4 Moisture Properties

Roger M. Rowell
USDA, Forest Service, Forest Products Laboratory,
and Biological Systems Engineering Department, University
of Wisconsin, Madison, WI

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Wood was designed by Nature over millions of years to perform in a wet environment. The wood structure is formed in a water-saturated environment in the living tree, and the water in the living tree keeps the wood elastic and able to withstand environmental strain such as high wind loads. We cut down a tree, dry the wood, and mainly use it in its dry state. But wood in use remains a hygroscopic resource. Wood's dimensions and mechanical, elastic, and thermal properties depend on the moisture content. Wood is also anisotropic, which means that its properties vary according to its growing direction (longitudinal [vertical or length direction], tangential [parallel to annual growth rings], and radial [perpendicular to the annual growth rings]). The mechanical properties depend very much on both moisture content and growing direction.

4.1 MOISTURE CONTENT OF GREEN WOOD

Moisture exists in wood as both liquid moisture in the cell voids or lumens (free water) and as moisture in the cell wall (bound water). The moisture content of green wood is defined as the total

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amount of free and bound water in the living tree. This is the maximum moisture content that can exist in a living tree. The moisture content of green wood varies from species to species and depends on the specific gravity. Lumen volume decreases as the specific gravity increases so the green moisture content decreases with increasing specific gravity. The maximum moisture content M_{max} can be calculated by the following:

$$\frac{M_{max} = 100(1.54 - G_{bsg})}{1.54\, G_{bsg}}$$

where G_{bsg} is the basic specific gravity based on oven-dry weight and green volume and 1.54 is the specific gravity of the wood cell wall.

Using this equation, the maximum possible moisture content of green wood would be 267% with a basic specific gravity of 0.3 and the minimum possible moisture content would be 44% with a basic specific gravity of 0.9. The density of most woods falls between 320 and 720 kg/m^3, although balsa is 160 kg/m^3 and some imported hardwoods are 1040 kg/m^3.

Table 4.1 shows some average moisture contents of green heartwood and sapwood of some common United States wood species. In some cases, the green moisture content is highest in heartwood and in others the sapwood is highest in moisture content.

TABLE 4.1
Average Moisture Content of Green Wood

	Moisture Content	
Species	**Heartwood**	**Sapwood**
Aspen	95	113
Basswood	81	133
Beech	55	72
Birch, Paper	89	72
Cedar, Incense	40	213
Cottonwood, Eastern	162	146
Douglas-fir, Coastal	37	115
Elm, American	95	92
Fir, Balsam	88	173
Hemlock, Western	85	170
Maple, Sugar	65	72
Oak, Red	83	75
Pine, Longleaf	31	106
Pine, Ponderosa	40	148
Pine, Sugar	98	219
Poplar, Yellow	83	106
Redwood, Old growth	86	210
Spruce, Sitka	41	142
Sweetgum	79	137
Sycamore, American	114	130
Walnut, Black	90	73

Source: USDA, 1999.

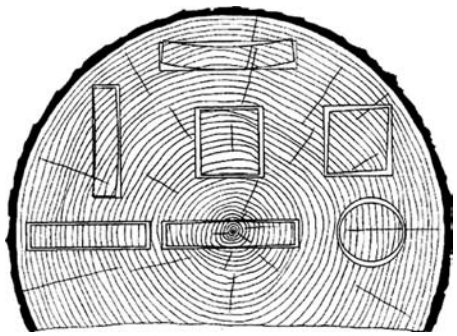


FIGURE 4.1 Shrinkage and distortion of wood upon drying.

4.2 FIBER SATURATION POINT

As water is lost in green wood, there is no change in the volume of the wood until it reaches the fiber saturation point (FSP). The FSP is defined as the moisture content of the cell wall when there is no free water in the voids and the cell walls are saturated with water. This point ranges from 20 to 50 percent weight gain depending on the wood species (Feist and Tarkow 1967). As moisture is removed below the FSP, the wood volume starts to shrink. As stated before, wood is anisotropic, so the shrinkage in wood is different in all three growing directions. Figure 4.1 shows the change in wood shape as a cross section of a log is dried below the FSP. It can be seen that, depending on where the piece of wood is located in the log, the wood will not only get smaller due to the loss of water but also will become distorted due to the anisotropic properties of wood. As will be discussed later, tangential shrinkage is about twice that of radial shrinkage, and longitudinal shrinkage, in most woods, is almost zero.

