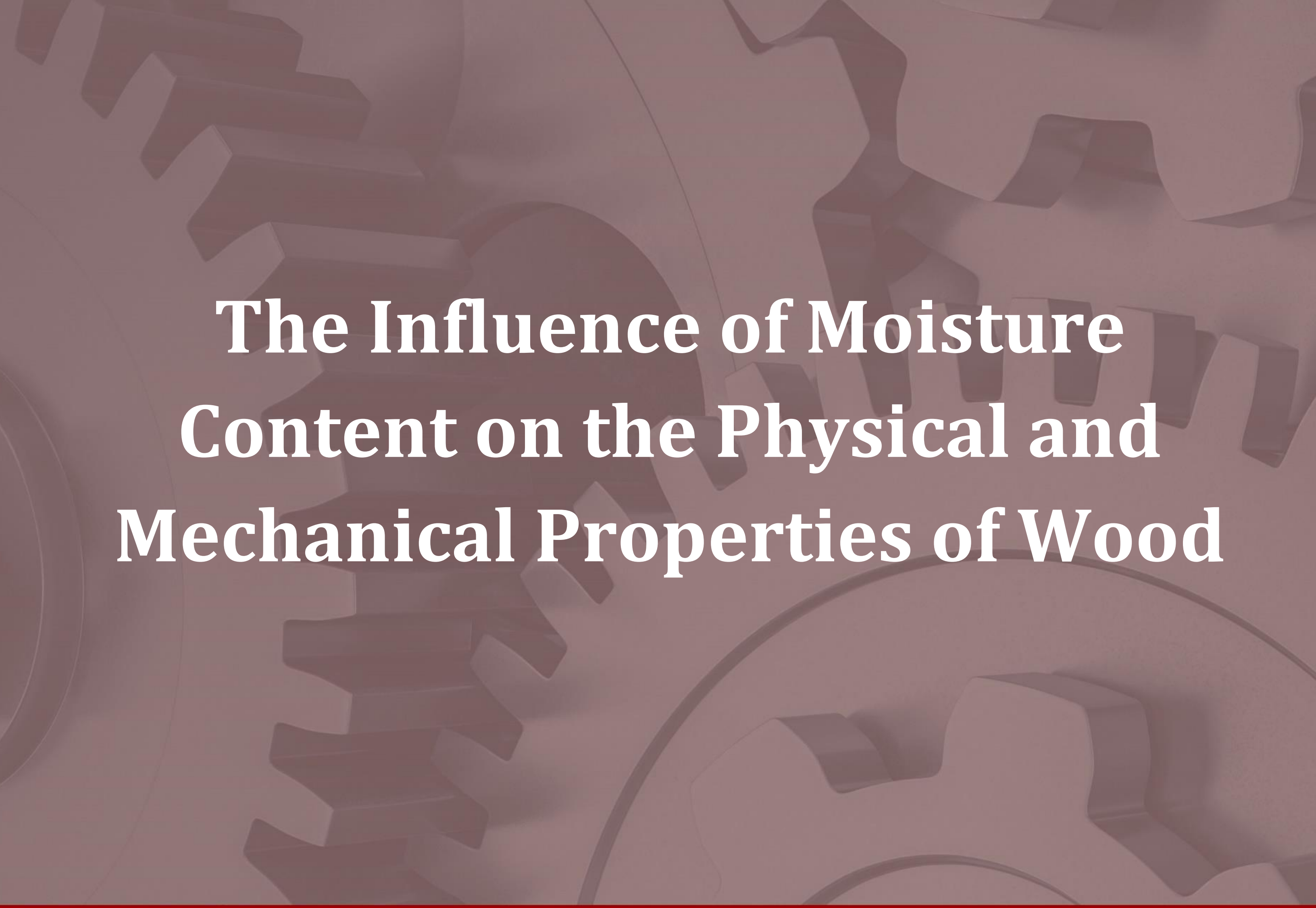

The Influence of Moisture Content on the Physical and Mechanical Properties of Wood

An Online Continuing Education Course for Engineers

Course Number: S-2013

Credit: 2 Hours / 2 PDH / 2 CPD

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Introduction

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 course 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 course 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 (Me) is usually expressed as a percentage and can be calculated from

$$\mathrm{MC} = \frac{m_{\mathrm{water}}}{m_{\mathrm{wood}}}(100\%) \qquad (1)$$

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

$$\mathrm{MC} = \frac{m_{\mathrm{wet}} - m_{\mathrm{dry}}}{m_{\mathrm{dry}}}(100\%) \qquad (2)$$

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

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

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

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, MC_{fs} Operationally, 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 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.

