Chapter 3

Physical Properties and Moisture Relations of Wood

William Simpson and Anton TenWolde

Contents

Appearance 3–1

Grain and Texture 3–1

Plainsawn and Quartersawn 3–2

Decorative Features 3–2

Moisture Content 3–5

Green Wood and Fiber Saturation Point 3–5

Equilibrium Moisture Content 3–5

Sorption Hysteresis 3–7

Shrinkage 3–7

Transverse and Volumetric 3–7

Longitudinal 3–8

Moisture–Shrinkage Relationship 3–8

Weight, Density, and Specific Gravity 3–11

Working Qualities 3–15

Decay Resistance 3–15

Thermal Properties 3–15

Conductivity 3–15

Heat Capacity 3–17

Thermal Diffusivity 3–17

Thermal Expansion Coefficient 3–21

Electrical Properties 3–21

Conductivity 3–21

Dielectric Constant 3–22

Dielectric Power Factor 3–22

Coefficient of Friction 3–22

Nuclear Radiation 3–23

References 3–23

The versatility of wood is demonstrated by a wide variety of products. This variety is a result of a spectrum of desirable physical characteristics or properties among the many species of wood. In many cases, more than one property of wood is important to the end product. For example, to select a wood species for a product, the value of appearance-type properties, such as texture, grain pattern, or color, may be evaluated against the influence of characteristics such as machinability, dimensional stability, or decay resistance.

Wood exchanges moisture with air; the amount and direction of the exchange (gain or loss) depend 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. This chapter discusses the physical properties of most interest in the design of wood products.

Some physical properties discussed and tabulated are influenced by species as well as variables like moisture content; other properties tend to be independent of species. The thoroughness of sampling and the degree of variability influence the confidence with which species-dependent properties are known. In this chapter, an effort is made to indicate either the general or specific nature of the properties tabulated.

Appearance

Grain and Texture

The terms grain and texture are commonly used rather loosely in connection with wood. Grain is often used in reference to annual rings, as in fine grain and coarse grain, but it is also used to indicate the direction of fibers, as in straight grain, spiral grain, and curly grain. Grain, as a synonym for fiber direction, is discussed in detail relative to mechanical properties in Chapter 4. Wood finishers refer to wood as open grained and close grained, which are terms reflecting the relative size of the pores, which determines whether the surface needs a filler. Earlywood and latewood within a growth increment usually consist of different kinds and sizes of wood cells. The difference in cells results in difference in appearance of the growth rings, and the resulting appearance is the texture of the wood. Coarse texture can result from wide bands of large vessels, such as in oak.

"Even" texture generally means uniformity in cell dimensions. Fine-textured woods have small, even-textured cells. Woods that have larger even-sized cells are considered medium-textured woods. When the words grain or texture are used in connection with wood, the meaning intended should be made clear (see Glossary).

Plainsawn and Quartersawn

Lumber can be cut from a log in two distinct ways: (a) tangential to the annual rings, producing flatsawn or plainsawn lumber in hardwoods and flatsawn or slash-grained lumber in softwoods, and (b) radially from the pith or parallel to the rays, producing quartersawn lumber in hardwoods and edge-grained or vertical-grained lumber in softwoods (Fig. 3–1). Quartersawn lumber is not usually cut strictly parallel with the rays. In plainsawn boards, the surfaces next to the edges are often far from tangential to the rings. In commercial practice, lumber with rings at angles of 45° to 90° to the wide surface is called quartersawn, and lumber with rings at angles of 0° to 45° to the wide surface is called plainsawn. Hardwood lumber in which annual rings form angles of 30° to 60° to the wide faces is sometimes called bastard sawn.

For many purposes, either plainsawn or quartersawn lumber is satisfactory. Each type has certain advantages that can be important for a particular use. Some advantages of plainsawn and quartersawn lumber are given in Table 3–1.

Decorative Features

The decorative value of wood depends upon its color, figure, and luster, as well as the way in which it bleaches or takes fillers, stains, and transparent finishes. Because of the combinations of color and the multiplicity of shades found in wood, it is impossible to give detailed color descriptions of the various kinds of wood. Sapwood of most species is light in color; in some species, sapwood is practically white.

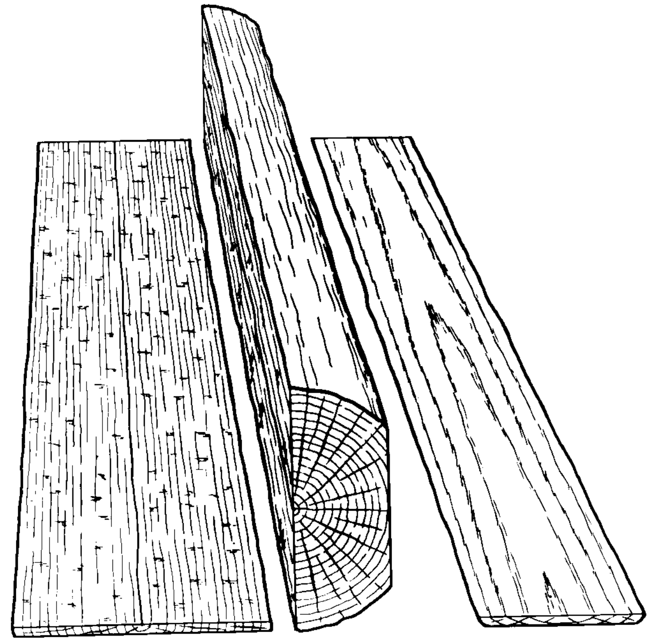

Figure 3–1. Quartersawn (A) and plainsawn (B) boards cut from a log.

White sapwood of certain species, such as maple, may be preferred to the heartwood for specific uses. In most species, heartwood is darker and fairly uniform in color. In some species, such as hemlock, spruce, the true firs, basswood, cottonwood, and beech, there is little or no difference in color between sapwood and heartwood. Table 3–2 describes the color and figure of several common domestic woods.

On the surface of plainsawn boards and rotary-cut veneer, the annual growth rings frequently form elliptic and parabolic patterns that make striking figures, especially when the rings are irregular in width and outline on the cut surface.

Table 3–1. Some advantages of plainsawn and quartersawn lumber

Plainsawn	Quartersawn
Shrinks and swells less in thickness	Shrinks and swells less in width
Surface appearance less affected by round or oval knots compared to effect of spike knots in quartersawn boards; boards with round or oval knots not as weak as boards with spike knots	Cups, surface-checks, and splits less in seasoning and in use
Shakes and pitch pockets, when present, extend through fewer boards	Raised grain caused by separation in annual rings does not become as pronounced
Figure patterns resulting from annual rings and some other types of figure brought out more conspicuously	Figure patterns resulting from pronounced rays, interlocked grain, and wavy grain are brought out more conspicuously
Is less susceptible to collapse in drying	Does not allow liquids to pass through readily in some species
Costs less because it is easy to obtain	Holds paint better in some species
	Sapwood appears in boards at edges and its width is limited by the width of the log