The shrinkage of wood upon drying depends on several variables, including specific gravity, rate of drying, and the size of the piece. As can be seen in Figure 4.1, the piece of wood cut from the center, left, and right middle is distorted the least (quarter sawing). Although quarter sawing is somewhat wasteful, it does result in minimum distortion in the cut lumber.

Table 4.2 shows the average shrinkage values for some common United States woods. It can be seen that most radial shrinkage values are less than about 6 percent, most tangential shrinkage values less than 10%, and most volumetric shrinkage values less than 15 percent.

To determine the approximate volumetric shrinkage that would occur at a moisture content greater than oven-dry but less than the FSP, the approximate volumetric value at a given moisture can be calculated using the following formula and using the data in Table 4.2:

$$\frac{S_m = S_o \times 30 - M}{30}$$

where

S_m is the volumetric shrinkage at a given moisture content
S_o is the total volumetric shrinkage
M is the moisture content

Table 4.2 does not include any longitudinal shrinkage (shrinkage parallel to the grain) because it is usually less than 0.2% for almost all United States species. If a piece of wood is cut near the center of a tree that contains a large amount of juvenile wood or a piece containing reaction wood, the longitudinal shrinkage from green to oven-dry can be as high as 2%.

TABLE 4.2
Average Radial, Tangential, and Volumetric Shrinkage

Species	Shrinkage from Green to Over-Dry Moisture Content		
	Radial	Tangential	Volumetric
Aspen	3.5	6.7	11.5
Basswood	6.6	9.3	15.8
Beech	5.5	11.9	17.2
Birch, Paper	6.3	8.6	16.2
Cedar, Incense	3.3	5.2	7.7
Cottonwood, Eastern	3.9	9.2	13.9
Douglas-fir, Costal	4.8	7.6	12.4
Elm, American	4.2	9.5	14.6
Fir, Balsam	2.9	6.9	11.2
Hemlock, Western	4.2	7.8	12.4
Maple, Sugar	4.8	9.9	14.7
Oak, Red	4.7	11.3	16.1
Pine, Longleaf	5.1	7.5	12.2
Pine, Ponderosa	3.9	6.2	9.7
Pine, Sugar	2.9	5.6	7.9
Redwood, Old growth	2.6	4.4	6.8
Spruce, Sitka	4.3	7.5	11.5
Sweetgum	5.3	10.2	15.8
Sycamore, American	5.0	8.4	14.1
Walnut, Black	5.5	7.8	12.8

Source: USDA, 1999.

The size of the cell cavities remains almost the same size during the loss of water in the cell wall (Tiemann 1944). The thickness of the cell wall decreases in proportion to the moisture lost below the FSP, but the size of the cell lumen remains approximately constant. If this relationship is constant, the volumetric shrinkage V_s of a wood with water soak specific gravity SP_w can be calculated as follows (Stamm and Loughborough 1942):

$$V_s = (M)\ (SP_w) \quad \text{or} \quad M = V_s / SP_w$$

This ratio should be the approximate FSP for most woods. The value of M for 107 hardwood species was 27 and for 52 softwood species the value was 26 (Stamm and Loughborough 1942).

4.3 EQUILIBRIUM MOISTURE CONTENT

As the green wood loses moisture, it does not change dimensions until the FSP is reached and after that the dimensions change respective to the relative humidity (RH) of the wood surroundings. When the wood is in equilibrium with the surrounding RH, the wood is defined as being at its equilibrium moisture content (EMC). The moisture content of wood is a dynamic property in that the moisture content of wood is constantly changing as the surrounding moisture content changes. When the wood stays at one RH for long periods of time, the wood will reach an equilibrium moisture content. Test results show that, for small pieces of wood at a constant RH, the EMC is reached in about 14 days. A larger wood member may take several weeks to reach its EMC. Wax and extractive content of wood can have a large effect on the length of time it takes for wood to reach its EMC.