Conceptually, fiber saturation distinguishes between the two ways water is held in wood. However, in actuality, a more gradual transition occurs between bound and free water near the fiber saturation point. Within a piece of wood, in one portion all cell lumina may be empty and the cell walls partially dried, while in another part of the same piece, cell walls may be saturated and lumina partially or completely filled with water. Even within a single cell, the cell wall may begin to dry before all water has left the lumen of that same cell.

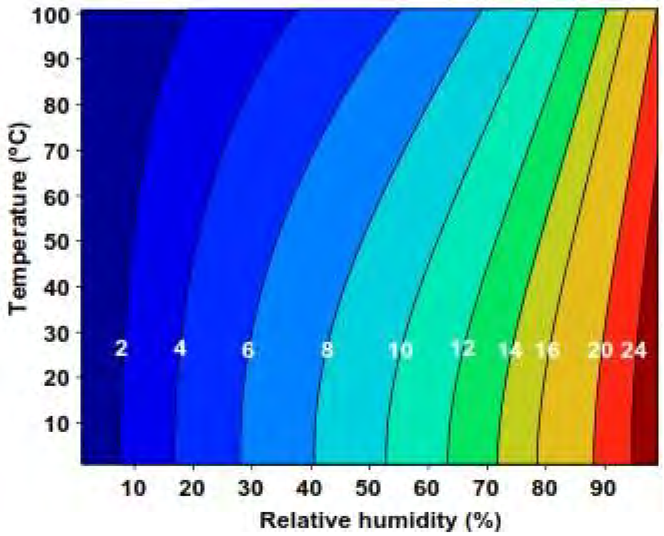

Figure 1. Equilibrium moisture content of wood (labeled contours) as a function of relative humidity and temperature.

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 ovendry mass and green volume-see section 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

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

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

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

Water Vapor Sorption

When wood is protected from contact with liquid water and shaded from sunlight, its moisture content below the fiber saturation point is a function of both relative humidity (RR) 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. The objective of wood drying is to bring the moisture content close to the expected value that a finished product will have in service.

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 is shown in Figure 1 and Table 2. For most practical purposes, the values in Table 2 may be applied to wood of any species. These values have been calculated from the following equation:

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

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

For temperature T in -C,

$$W = 349 + 1.29T + 0.0135T^2$$
$$K = 0.805 + 0.000736T \quad 0.00000273T^2$$
$$K_1 = 6.27 \quad 0.00938T \quad 0.000303T^2$$
$$K_2 = 1.91 + 0.0407T \quad 0.000293T^2$$

For temperature T in -F,

$$W = 330 + 0.452T + 0.00415T^2$$
$$K = 0.791 + 0.000463T \quad 0.000000844T^2$$
$$K_1 = 6.34 + 0.000775T \quad 0.0000935T^2$$
$$K_2 = 1.09 + 0.0284T \quad 0.0000904T^2$$

Simpson (1973) showed that this equation provides a good fit to EMC-RH-temperature data.

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 2. A desorption isotherm is measured by bringing wood that was initially wet to equilibrium with successively lower values of relative humidity. A resorption, or adsorption, isotherm is measured in the opposite direction (from the dry state to successively higher RR values). As wood is dried from the initial green condition below the fiber saturation point (initial desorption), the EMC is greater than in subsequent desorption isotherms (Spalt 1958). Furthermore, the EMC

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

Temperature		Moisture content (%) at various relative humidity values																		
(oC	(oF))	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 resorption (adsorption) is lower than for desorption. The ratio of adsorption EMC to desorption EMC varies with species, RH, and temperature, with a mean value of about 0.8 near room temperature (Stamm 1964, Skaar 1988). EMC values in Table 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 adsorption and desorption. The tabulated EMC values thus provide a suitable and practical compromise for use when the direction of sorption is not always known.