Table 3–2. Color and figure of several common domestic woods

Species	Color of dry heartwood[a]	Type of figure: Plainsawn lumber or rotary-cut veneer	Type of figure: Quartersawn lumber or quarter-sliced veneer
Hardwoods			
Alder, red	Pale pinkish brown	Faint growth ring	Scattered large flakes, sometimes entirely absent
Ash, black	Moderately dark grayish brown	Conspicuous growth ring; occasional burl	Distinct, inconspicuous growth ring stripe; occasional burl
Ash, Oregon	Grayish brown, sometimes with reddish tinge	Conspicuous growth ring; occasional burl	Distinct, inconspicuous growth ring stripe; occasional burl
Ash, white	Grayish brown, sometimes with reddish tinge	Conspicuous growth ring; occasional burl	Distinct, inconspicuous growth ring stripe; occasional burl
Aspen	Light brown	Faint growth ring	None
Basswood	Creamy white to creamy brown, sometimes reddish	Faint growth ring	None
Beech, American	White with reddish to reddish brown tinge	Faint growth ring	Numerous small flakes up to 3.2 mm (1/8 in.) in height
Birch, paper	Light brown	Faint growth ring	None
Birch, sweet	Dark reddish brown	Distinct, inconspicuous growth ring; occasionally wavy	Occasionally wavy
Birch, yellow	Reddish brown	Distinct, inconspicuous growth ring; occasionally wavy	Occasionally wavy
Butternut, light	Chestnut brown with occasional reddish tinge or streaks	Faint growth ring	None
Cherry, black	Light to dark reddish brown	Faint growth ring; occasional burl	Occasional burl
Chestnut, American	Grayish brown	Conspicuous growth ring	Distinct, inconspicuous growth ring stripe
Cottonwood	Grayish white to light grayish brown	Faint growth ring	None
Elm, American & rock	Light grayish brown, usually with reddish tinge	Distinct, inconspicuous grown ring with fine wavy pattern	Faint growth ring stripe
Elm, slippery	Dark brown with shades of red	Conspicuous growth ring with fine pattern	Distinct, inconspicuous growth ring stripe
Hackberry	Light yellowish or greenish gray	Conspicuous growth ring	Distinct, inconspicuous growth ring stripe
Hickory	Reddish brown	Distinct, inconspicuous growth ring	Faint growth ring stripe
Honeylocust	Cherry red	Conspicuous growth ring	Distinct, inconspicuous growth ring stripe
Locust, black	Golden brown, sometimes with tinge of green	Conspicuous growth ring	Distinct, inconspicuous growth ring stripe
Magnolia	Light to dark yellowish brown with greenish or purplish tinge	Faint growth ring	None
Maple: black, bigleaf, red, silver, and sugar	Light reddish brown	Faint growth ring, occasionally birds-eye, curly, and wavy	Occasionally curly and wavy
Oaks, all red oaks	Light brown, usually with pink or red tinge	Conspicuous growth ring	Pronounced flake; distinct, inconspicuous growth ring stripe
Oaks, all white oaks	Light to dark brown, rarely with reddish tinge	Conspicuous growth ring	Pronounced flake; distinct, inconspicuous growth ring stripe
Sweetgum	Reddish brown	Faint growth ring; occasional irregular streaks	Distinct, inconspicuous ribbon; occasional streak
Sycamore	Light to dark or reddish brown	Faint growth ring	Numerous pronounced flakes up to 6.4 mm (1/4 in.) in height
Tupelo, black and water	Pale to moderately dark brownish gray	Faint growth ring	Distinct, not pronounced ribbon
Walnut, black	Chocolate brown, occasionally with darker, sometimes purplish streaks	Distinct, inconspicuous growth ring; occasionally wavy, curly, burl, and other types	Distinct, inconspicuous growth ring stripe; occasionally wavy, curly, burl, crotch, and other types
Yellow-poplar	Light to dark yellowish brown with greenish or purplish tinge	Faint growth ring	None

Table 3–2. Color and figure of several common domestic woods—con.

Species	Color of dry heartwood[a]	Type of figure: Plainsawn lumber or rotary-cut veneer	Type of figure: Quartersawn lumber or quarter-sliced veneer
Softwoods			
Baldcypress	Light yellowish to reddish brown	Conspicuous irregular growth ring	Distinct, inconspicuous growth ring stripe
Cedar, Atlantic White	Light brown with reddish tinge	Distinct, inconspicuous growth ring	None
Cedar, Eastern red	Brick red to deep reddish brown	Occasionally streaks of white sapwood alternating with heartwood	Occasionally streaks of white sapwood alternating with heartwood
Cedar, incense	Reddish brown	Faint growth ring	Faint growth ring stripe
Cedar, northern White	Light to dark brown	Faint growth ring	Faint growth ring stripe
Cedar, Port-Orford	Light yellow to pale brown	Faint growth ring	None
Cedar, western red	Reddish brown	Distinct, inconspicuous growth ring	Faint growth ring stripe
Cedar, yellow	Yellow	Faint growth ring	None
Douglas-fir	Orange red to red, sometimes yellow	Conspicuous growth ring	Distinct, inconspicuous growth ring stripe
Fir, balsam	Nearly white	Distinct, inconspicuous growth ring	Faint growth ring stripe
Fir, white	Nearly white to pale reddish brown	Conspicuous growth ring	Distinct, inconspicuous growth ring stripe
Hemlock, eastern	Light reddish brown	Distinct, inconspicuous growth ring	Faint growth ring stripe
Hemlock, western	Light reddish brown	Distinct, inconspicuous growth ring	Faint growth ring stripe
Larch, western	Russet to reddish brown	Conspicuous growth ring	Distinct, inconspicuous growth ring stripe
Pine, eastern white	Cream to light reddish brown	Faint growth ring	None
Pine, lodgepole	Light reddish brown	Distinct, inconspicuous growth ring; faint pocked appearance	None
Pine, ponderosa	Orange to reddish brown	Distinct, inconspicuous growth ring	Faint growth ring
Pine, red	Orange to reddish brown	Distinct, inconspicuous growth ring	Faint growth ring
Pine, Southern: longleaf, loblolly, shortleaf, and slash	Orange to reddish brown	Conspicuous growth ring	Distinct, inconspicuous growth ring stripe
Pine, sugar	Light creamy brown	Faint growth ring	None
Pine, western white	Cream to light reddish brown	Faint growth ring	None
Redwood	Cherry red to deep reddish brown	Distinct, inconspicuous growth ring; occasionally wavy and burl	Faint growth ring stripe; occasionally wavy and burl
Spruce: black, Engelmann, red, and white	Nearly white	Faint growth ring	None
Spruce, Sitka	Light reddish brown	Distinct, inconspicuous growth ring	Faint growth ring stripe
Tamarack	Russet brown	Conspicuous growth ring	Distinct, inconspicuous growth ring stripe

[a]Sapwood of all species is light in color or virtually white unless discolored by fungus or chemical stains.

On quartersawn surfaces, these rings form stripes, which are not especially ornamental unless they are irregular in width and direction. The relatively large rays sometimes appear as flecks that can form a conspicuous figure in quartersawn oak and sycamore. With interlocked grain, which slopes in alternate directions in successive layers from the center of the tree outward, quartersawn surfaces show a ribbon effect, either because of the difference in reflection of light from successive layers when the wood has a natural luster or because cross grain of varying degree absorbs stains unevenly. Much of this type of figure is lost in plainsawn lumber.

In open-grained hardwoods, the appearance of both plainsawn and quartersawn lumber can be varied greatly by the use of fillers of different colors. In softwoods, the annual growth layers can be made to stand out by applying a stain. The visual effect of applying stain to softwood is an overall darkening and a contrast reversal with earlywood of initially lighter color absorbing more stain, thus becoming darker than latewood. The final contrast is often greater than that in unstained softwood and sometimes appears unnatural.

