
Sitka	0.42	0.10 (0.69)	0.12 (0.84)	10 (1.4)	8.3 (1.2)
White	0.37	0.090 (0.63)	0.11 (0.75)	11 (1.6)	9.2 (1.3)

^aValues in this table are approximate and should be used with caution; actual conductivities may vary by as much as 20%. The specific gravities also do not represent species averages.

Table 4–8. Heat capacity of solid wood at selected temperatures and moisture contents

Temperature		Heat capacity (kJ kg ⁻¹ K ⁻¹ (Btu lb ⁻¹ °F ⁻¹))			
(K)	(°C (°F))	Ovendry	5% MC	12% MC	20% MC
280	7 (44)	1.2 (0.28)	1.3 (0.32)	1.5 (0.37)	1.7 (0.41)
290	17 (62)	1.2 (0.29)	1.4 (0.33)	1.6 (0.38)	1.8 (0.43)
300	27 (80)	1.3 (0.30)	1.4 (0.34)	1.7 (0.40)	1.9 (0.45)
320	47 (116)	1.3 (0.32)	1.5 (0.37)	1.8 (0.43)	2.0 (0.49)
340	67 (152)	1.4 (0.34)	1.6 (0.39)	1.9 (0.46)	2.2 (0.52)
360	87 (188)	1.5 (0.36)	1.7 (0.41)	2.0 (0.49)	2.3 (0.56)

moderate density and heat capacity of wood, the thermal diffusivity of wood is much lower than that of other structural materials, such as metal, brick, and stone. A typical value for wood is $1.6 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$ ($0.00025 \text{ in}^2 \text{ s}^{-1}$), compared with $1 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ ($0.02 \text{ in}^2 \text{ s}^{-1}$) for steel and $1 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ ($0.002 \text{ in}^2 \text{ s}^{-1}$) for stone and mineral wool. For this reason, wood does not feel extremely hot or cold to the touch as do some other materials.

Coefficient of Thermal Expansion

The coefficient of thermal expansion is a measure of the relative change of dimension caused by temperature change. The thermal expansion coefficients of completely dry wood are positive in all directions; that is, wood expands on heating and contracts on cooling. Limited research has been carried out to explore the influence of wood property variability on thermal expansion. The thermal expansion coefficient of oven-dry wood parallel to the grain appears to be independent of specific gravity and species. In tests of both hardwoods and softwoods, the parallel-to-grain values have ranged from about 3.1 to $4.5 \times 10^{-6} \text{ K}^{-1}$ (1.7 to $2.5 \times 10^{-6} \text{ °F}^{-1}$).

Thermal expansion coefficients across the grain (radial and tangential) are proportional to specific gravity. These coefficients range from about 5 to more than 10 times greater than the parallel-to-grain coefficients and are of more practical interest. The radial and tangential thermal expansion coefficients for oven-dry wood, α_r and α_t , can be approximated by the following equations, over an oven-dry specific gravity range of about 0.1 to 0.8:

$$\alpha_r = (32.4G_0 + 9.9)10^{-6} \text{ K}^{-1} \quad (4-21a)$$

$$\alpha_r = (18G_0 + 5.5)10^{-6} \text{ °F}^{-1} \quad (4-21b)$$

$$\alpha_t = (32.4G_0 + 18.4)10^{-6} \text{ K}^{-1} \quad (4-22a)$$

$$\alpha_t = (18G_0 + 10.2)10^{-6} \text{ °F}^{-1} \quad (4-22b)$$

Thermal expansion coefficients can be considered independent of temperature over the temperature range of -51 to 54 °C (-60 to 130 °F).

Wood that contains moisture reacts differently to varying temperature than does dry wood. When moist wood is

heated, it tends to expand because of normal thermal expansion and to shrink because of loss in moisture content. Unless the wood is very dry initially (perhaps 3% or 4% moisture content or less), shrinkage caused by moisture loss on heating will be greater than thermal expansion, so the net dimensional change on heating will be negative. Wood at intermediate moisture levels (about 8% to 20%) will expand when first heated, and then gradually shrink to a volume smaller than the initial volume as the wood gradually loses water while in the heated condition.

Even in the longitudinal (grain) direction, where dimensional change caused by moisture change is very small, such changes will still predominate over corresponding dimensional changes as a result of thermal expansion unless the wood is very dry initially. For wood at usual moisture levels, net dimensional changes will generally be negative after prolonged heating.

Electrical Properties

The electrical properties of wood depend strongly on moisture content, exhibiting changes that span almost 10 orders of magnitude over the range of possible moisture contents. Because electrical properties of wood undergo large changes with relatively small changes in moisture content, electrical measurements have been used to accurately predict the moisture content of wood.