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 (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.

International Standard ISO 15148 (ISO 2002) describes a method for measuring the rate of water absorption. 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 (kg m^{-2} $s^{-1/2}$). Measured values of A_w for softwoods are in the range 10-16 g m^{-2} $s^{-1/2}$ in the longitudinal direction and 1-7 g m^{-2} $s^{-1/2}$ in the transverse directions (IEA 1991; Kumaran 1999, 2002).

The liquid water diffusivity D_w (m^2 s^{-1}) is a measure of the rate of moisture flow (kg m^{-2} s^{-1}) through a material

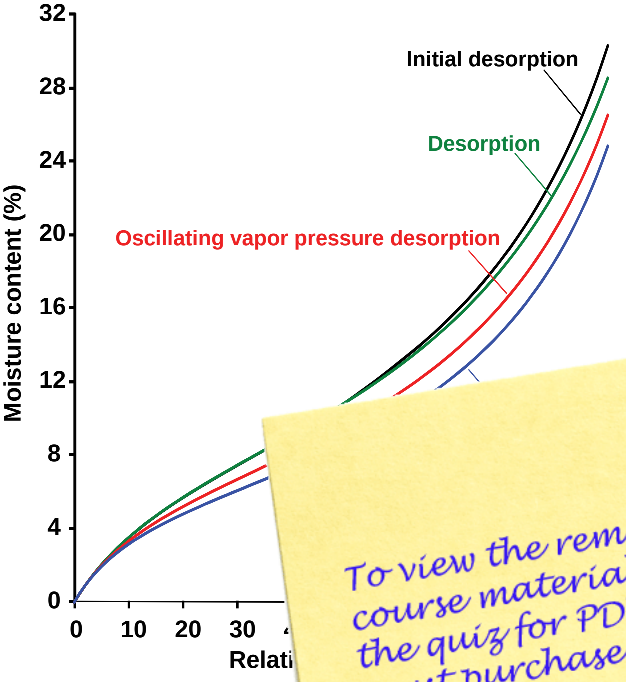

Figure 2. Moisture conten
ship for wood under adso
conditions.

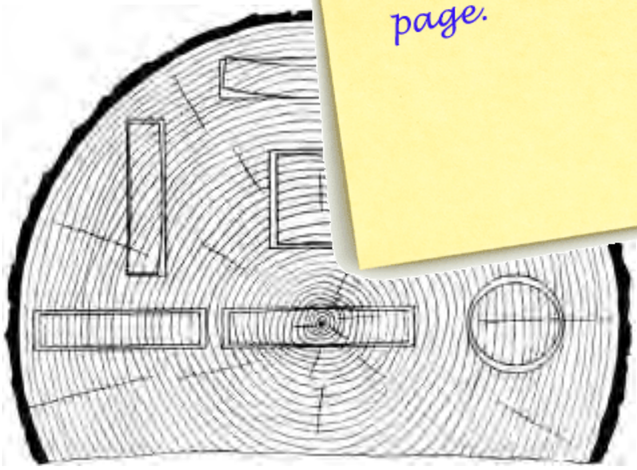

Figure 3. Characteristic shrinkage and distortion of flat, square, and round pieces as affected by direction of growth rings. Tangential shrinkage is about twice as great as radial.

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

$$D_w \approx \left(\frac{A_w}{c_{sat}}\right)^2 \qquad (6)$$

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

Dimensional Stability

Wood is dimensionally stable when 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 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
dim ity be understood and considered when a
be exposed to large moisture fluctuations

ensional stability, wood is an anisotropic
swells) most in the direction of the an-
ngentially), about half as much across
nd only slightly along the grain (lon-
bined effects of radial and tangential
he shape of wood pieces because
rinkage and the curvature of annual
of distortion as a result of these ef-
igure 3.

etric Shrinkage

l to represent the average radial,
c shrinkage of numerous domestic
ibed in American Society for Test-
) D 143—Standard Test Meth-
nens of Timber (ASTM 2007).
d as a percentage of the green
le 3. Shrinkage values collect-
nd literature for selected imported species
are listed in Table 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 can affect shrinkage for some species. 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 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