Knots, pin wormholes, bird pecks, decay in isolated pockets, birdseye, mineral streaks, swirls in grain, and ingrown bark are decorative in some species when the wood is carefully selected for a particular architectural treatment.

Moisture Content

Moisture content of wood is defined as the weight of water in wood expressed as a fraction, usually a percentage, of the weight of ovendry wood. Weight, shrinkage, strength, and other properties depend upon the moisture content of wood.

In trees, moisture content can range from about 30% to more than 200% of the weight of wood substance. In softwoods, the moisture content of sapwood is usually greater than that of heartwood. In hardwoods, the difference in moisture content between heartwood and sapwood depends on the species. The average moisture content of heartwood and sapwood of some domestic species is given in Table 3–3. These values are considered typical, but there is considerable variation within and between trees. Variability of moisture content exists even within individual boards cut from the same tree. Additional information on moisture in wood is given in Chapter 12.

Green Wood and Fiber Saturation Point

Moisture can exist in wood as liquid water (free water) or water vapor in cell lumens and cavities and as water held chemically (bound water) within cell walls. Green wood is often defined as freshly sawn wood in which the cell walls are completely saturated with water; however, green wood usually contains additional water in the lumens. The moisture content at which both the cell lumens and cell walls are completely saturated with water is the maximum possible moisture content. Specific gravity is the major determinant of maximum moisture content. Lumen volume decreases as specific gravity increases, so maximum moisture content also decreases as specific gravity increases because there is less room available for free water. Maximum moisture content M_{max} for any specific gravity can be calculated from

$$M_{\text{max}} = 100(1.54 - G_{\text{b}}) / 1.54G_{\text{b}} \qquad (3\text{–}1)$$

where G_{b} is basic specific gravity (based on ovendry weight and green volume) and 1.54 is specific gravity of wood cell walls. Maximum possible moisture content varies from 267% at specific gravity of 0.30 to 44% at specific gravity 0.90. Maximum possible moisture content is seldom attained in trees. However, green moisture content can be quite high in some species naturally or through waterlogging. The moisture content at which wood will sink in water can be calculated by

$$M_{\text{sink}} = 100(1 - G_{\text{b}}) / G_{\text{b}} \qquad (3\text{–}2)$$

Conceptually, the moisture content at which only the cell walls are completely saturated (all bound water) but no water exists in cell lumens is called the fiber saturation point. While a useful concept, the term fiber saturation point is not very precise. In concept, it distinguishes between the two ways water is held in wood. In fact, it is possible for all cell lumens to be empty and have partially dried cell walls in one part of a piece of wood, while in another part of the same piece, cell walls may be saturated and lumens partially or completely filled with water. It is even probable that a cell wall will begin to dry before all the water has left the lumen of that same cell. The fiber saturation point of wood 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 fiber saturation point also is often considered as that moisture content below which the physical and mechanical properties of wood begin to change as a function of moisture content. During drying, the outer parts of a board can be less than fiber saturation while the inner parts are still greater than fiber saturation.

Equilibrium Moisture Content

The moisture content of wood below the fiber saturation point is a function of both relative humidity and temperature of the surrounding air. Equilibrium moisture content (EMC) is defined as that moisture content at which the wood is neither gaining nor losing moisture; an equilibrium condition has been reached. The relationship between EMC, relative humidity, and temperature is shown in Table 3–4. For most practical purposes, the values in Table 3–4 may be applied to wood of any species. Data in Table 3–4 can be approximated by the following:

$$M = \frac{1{,}800}{W}\left[\frac{Kh}{1 - Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2}\right] \qquad (3\text{–}3)$$

where h is relative humidity (%/100), and M is moisture content (%).

For temperature T in Celsius,

$$W = 349 + 1.29T + 0.0135T^2$$

$$K = 0.805 + 0.000736T - 0.00000273T^2$$

$$K_1 = 6.27 - 0.00938T - 0.000303T^2$$

$$K_2 = 1.91 + 0.0407T - 0.000293T^2$$

and for temperature in Fahrenheit,

$$W = 330 + 0.452T + 0.00415T^2$$

$$K = 0.791 + 0.000463T - 0.000000844T^2$$

$$K_1 = 6.34 + 0.000775T - 0.0000935T^2$$

$$K_2 = 1.09 + 0.0284T - 0.0000904T^2$$

Wood in service is exposed to both long-term (seasonal) and short-term (daily) changes in relative humidity and temperature of the surrounding air. Thus, wood is always undergoing at least slight changes in 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. The objective of wood drying is to bring the wood close to the moisture content a finished product will have in service (Chs. 12 and 15).

Table 3–3. Average moisture content of green wood, by species

Species	Moisture content[a] (%) Heartwood	Sapwood	Species	Moisture content[a] (%) 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			

[a]Based on weight when ovendry.

Table 3–4. 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													

Sorption Hysteresis

The amount of water adsorbed from a dry condition to equilibrium with any relative humidity is always less than the amount retained in the process of drying from a wetter condition to equilibrium with that same relative humidity. The ratio of adsorption EMC to desorption EMC is constant at about 0.85. Furthermore, EMC in the initial desorption (that is, from the original green condition of the tree) is always greater than in any subsequent desorptions. Data in Table 3–4 were derived primarily under conditions described as oscillating desorption (Stamm and Loughborough 1935), which is thought to represent a condition midway between adsorption and desorption and a suitable and practical compromise for use when the direction of sorption is not always known. Hysteresis is shown in Figure 3–2.

Shrinkage

Wood is dimensionally stable when the moisture content is greater than the fiber saturation point. Wood changes dimension as it gains or loses moisture below that point. It shrinks when losing moisture from the cell walls and swells when gaining moisture in the cell walls. This shrinking and swelling can result in warping, checking, splitting, and loosening of tool handles, gaps in strip flooring, or performance problems that detract from the usefulness of the wood product. Therefore, it is important that these phenomena be understood and considered when they can affect a product in which wood is used.

With respect to shrinkage characteristics, wood is an anisotropic material. It shrinks 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 as a result of these effects are illustrated in Figure 3–3.

Transverse and Volumetric

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 Method of Testing Small Clear Specimens of Timber (ASTM 1997). Shrinkage values, expressed as a percentage of the green dimension, are listed in Table 3–5. Shrinkage values

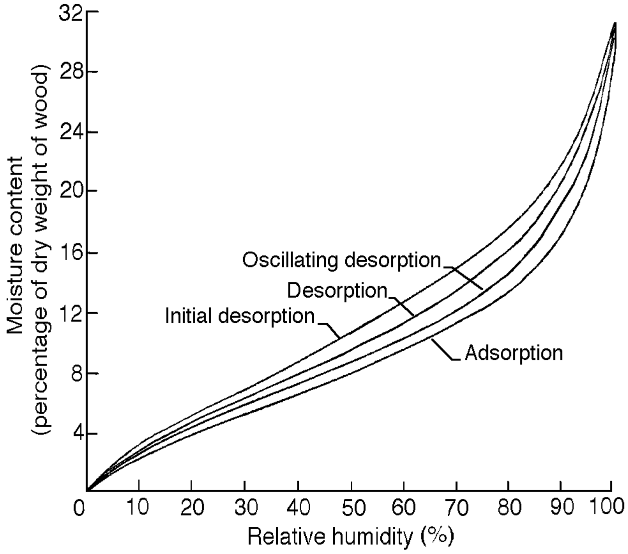

Figure 3–2. Moisture content–relative humidity relationship for wood under adsorption and various desorption conditions.