TABLE 4.3
Equilibrium Moisture Content of Pine and Aspen

Species	Equilibrium Moisture Content at			
	30%RH	65%RH	80%RH	90%RH
Southern pine	5.8	12.0	16.3	21.7
Aspen	4.9	11.1	15.6	21.5

Table 4.3 shows EMC experimental values for southern pine and aspen at 30, 65, 80, and 90% RH.

4.4 SORPTION ISOTHERMS

A sorption isotherm for wood is defined as the sorption of water in wood at a defined temperature. Figure 4.2 shows the sorption isotherm for Douglas fir at 32ºC (Spalt 1958). It is a plot of moisture content (**M%**) vs. relative vapor pressure (**h** = relative humidity/100); note that as moisture is lost from green wood (**IN DES**—initial descending), it follows a different curve than both the rewetting curve (**ADS**—adsorbing) and the second redrying (**SEC DES**—secondary descending) curve. The second, third, fourth, and all subsequent redrying and the second, third, and subsequent rewetting will approximately follow the **SEC SEC** and **ADS** curves. The difference between these curves is referred to as sorption hysteresis for wood (Skaar 1984). Understanding of the difference in moisture content from wet to dry and from dry to wet is very important when it comes to mechanical properties of wood that will be discussed later. The adsorbing (A) curve is always lower than the desorbing (D) curve and the A/D ratio generally ranges from 0.8 and 0.9 depending on the relative humidity and wood species (Okoh and Skaar 1980). Most mechanical properties of wood are very dependent on moisture content and Figure 4.2 shows that at a given relative humidity of, for example, 60% (**h** = 0.6), the moisture content going from wet to dry is approximately 13%, whereas the same wood going from dry to wet would have a moisture content of approximately 10%. This difference of 3% can make a major difference in mechanical properties of the wood. Wax and extractive content of wood can have a large effect on the sorption isotherm.

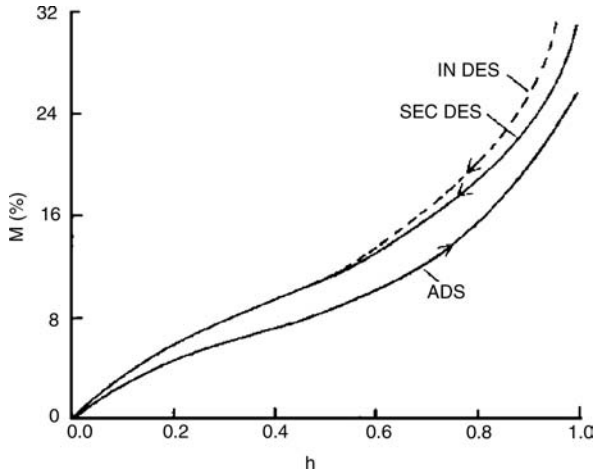


FIGURE 4.2 Sorption isotherm for wood.

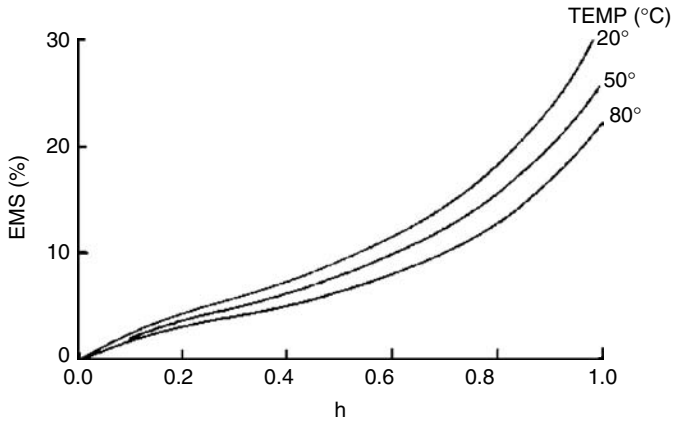


FIGURE 4.3 Effect of temperature on sorption isotherm.