The literature on electrical properties of wood has been divided into measurements of either dielectric constant or resistivity. In general, dielectric constant data were measured with alternating current (AC), whereas resistivity measurements used direct current (DC). In a way, this is a false dichotomy because the dielectric constant can be measured using DC signals for some materials, and the complex resistivity, which is related to impedance, can be measured from AC signals. Furthermore, given the AC dielectric constant, one can calculate the AC resistivity. The remainder of this section will review AC and DC measurements of the electrical properties of wood, with emphasis on clarifying the nomenclature that is often used in the wood literature.

DC Electrical Properties

Resistivity

When an electric potential or voltage V is applied between two points on a conducting solid, the amount of current I that will flow between those points depends on the resistance R of the material. This measured resistance depends on the geometry of the specimen:

$$R = \rho \frac{L}{A} \quad (4-23)$$

where L is the distance the current travels, A is the cross-sectional area through which the current travels, and ρ is

a materials parameter, the resistivity with units of $\Omega \cdot \text{m}$. In some situations, it is more convenient to talk about the conductivity σ , which is the reciprocal of the resistivity ($\sigma \equiv 1/\rho$).

The conductivity of wood is a strong function of moisture content. For example, Figure 4–8 illustrates this dependence for slash pine (*Pinus elliottii*) in the longitudinal direction between 8% MC and 180% MC (Stamm 1964). As the moisture content of wood increases from near zero to fiber saturation, conductivity can increase by a factor of over 10^{10} (in comparison, the circumference of the earth at the equator is 4×10^{10} mm). Conductivity is about 10^{-15} – 10^{-16} S m^{-1} for oven-dry wood and 10^{-3} – 10^{-4} S m^{-1} for wood at fiber saturation (Stamm 1964). As the moisture content increases from fiber saturation to complete saturation of the wood structure, the further increase in conductivity is smaller, generally amounting to less than a hundredfold.

The conductivity of wood also depends on temperature, grain angle, and the amount of water-soluble salts. Unlike conductivity of metals, the conductivity of wood increases with increasing temperature. Conductivity is greater along the grain than across the grain and slightly greater in the radial direction than in the tangential direction. Relative conductivity values in the longitudinal, radial, and tangential directions are related by the approximate ratio of 1.0:0.55:0.50. When wood contains abnormal quantities of water-soluble salts or other electrolytic substances, such as preservative or fire-retardant treatment, or is in prolonged contact with seawater, electrical conductivity can be substantially increased.

DC Dielectric Constant

When an electric potential or voltage V is applied to a perfect insulating material ($\sigma \equiv 0$) between two parallel plates, no current will flow and instead charge will build up on the plates. The amount of charge per unit voltage that these plates can store is called the capacitance C and is given by

$$C = \epsilon \epsilon_0 \frac{A}{L} \quad (4-24)$$

where A and L have the same meanings as in Equation (4–23), ϵ is a unitless materials parameter, the DC dielectric constant, and ϵ_0 is a universal constant, the permittivity of a vacuum, and is 8.854×10^{-12} F m^{-1} . The DC dielectric constant is the ratio of the dielectric permittivity of the material to ϵ_0 ; it is essentially a measure of the potential energy per unit volume stored in the material in the form of electric polarization when the material is in a given electric field. As measured by practical tests, the dielectric constant of a material is the ratio of the capacitance of a capacitor using the material as the dielectric to the capacitance of the same capacitor using free space as the dielectric.

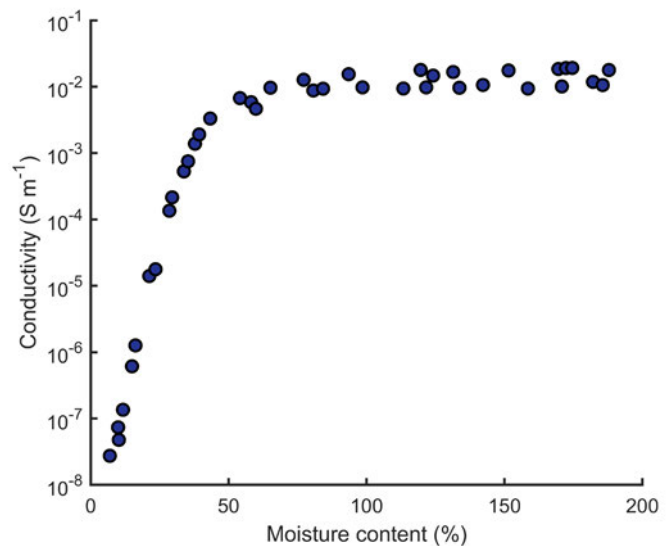


Figure 4–8. Conductivity of slash pine (*Pinus elliottii*) as a function of moisture content.