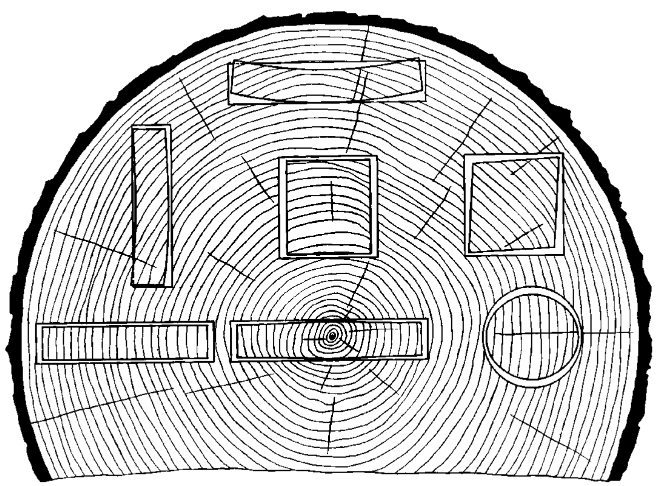

Figure 3–3. Characteristic shrinkage and distortion of flat, square, and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial.

collected from the world literature for selected imported species are listed in Table 3–6.

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%.

Longitudinal

Longitudinal shrinkage of wood (shrinkage parallel to the grain) is generally quite small. Average values for shrinkage from green to ovendry 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. 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 ovendry. 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.

Moisture–Shrinkage Relationship

The shrinkage of a small piece of wood 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. When the surface gets below the fiber saturation point, it begins to shrink. Meanwhile, the interior can still be quite wet and not shrink. The result is that shrinkage of lumber can begin before the average moisture content of the entire piece is below the fiber saturation point, and the moisture content–shrinkage curve can actually look like the one in Figure 3–4. The exact form of the curve 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. Shrinkage data for Douglas-fir boards, 22.2 by 139.7 mm (7/8 by 5-1/2 in.) in cross section, are given in Figure 3–5. The material was grown in one locality and dried under mild conditions from green to near equilibrium at 18°C (65°F) and 30% relative humidity. The figure shows that it is impossible to accurately predict the shrinkage of an individual piece of wood; the average shrinkage of a quantity of pieces is more predictable.

If the shrinkage–moisture content relationship is not known for a particular product and drying condition, data in Tables 3–5 and 3–6 can be used to estimate shrinkage from the green condition to any moisture content using

$$S_{\mathrm{m}} = S_0\left(\frac{30 - M}{30}\right) \qquad (3\text{–}4)$$

where S_{m} is shrinkage (%) from the green condition to moisture content M (<30%), and S_0 is total shrinkage (radial, tangential, or volumetric (%)) from Table 3–5 or 3–6.

Table 3–5. Shrinkage values of domestic woods

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

[a]Expressed as a percentage of the green dimension.
[b]Coast 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.

Table 3–6. Shrinkage for some woods imported into the United States[a]

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

[a]Shrinkage values were obtained from world literature and may not represent a true species average.
[b]Expressed as a percentage of the green dimension.
[c]AF is Africa; AM is Tropical America; AS is Asia and Oceania.

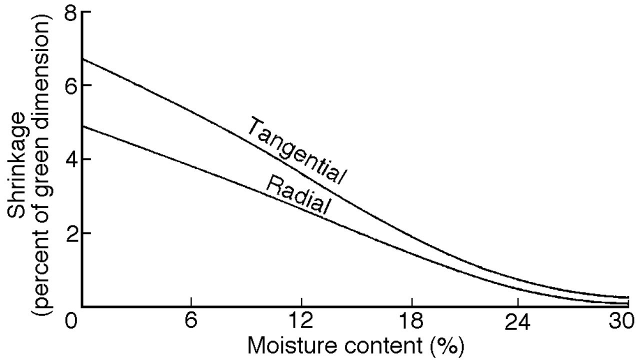

Figure 3–4. Typical moisture content–shrinkage curves.

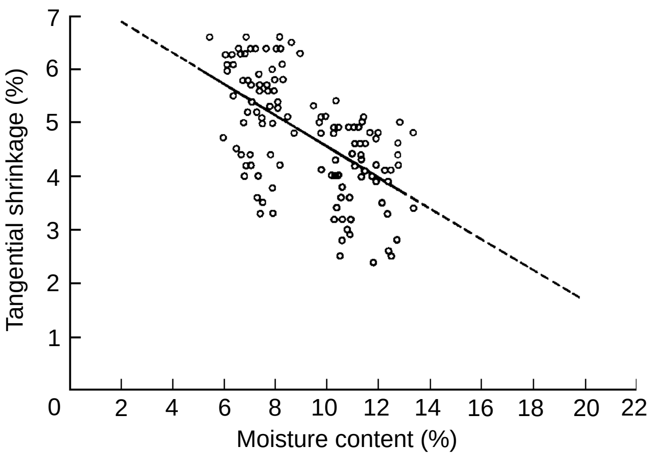

Figure 3–5. Variation in individual tangential shrinkage values of several Douglas-fir boards from one locality, dried from green condition.

If the moisture content at which shrinkage from the green condition begins is known to be other than 30% for a species, the shrinkage estimate can be improved by replacing the value of 30 in Equation (3–4) with the appropriate moisture content value.

Tangential values for S_0 should be used for estimating width shrinkage of flatsawn 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 12 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 6.

Weight, Density, and Specific Gravity

Two primary factors affect the weight of wood products: density of the basic wood structure and moisture content. A third factor, minerals and extractable substances, has a marked effect only on a limited number of species.

The density of wood, exclusive of water, varies greatly both within and between species. Although the density of most species falls between about 320 and 720 kg/m^3 (20 and 45 lb/ft^3), the range of density actually extends from about 160 kg/m^3 (10 lb/ft^3) for balsa to more than 1,040 kg/m^3 (65 lb/ft^3) for some other imported woods. A coefficient of variation of about 10% is considered suitable for describing the variability of density within common domestic species.

Wood is used in a wide range of conditions and has a wide range of moisture content values in use. Moisture makes up part of the weight of each product in use; therefore, the density must reflect this fact. This has resulted in the density of wood often being determined and reported on the basis of moisture content in use.

The calculated density of wood, including the water contained in the wood, is usually based on average species characteristics. This value should always be considered an approximation because of the natural variation in anatomy, moisture content, and ratio of heartwood to sapwood that occurs. Nevertheless, this determination of density usually is sufficiently accurate to permit proper utilization of wood products where weight is important. Such applications range from the estimation of structural loads to the calculation of approximate shipping weights.

To standardize comparisons of species or products and estimations of product weight, specific gravity is used as a standard reference basis, rather than density. The traditional definition of specific gravity is the ratio of the density of the wood to the density of water at a specified reference temperature (often 4.4°C (40°F)) where the density of water is 1.0000 g/cm^3). To reduce confusion introduced by the variable of moisture content, the specific gravity of wood usually is based on the ovendry weight and the volume at some specified moisture content.

Commonly used bases for determining specific gravity are ovendry weight and volume at (a) green, (b) ovendry, and (c) 12% moisture content. Ovendry weight and green volume are often used in databases to characterize specific gravity of species, which is referred to as basic specific gravity. Some specific gravity data are reported in Tables 4–3, 4–4, and 4–5 (Ch. 4) on both the 12% and green volume basis. A coefficient of variation of about 10% describes the variability inherent in many common domestic species.

Design specifications for wood, such as contained in the *National Design Specification for Wood Construction*, are based on ovendry weight and ovendry volume.

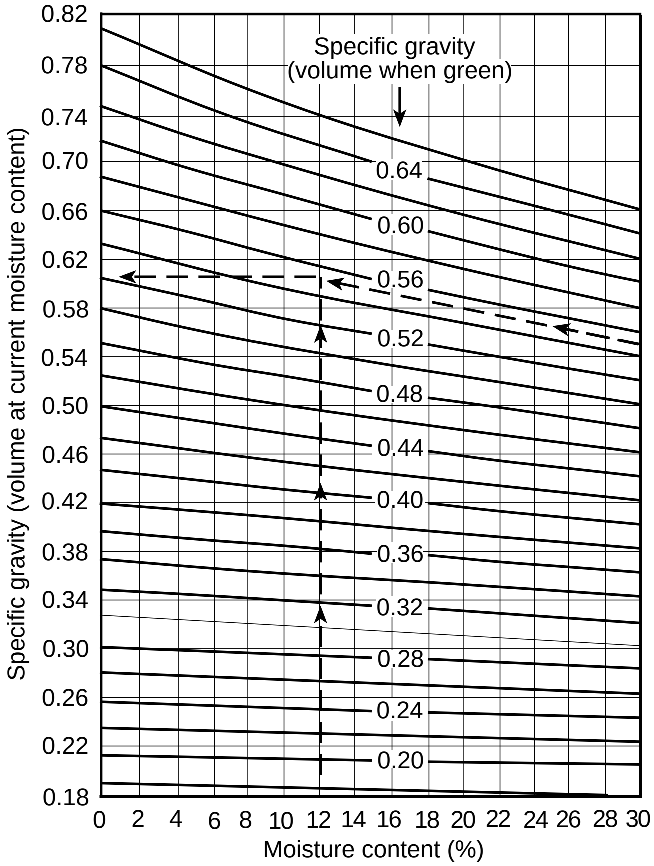

Figure 3–6. Relationship of specific gravity and moisture content.

If the specific gravity of wood is known, based on ovendry weight and volume at a specified moisture content, the specific gravity at any other moisture content between 0 and 30% can be approximated from Figure 3–6. This figure adjusts for average shrinkage and swelling that occurs below 30% moisture content and affects the volume of wood. The specific gravity of wood based on ovendry weight does not change at moisture content values above approximately 30% (the approximate fiber saturation point) because the volume does not change. To use Figure 3–6, locate the inclined line corresponding to the known 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 new specific gravity 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 4–3a in Chapter 4. The average green (basic) specific gravity G_b for this species is 0.55. Using Figure 3–6, the 0.55 green specific gravity curve is found to intersect with the vertical 12% moisture content line at a point corresponding to a specific gravity of 0.605 based on ovendry weight and volume at 12% moisture content, G_m (see dashed lines in Fig. 3–6). The density of wood including water at this moisture content can then be obtained from Table 3–7, which converts the specific gravity of 0.605 to a density of 675 kg/m^3 (42 lb/ft^3). An alternative to usage of Figure 3–6 is direct calculation of G_m using the following:

$$G_m = G_b/(1 - 0.265aG_b) \qquad (3–5)$$

where G_m is specific gravity based on volume at moisture content M, G_b is basic specific gravity (based on green volume), and $a = (30 - M)/30$, where $M < 30$.

Alternatively, the density values in Table 3–7 can be calculated by

$$\rho = 1{,}000\ G_m(1 + M/100) \quad (\text{kg/m}^3) \qquad (3–6a)$$

$$\rho = 62.4\ G_m(1 + M/100) \quad (\text{lb/ft}^3) \qquad (3–6b)$$

It is often useful to know the weight of lumber on a volumetric basis. We can make these estimates using Table 3–7 or with equations only. These results assume an average shrinkage–specific gravity relationship and provide a good estimate. Both methods are illustrated. For weights based on the actual shrinkage of individual species, refer to the *Dry Kiln Operator's Manual* (Simpson 1991).

Method 1—Use of Table 3–7

Determine the weight per actual unit volume (cubic meter or 1,000 board feet) of sugar maple at 20% moisture content and at 50% moisture content. From Table 4–3a, the specific gravity G_b (ovendry weight–green volume) is 0.56. Because the specific gravity in Table 3–7 is based on volume at tabulated moisture content G_m, we must convert G_b to G_m by either Figure 3–6 or Equation (3–5):

At 20%,

$$G_m = 0.56/\{1 - 0.265[(30 - 20)/30]0.56\} = 0.59$$

Determine the density from Table 3–7 at $G_m = 0.59$ and 20% moisture content. The result is approximately 708 kg/m^3 (44.1 lb/ft^3) (by interpolation).

At 50%,

$$G_m = G_b = 0.56$$

Determine the density from Table 3–7 at $G_m = 0.56$ and 50% moisture content. The result is 840 kg/m^3 (52.4 lb/ft^3).

Method 2—Use of equations only

At 20%, G_m is calculated as 0.589 as in Method 1. Density is then calculated from Equation (3–6) as

$$\rho = 1{,}000\ G_m(1+M/100)$$
$$= 1{,}000\ (0.58\ (1+20/100) = 707\ \text{kg/m}^3$$

$$\rho = 62.4\ G_m(1+M/100)$$
$$= 62.4(0.589)\ (1+20/100) = 44.1\ \text{lb/ft}^3$$

At 50%,

$$\rho = 1{,}000\ (0.56)(1+50/100) = 840\ \text{kg/m}^3$$

$$\rho = 62.4(0.56)(1+50/100) = 52.4\ \text{lb/ft}^3$$

Table 3–7a. Density of wood as a function of specific gravity and moisture content (metric)

Moisture content of wood (%)	Density (kg/m^3) when the specific gravity G_m 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	854	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	8B0	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	1030	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	I,000	1,040	1,080	1,120	1,160	1,200					
110	630	672	714	756	798	840	832	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								

Table 3–7b. Density of wood as a function of specific gravity and moisture content (inch–pound)

Moisture content of wood (%)	Density (lb/ft^3) when the specific gravity G_m 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								

Working Qualities

The ease of working wood with hand tools generally varies directly with the specific gravity of the wood. The lower the specific gravity, the easier it is to cut the wood with a sharp tool. Tables 4–3 and 4–5 (Ch. 4) list the specific gravity values for various native and imported species. These specific gravity values can be used as a general guide to the ease of working with hand tools.

A wood species that is easy to cut does not necessarily develop a smooth surface when it is machined. Consequently, tests have been made with many U.S. hardwoods to evaluate them for machining properties. Results of these evaluations are given in Table 3–8.