Because wood is not a perfect insulator ($\sigma \neq 0$ at any moisture content), the DC dielectric constant of wood is not well defined and theoretically cannot be measured with DC techniques. Nevertheless, people have tried to measure this quantity and have found that it is difficult to measure and depends on experimental technique (Skaar 1988).

AC Electrical Properties

AC Dielectric Constant and Related Properties

When an alternating current is applied, the dielectric constant can no longer be represented by a scalar, because response will be out of phase with the original signal. The AC dielectric constant is a complex number $\epsilon = \epsilon' + j\epsilon''$ with real component ϵ' , imaginary component ϵ'' , and $j \equiv \sqrt{-1}$. Instead of presenting the real and imaginary components of the dielectric constant, it is customary in the wood literature to present the real component of the dielectric constant ϵ' and the loss tangent, $\tan(\delta)$, defined by

$$\tan(\delta) = \frac{\epsilon''}{\epsilon'} \quad (4-25)$$

It is also customary in the wood literature to refer to the real component of the dielectric constant ϵ' as simply “the dielectric constant” and to represent this with ϵ . This notation should not be encouraged, because it is ambiguous and also implies that the dielectric constant is not a complex number.

Both ϵ' and $\tan(\delta)$ depend nonlinearly on the frequency at which they are measured. The frequency dependence is related to the mechanism of conduction in wood, and this relationship between the frequency dependence and mechanism has been explored in the literature (James 1975, Zelinka and others 2007).

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At a given frequency, ϵ' increases with temperature and moisture content. At 20 Hz, ϵ' may range from about 4 for dry wood to near 1×10^6 for wet wood; at 1 kHz, from about 4 when dry to about 5,000 when wet; and at 1 MHz, from about 3 when dry to about 100 when wet. ϵ' is larger for polarization parallel to the grain than across the grain.

Another parameter, the dielectric power factor f_p , is given by

$$f_p = \sin(\delta) = \frac{\epsilon''}{\sqrt{(\epsilon')^2 + (\epsilon'')^2}} \quad (4-26)$$

The power factor is a measure of the heat produced from placing a dielectric material in an electric field and is used in alternating current (dielectric) moisture meters to calculate the moisture content (James 1988). The power factor of wood is large compared with that of inert plastic insulating materials, but some materials, for example some formulations of rubber, have equally large power factors. The power factor of wood varies from about 0.01 for dry, low-density woods to as large as 0.95 for dense woods at high moisture levels. The power factor is usually, but not always, greater for electric fields along the grain than across the grain.

Because the power factor of wood is derived from ϵ' and ϵ'' , it is also affected by frequency, moisture content, and temperature. These factors interact in such a way to cause f_p to have maximum and minimum values at various combinations of these factors.

Impedance

Just as the AC dielectric constant is represented by a complex number to account for both magnitude and phase, the “resistance” of an AC circuit is also represented by a complex number called impedance, $Z = Z' + jZ''$ with real component Z' and imaginary component Z'' . Impedance is related to the AC dielectric constant through

$$Z = (j\omega C_c \cdot \epsilon)^{-1} \quad (4-27)$$

where ω is the angular frequency and C_c is a geometrical factor needed for unit analysis and represents the capacitance of an empty cell (that is, $C_c = \epsilon_0 A/L$) (MacDonald and Johnson 1987). In short, this transforms the real component of the dielectric constant to the imaginary component of the impedance, and vice versa.

More recently, measurements of the impedance of wood have been used to determine moisture gradients (Tiitta and Olkkonen 2002), better understand the mechanism of electrical conduction in wood (Zelinka and others 2007), and quantify the corrosion of metals embedded in wood (Zelinka and Rammer 2005).

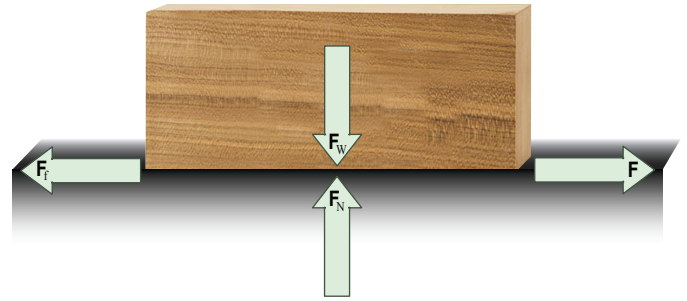


Figure 4-9. Diagram depicting the forces acting on an object in contact with a surface.