Machining evaluations are not available for many imported woods. However, three major factors other than density can affect production of smooth surfaces during wood machining: interlocked and variable grain, hard mineral deposits, and reaction wood, particularly tension wood in hardwoods. Interlocked grain is characteristic of a few domestic species and many tropical species, and it presents difficulty in planing quartersawn boards unless attention is paid to feed rate, cutting angles, and sharpness of knives. Hard deposits in the cells, such as calcium carbonate and silica, can have a pronounced dulling effect on all cutting edges. This dulling effect becomes more pronounced as the wood is dried to the usual in-service requirements. Tension wood can cause fibrous and fuzzy surfaces. It can be very troublesome in species of lower density. Reaction wood can also be responsible for the pinching effect on saws as a result of stress relief. The pinching can result in burning and dulling of the saw teeth. Table 3–9 lists some imported species that have irregular grain, hard deposits, or tension wood.

Decay Resistance

Wood kept constantly dry does not decay. In addition, if wood is kept continuously submerged in water, even for long periods of time, it does not decay significantly by the common decay fungi regardless of the wood species or the presence of sapwood. Bacteria and certain soft-rot fungi can attack submerged wood, but the resulting deterioration is very slow. A large proportion of wood in use is kept so dry at all times that it lasts indefinitely.

Moisture and temperature, which vary greatly with local conditions, are the principal factors that affect rate of decay. Wood deteriorates more rapidly in warm, humid areas than in cool or dry areas. High altitudes, as a rule, are less favorable to decay than are low altitudes because the average temperatures at higher altitudes are lower and the growing season for fungi, which cause decay, is shorter. The heartwood of common native species of wood has varying degrees of natural decay resistance. Untreated sapwood of substantially all species has low resistance to decay and usually has a short service life under decay-producing conditions. The decay resistance of heartwood is greatly affected by differences in the preservative qualities of the wood extractives, the attacking fungus, and the conditions of exposure. Considerable difference in service life can be obtained from pieces of wood cut from the same species, even from the same tree, and used under apparently similar conditions. There are further complications because, in a few species, such as the spruces and the true firs (not Douglas-fir), heartwood and sapwood are so similar in color that they cannot be easily distinguished.

Marketable sizes of some species, such as the southern and eastern pines and baldcypress, are becoming primarily second growth and contain a high percentage of sapwood. Consequently, substantial quantities of heartwood lumber of these species are not available.

Precise ratings of decay resistance of heartwood of different species are not possible because of differences within species and the variety of service conditions to which wood is exposed. However, broad groupings of many native species, based on service records, laboratory tests, and general experience, are helpful in choosing heartwood for use under conditions favorable to decay. Table 3–10 lists such groupings for some domestic and imported woods, according to their average heartwood decay resistance. The extent of variations in decay resistance of individual trees or wood samples of a species is much greater for most of the more resistant species than for the slightly or nonresistant species.

Where decay hazards exist, heartwood of species in the resistant or very resistant category generally gives satisfactory service, but heartwood of species in the other two categories will usually require some form of preservative treatment. For mild decay conditions, a simple preservative treatment—such as a short soak in preservative after all cutting and boring operations are complete—will be adequate for wood low in decay resistance. For more severe decay hazards, pressure treatment is often required. Even the very decay-resistant species may require preservative treatment for important structural uses or other uses where failure would endanger life or require expensive repairs. Preservative treatments and methods for wood are discussed in Chapter 14.

Thermal Properties

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

Conductivity

Thermal conductivity is a measure of the rate of heat flow through one unit thickness of a material subjected to a temperature gradient. 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 material. For example, the conductivity of structural softwood lumber at 12% moisture content is in the range of 0.1 to 1.4 W/(m·K) (0.7 to 1.0 Btu·in/(h·ft^2·°F)) 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.

Table 3–8. Some machining and related properties of selected domestic hardwoods

Kind of wood[a]	Planing: perfect pieces (%)	Shaping: good to excellent pieces (%)	Turning: fair to excellent pieces (%)	Boring: good to excellent pieces (%)	Mortising: fair to excellent pieces (%)	Sanding: good to excellent pieces (%)	Steam bending: unbroken pieces (%)	Nail splitting: pieces free from complete splits (%)	Screw splitting: pieces free from complete splits (%)
Alder, red	61	20	88	64	52	—	—	—	—
Ash	75	55	79	94	58	75	67	65	71
Aspen	26	7	65	78	60	—	—	—	—
Basswood	64	10	68	76	51	17	2	79	68
Beech	83	24	90	99	92	49	75	42	58
Birch	63	57	80	97	97	34	72	32	48
Birch, paper	47	22	—	—	—	—	—	—	—
Cherry, black	80	80	88	100	100	—	—	—	—
Chestnut	74	28	87	91	70	64	56	66	60
Cottonwood[b]	21	3	70	70	52	19	44	82	78
Elm, soft[b]	33	13	65	94	75	66	74	80	74
Hackberry	74	10	77	99	72	—	94	63	63
Hickory	76	20	84	100	98	80	76	35	63
Magnolia	65	27	79	71	32	37	85	73	76
Maple, bigleaf	52	56	80	100	80	—	—	—	—
Maple, hard	54	72	82	99	95	38	57	27	52
Maple, soft	41	25	76	80	34	37	59	58	61
Oak, red	91	28	84	99	95	81	86	66	78
Oak, white	87	35	85	95	99	83	91	69	74
Pecan	88	40	89	100	98	—	78	47	69
Sweetgum[b]	51	28	86	92	58	23	67	69	69
Sycamore[b]	22	12	85	98	96	21	29	79	74
Tanoak	80	39	81	100	100	—	—	—	—
Tupelo, water[b]	55	52	79	62	33	34	46	64	63
Tupelo, black[b]	48	32	75	82	24	21	42	65	63
Walnut, black	62	34	91	100	98	—	78	50	59
Willow	52	5	58	71	24	24	73	89	62
Yellow-poplar	70	13	81	87	63	19	58	77	67

[a]Commercial lumber nomenclature.
[b]Interlocked grain present.

Table 3–9. Some characteristics of imported woods that may affect machining

Irregular and interlocked grain	Hard mineral deposits (silica or calcium carbonate)	Reaction wood (tension wood)
Avodire	Angelique	Andiroba
Courbaril	Iroko	Banak
Ekop	Kapur	Cativo
Goncalo alves	Keruing (Apitong)	Ceiba
Ipe	Manbarklak	Hura
Iroko	Marishballi	Mahogany, African
Jarrah	Mersawa	Mahogany, American
Kapur	Okoume	Sande
Karri	Rosewood, Indian	Spanish-cedar
Keruing (Apitong)	Teak	
Kokrodua		
Lauan/meranti		
Lignumvitae		
Limba		
Mahogany, African		
Merasawa		
Obeche		
Okoume		
Rosewood, Indian		
Santa Maria		
Sapele		

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 with respect to the growth rings. Conductivity along the grain has been reported as 1.5 to 2.8 times greater than conductivity across the grain, with an average of about 1.8, but reported values vary widely.

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

$$k = G(B + CM) + A \qquad (3\text{–}7)$$

where G is specific gravity based on ovendry weight and volume at a given moisture content M (%) and A, B, and C are constants. For specific gravity >0.3, temperatures around 24°C (75°F), and moisture content values <25%, A = 0.01864, B = 0.1941, and C = 0.004064 (with k in W/(m·K)) (or A = 0.129, B = 1.34, and C = 0.028 with k in Btu·in/(h·ft^2·F)). Equation (3–7) was derived from measurements made by several researchers on a variety of species. Table 3–11 provides average approximate conductivity values for selected wood species, based on Equation (3–7). However, actual conductivity may vary as much as 20% from the tabulated values.