Friction Properties

Figure 4-9 depicts the forces acting on an object. The weight of the object F_W (the gravitational force acting downward) is opposed by the normal force F_N exerted by the surface supporting it. The applied horizontal force F is opposed by the friction force F_f parallel to the surface. In the case in which the object is not moving but is on the verge of sliding across the surface, the coefficient of static friction μ_s is defined as

$$\mu_s = \frac{F_f(\text{max})}{F_N} \quad (4-28)$$

where $F_f(\text{max})$ is the magnitude of the maximum friction force and F_N is the magnitude of the normal force. In the case in which the object is sliding across the surface at constant speed, the coefficient of kinetic friction μ_k is defined as

$$\mu_k = \frac{F_f}{F_N} \quad (4-29)$$

These coefficients depend on the moisture content of the wood, the roughness of the wood surface, and the characteristics of the opposing surface. They vary little with species except for woods that contain abundant oily or waxy extractives, such as *lignumvitae* (see Chap. 2). The coefficients of friction are an important safety consideration in applications such as wood decks and stairs.

On most materials, the coefficients of friction for wood increase continuously as the moisture content of the wood increases from oven-dry to fiber saturation, then remain about constant as the moisture content increases further until considerable free water is present. When the surface is flooded with water, the coefficients of friction decrease.

Coefficients of static friction are generally greater than those of kinetic friction, and the latter depend somewhat on the speed of sliding. Coefficients of kinetic friction vary only slightly with speed when the wood moisture content is less than about 20%; at high moisture content, the coefficient of kinetic friction decreases substantially as speed increases.

Coefficients of kinetic friction for smooth, dry wood against hard, smooth surfaces commonly range from 0.3 to 0.5; at

intermediate moisture content, 0.5 to 0.7; and near fiber saturation, 0.7 to 0.9.

Nuclear Radiation Properties

Several techniques using high-energy radiation can be used to measure density and moisture content of wood. Radiation passing through matter is reduced in intensity according to the relationship

$$I = I_0 \exp(-\mu z) \quad (4-30)$$

where I is the reduced intensity of the beam at depth z in the material, I_0 is the incident intensity of a beam of radiation, and μ , the linear absorption coefficient of the material, is the fraction of energy removed from the beam per unit depth traversed. When density is a factor of interest in energy absorption, the linear absorption coefficient is divided by the density of the material to derive the mass absorption coefficient. The absorption coefficient of a material varies with the type and energy of radiation.

The linear absorption coefficient of wood for γ radiation is known to vary directly with moisture content and density and inversely with the γ ray energy. As an example, the irradiation of oven-dry yellow-poplar with 0.047-MeV γ rays yields linear absorption coefficients ranging from about 0.065 to about 0.11 cm^{-1} over the oven-dry specific gravity range of about 0.33 to 0.62. An increase in the linear absorption coefficient of about 0.01 cm^{-1} occurs with an increase in moisture content from oven-dry to fiber saturation. Absorption of γ rays in wood is of practical interest, in part for measuring the density of wood.

The interaction of wood with β radiation is similar in character to that with γ radiation, except that the absorption coefficients are larger. The linear absorption coefficient of wood with a specific gravity of 0.5 for a 0.5-MeV β ray is about 3.0 cm^{-1} . The result of the larger coefficient is that even very thin wood products are virtually opaque to β rays.

The interaction of neutrons with wood is of interest because wood and the water it contains are compounds of hydrogen, and hydrogen has a relatively large probability of interaction with neutrons. Higher energy neutrons lose energy much more quickly through interaction with hydrogen than with other elements found in wood. Lower energy neutrons that result from this interaction are thus a measure of the hydrogen density of the specimen. Measurement of the lower energy level neutrons can be related to the moisture content of the wood.

When neutrons interact with wood, an additional result is the production of radioactive isotopes of the elements present in the wood. The radioisotopes produced can be identified by the type, energy, and half-life of their emissions, and the specific activity of each indicates the amount of isotope present. This procedure, called neutron

activation analysis, provides a sensitive nondestructive method of analysis for trace elements.

Discussions in this section assume moderate radiation levels that leave the wood physically unchanged. However, very large doses of γ rays or neutrons can cause substantial degradation of wood. The effect of large radiation doses on mechanical properties of wood is discussed in Chapter 5.

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Wood Handbook

Wood as an Engineering Material

Abstract

Summarizes information on wood as an engineering material. Presents properties of wood and wood-based products of particular concern to the architect and engineer. Includes discussion of designing with wood and wood-based products along with some pertinent uses.

Keywords: wood structure, physical properties (wood), mechanical properties (wood), lumber, wood-based composites, plywood, panel products, design, fastenings, wood moisture, drying, gluing, fire resistance, finishing, decay, preservation, wood-based products, heat sterilization, sustainable use

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