Although thermal conductivity measurements have been made at moisture content values >25%, measurements have been few in number and generally lacking in accuracy. Therefore, we do not provide values for moisture content values >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·K, Btu/lb·°F) is approximately related to temperature t (K, °F) by

$$c_{p0} = 0.1031 + 0.003867t \quad \text{(metric)} \qquad (3\text{–}8a)$$

$$c_{p0} = 0.2605 + 0.0005132t \quad \text{(inch–pound)} \qquad (3\text{–}8b)$$

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:

$$c_p = (c_{p0} + 0.01Mc_{pw})/(1 + 0.01M) + A_c \qquad (3\text{–}9)$$

where M is moisture content (%). The heat capacity of water is about 4.19 kJ/kg·K (1 Btu/lb·°F). The adjustment factor can be derived from

$$A_c = M(b_1 + b_2t + b_3M) \qquad (3\text{–}10)$$

with $b_1 = -0.06191$, $b_2 = 2.36 \times 10^{-4}$, and $b_3 = -1.33 \times 10^{-4}$ with temperature in kelvins ($b_1 = -4.23 \times 10^{-4}$, $b_2 = 3.12 \times 10^{-5}$, and $b_3 = -3.17 \times 10^{-5}$ with temperature in °F). These formulas are valid for wood below fiber saturation at temperatures between 7°C (45°F) and 147°C (297°F). Representative values for heat capacity can be found in Table 3–12. The moisture above fiber saturation contributes to specific heat 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 the ratio of thermal conductivity to the product of density and heat capacity. Diffusivity is defined as the ratio of conductivity to the product of heat capacity and density; therefore, conclusions regarding its variation with temperature and density are often based on calculating the effect of these variables on heat capacity and conductivity. Because of the low thermal conductivity and 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 0.161×10^{-6} m^2/s (0.00025 in^2/s) compared with 12.9×10^{-6} m^2/s (0.02 in^2/s) for steel and 0.645×10^{-6} m^2/s (0.001 in^2/s) for mineral wool. For this reason, wood does not feel extremely hot or cold to the touch as do some other materials.

Table 3–10. Grouping of some domestic and imported woods according to average heartwood decay resistance

Resistant or very resistant	Moderately resistant	Slightly or nonresistant
Domestic		
Baldcypress, old growth	Baldcypress, young growth	Alder, red
Catalpa	Douglas-fir	Ashes
Cedar	Larch, western	Aspens
Atlantic white	Pine, longleaf, old growth	Beech
Eastern redcedar	Pine, slash, old growth	Birches
Incense	Redwood, young growth	Buckeye
Northern white	Tamarack	Butternut
Port-Orford		Cottonwood
Western redcedar		Elms
Yellow	Pine, eastern white, old growth	Basswood
Cherry, black		Firs, true
Chestnut		Hackberry
Cypress, Arizona		Hemlocks
Junipers		Hickories
Locust,		Magnolia
Black[a]		Maples
Honeylocust		Pines (other than those listed)[b]
Mesquite		Spruces
Mulberry, red[a]		Sweetgum
Oaks, white[b]		Sycamore
Osage orange[a]		Tanoak
Redwood, old growth		Willows
Sassafras		Yellow-poplar
Walnut, black		
Yew, Pacific[a]		
Imported		
Aftotmosia (Kokrodua)	Andiroba	Balsa
Angelique[a]	Avodire	Banak
Apamate (Roble)	Benge	Cativo
Azobe[a]	Bubinga	Ceiba
Balata[a]	Ehie	Hura
Balau[b]	Ekop	Jelutong
Courbaril	Keruing[b]	Limba
Determa	Mahogany, African	Meranti, light red[b]
Goncalo alves[a]	Meranti, dark red[b]	Meranti, yellow[b]
Greenheart[a]	Mersawa[b]	Meranti, white[b]
Ipe (lapacho)[a]	Sapele	Obeche
Iroko	Teak , young growth	Okoume
Jarrah[a]	Tornillo	Parana pine
Kapur		Ramin
Karri		Sande
Kempas		Sepitir
Lignumvitae[a]		Seraya, white
Mahogany, American		
Manni		
Purpleheart[a]		
Spanish-cedar		
Sucupira		
Teak, old growth[a]		
Wallaba		

[a]Exceptionally high decay resistance.
[b]More than one species included, some of which may vary in resistance from that indicated.

Table 3–11. Thermal conductivity of selected hardwoods and softwoods[a]

		Conductivity (W/m·K (Btu·in/h·ft²·°F))		Resistivity (K·m/W (h·ft²·°F/Btu·in))	
Species	Specific gravity	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 3–11. Thermal conductivity of selected hardwoods and softwoods[a]—con.

Species	Specific gravity	Conductivity (W/m·K (Btu·in/h·ft^2·°F)) Ovendry	Conductivity 12% MC	Resistivity (W/m·K (h·ft^2·°F/Btu·in)) Ovendry	Resistivity 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)

[a]Values 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 3–12. Heat capacity of solid wood at selected temperatures and moisture contents

Temperature			Specific heat (kJ/kg·K (Btu/lb·°F))			
(K)	(°C	(°F))	Ovendry	5% MC	12% MC	20% MC
280	7	(45)	1.2 (0.28)	1.3 (0.32)	1.5 (0.37)	1.7 (0.41)
290	17	(75)	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)

Thermal Expansion Coefficient

The coefficient of thermal expansion is a measure of the 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 ovendry 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 0.000031 to 0.0000045 per K (0.0000017 to 0.0000025 per °F).

The thermal expansion coefficients across the grain (radial and tangential) are proportional to wood 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 ovendry wood, α_r and α_t, can be approximated by the following equations, over an ovendry specific gravity range of about 0.1 to 0.8:

$$\alpha_r = (32.4G + 9.9)10^{-6} \text{ per K} \quad (3\text{–}11a)$$

$$\alpha_r = (18G + 5.5)10^{-6} \text{ per °F} \quad (3\text{–}11b)$$

$$\alpha_t = (32.4G + 18.4)10^{-6} \text{ per K} \quad (3\text{–}12a)$$

$$\alpha_t = (18G + 10.2)10^{-6} \text{ per °F} \quad (3\text{–}12b)$$

Thermal expansion coefficients can be considered independent of temperature over the temperature range of −51.1°C to 54.4°C (−60°F 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, 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 most important electrical properties of wood are conductivity, dielectric constant, and dielectric power factor. The conductivity of a material determines the electric current that will flow when the material is placed under a given voltage gradient. The dielectric constant of a nonconducting material determines the amount of potential electric energy, in the form of induced polarization, that is stored in a given volume of the material when that material is placed in an electric field. The power factor of a nonconducting material determines the fraction of stored energy that is dissipated as heat when the material experiences a complete polarize–depolarize cycle.

Examples of industrial wood processes and applications in which electrical properties of wood are important include crossarms and poles for high voltage powerlines, utility worker's tools, and the heat-curing of adhesives in wood products by high frequency electric fields. Moisture meters for wood utilize the relationship between electrical properties and moisture content to estimate the moisture content.

Conductivity

The electrical conductivity of wood varies slightly with applied voltage and approximately doubles for each temperature increase of 10°C (18°F). The electrical conductivity of wood (or its reciprocal, resistivity) varies greatly with moisture content, especially below the fiber saturation point. As the moisture content of wood increases from near zero to fiber saturation, electrical conductivity increases (resistivity decreases) by 10^{10} to 10^{13} times. Resistivity is about 10^{14} to 10^{16} Ω·m for ovendry wood and 10^3 to 10^4 Ω·m for wood at fiber saturation. As the moisture content increases from fiber saturation to complete saturation of the wood structure, the

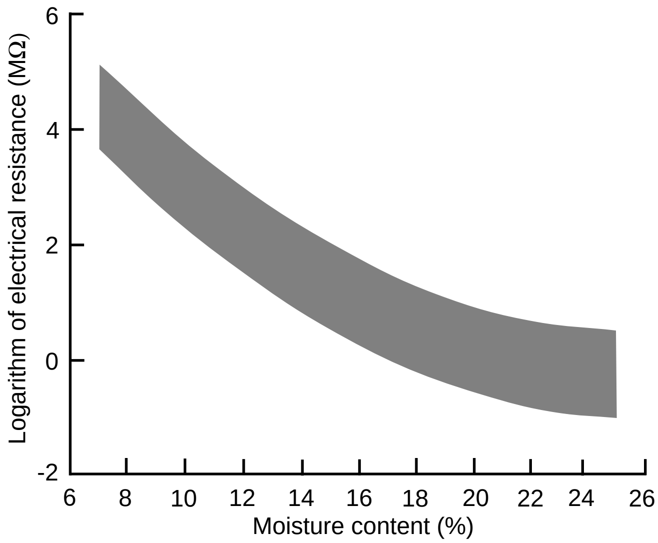

Figure 3–7. Change in electrical resistance of wood with varying moisture content levels for many U.S. species; 90% of test values are represented by the shaded area.

further increase in conductivity is smaller and erratic, generally amounting to less than a hundredfold.

Figure 3–7 illustrates the change in resistance along the grain with moisture content, based on tests of many domestic species. Variability between test specimens is illustrated by the shaded area. Ninety percent of the experimental data points fall within this area. The resistance values were obtained using a standard moisture meter electrode at 27°C (80°F). 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. The increase is small when the moisture content of the wood is less than about 8% but quickly increases as the moisture content exceeds 10% to 12%.

Dielectric Constant

The dielectric constant is the ratio of the dielectric permittivity of the material to that of free space; 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.

The dielectric constant of ovendry wood ranges from about 2 to 5 at room temperature and decreases slowly but steadily with increasing frequency of the applied electric field. It increases as either temperature or moisture content increases, with a moderate positive interaction between temperature and moisture. There is an intense negative interaction between moisture and frequency. At 20 Hz, the dielectric constant may range from about 4 for dry wood to near 1,000,000 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. The dielectric constant is larger for polarization parallel to the grain than across the grain.

Dielectric Power Factor

When a nonconductor is placed in an electric field, it absorbs and stores potential energy. The amount of energy stored per unit volume depends upon the dielectric constant and the magnitude of the applied field. An ideal dielectric releases all this energy to the external electric circuit when the field is removed, but practical dielectrics dissipate some of the energy as heat. The power factor is a measure of that portion of the stored energy converted to heat. Power factor values always fall between zero and unity. When the power factor does not exceed about 0.1, the fraction of the stored energy that is lost in one charge–discharge cycle is approximately equal to 2π times the power factor of the dielectric; for larger power factors, this fraction is approximated simply by the power factor itself.

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.

The power factor of wood is affected by several factors, including frequency, moisture content, and temperature. These factors interact in complex ways to cause the power factor to have maximum and minimum values at various combinations of these factors.

Coefficient of Friction

The coefficient of friction depends on the moisture content of the wood and the roughness of the surface. It varies little with species except for those species, such as lignumvitae, that contain abundant oily or waxy extractives.

On most materials, the coefficients of friction for wood increase continuously as the moisture content of the wood increases from ovendry 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 coefficient of friction decreases.

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

Coefficients of sliding 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

Radiation passing through matter is reduced in intensity according to the relationship

$$I = I_0 \exp(-\mu x) \qquad (3\text{–}13)$$

where I is the reduced intensity of the beam at depth x 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 ovendry 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 ovendry 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 ovendry 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.

In the previous discussions, moderate radiation levels that leave the wood physically unchanged have been assumed. Very large doses of γ rays or neutrons can cause substantial degradation of wood. The effect of large radiation doses on the mechanical properties of wood is discussed in Chapter 4.

References

ASHRAE. 1981. American Society of Heating, Refrigeration, and Air-Conditioning Engineers handbook, 1981 fundamentals. Atlanta, GA: American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

ASTM. 1997. Standard methods for testing small clear specimens of timber. ASTM D143. West Conshohocken, PA: American Society for Testing and Materials.

Beall, F.C. 1968. Specific heat of wood—further research required to obtain meaningful data. Res. Note FPL–RN–0184. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

James, W.L. 1975. Electric moisture meters for wood. Gen. Tech. Rep. FPL–GTR–6. Madison WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Kleuters, W. 1964. Determining local density of wood by beta ray method. Forest Products Journal. 14(9): 414.

Kollman, F.F.P.; Côté, W.A., Jr. 1968. Principles of wood science and technology I—solid wood. New York, Springer–Verlag New York, Inc.

Kubler, H.; Liang, L.; Chang, L.S. 1973. Thermal expansion of moist wood. Wood and Fiber. 5(3): 257–267.

Kukachka, B.F. 1970. Properties of imported tropical woods. Res. Pap. FPL–RP–125. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Lin, R.T. 1967. Review of dielectric properties of wood and cellulose. Forest Products Journal. 17(7): 61.

McKenzie, W.M.; Karpovich, H. 1968. Frictional behavior of wood. Munich: Wood Science and Technology. 2(2): 138.

Murase, Y. 1980. Frictional properties of wood at high sliding speed. Journal of the Japanese Wood Research Society. 26(2): 61–65.

Panshin, A.J.; deZeeuw, C. 1980. Textbook of wood technology. New York: McGraw–Hill. Vol. 1, 4th ed.

Simpson, W.T., ed. 1991. Dry kiln operator's manual. Agric. Handb. 188. Washington, DC: U.S. Department of Agriculture, Forest Service.

Simpson, W.T. 1993. Specific gravity, moisture content, and density relationships for wood. U.S. Department of Agriculture Gen. Tech. Rep. FPL–GTR–76. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Skaar, C. 1988. Wood–water relations. New York: Springer–Verlag. New York, Inc.

Stamm, A.J.; Loughborough, W.K. 1935. Thermodynamics of the swelling of wood. Journal of Physical Chemistry. 39(1): 121.

Steinhagen, H.P. 1977. Thermal conductive properties of wood, green or dry, from –40° to +100°C: a literature review. Gen. Tech. Rep. FPL–GTR–9. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

TenWolde, A., McNatt, J.D., Krahn, L. 1988. Thermal properties of wood panel products for use in buildings. ORNL/Sub/87–21697/1. Oak Ridge, TN: Oak Ridge National Laboratory.

Weatherwax, R.C.; Stamm, A.J. 1947. The coefficients of thermal expansion of wood and wood products. Transactions of American Society of Mechanical Engineers. 69(44): 421–432.

From
Forest Products Laboratory. 1999. Wood handbook—Wood as an engineering material.
Gen. Tech. Rep. FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service,
Forest Products Laboratory. 463 p.