4.4.1 Effect of Temperature on Sorption and Desorption of Water

Sorption isotherms for wood decrease with increasing temperature at temperatures about 0ºC. Figure 4.3 shows the effect of temperature on the sorption isotherm of wood (Skaar 1984). The desorption isotherm follows the same trend. Because temperature effects sorption and desorption of moisture in wood, EMC values must be determined at a single constant temperature.

4.5 SWELLING OF DRY WOOD IN WATER

Theoretically, it is possible to have absolutely dry wood, wood with a zero moisture content. In actual fact, wood with zero moisture content has never been achieved. When we talk about "oven-dry" (dried above 100ºC) wood, the actual moisture content is less than one percent but not zero. There is a small amount of water that is so tightly bound to wood that it is impossible to remove. Because of this, there is no such thing as the volume of zero moisture content wood. But, the amount of water in oven-dry wood is so small, that the water volume is considered to be negligible.

For wood to swell from the dry state, water or some other swelling agent must enter the cell wall. Entry may result from mass flow or diffusion of water vapor into the cell lumens and diffusion from there into the cell wall, or from a diffusion of bound water entirely within the cell wall. In most cases, both processes probably occur. Penetration by mass flow followed by diffusion into the cell wall is a much more rapid process than either vapor-phase or bound-water diffusion (Banks 1973).

Caulfield (1978) proposed a "zipper" model for the movement of water into the wood structure. That is, water moves through wood by forcing cell wall polymers apart as it moves deeper into the wood structure.

Wood is much more permeable in the longitudinal direction than in the radial or tangential directions. Because of this anisotropy, longitudinal flow paths are of major importance in the wetting of wood exposed to the weather (Miller and Boxall 1984). Wood is a hydroscopic resource, which means that the hydroxyl groups in the cell wall polymers are attracted to and form hydrogen bonds with environmental moisture. As water is added to the cell wall, wood volume increases nearly proportionally to the volume of water added (Stamm 1964). Swelling of the wood continues until the cell reaches the FSP, and water beyond the FSP is free water in the void structure and does not contribute to further swelling. This process is reversible, and wood shrinks as it loses moisture below the FSP. This dimensional instability restricts wood from many applications where movement of a material due to changes in moisture content cannot be tolerated.

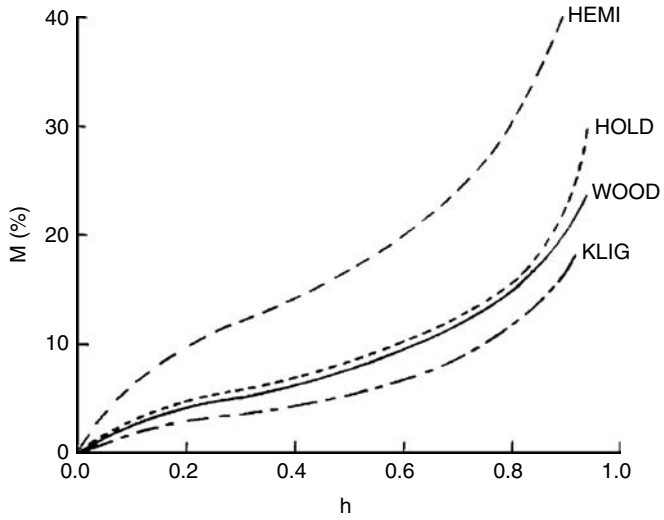


FIGURE 4.4 Sorption isotherms for wood cell wall components.

The amount of swelling that occurs in wood because of hygroscopic expansion is dependent on the density of the wood (Stamm 1964). The percent volumetric swelling V is a function of the dry density d (in g/cc) and the FSP (K_{fsp}, in cc/g) as shown in the following:

$$V = K_{fsp}d$$

This equation determines the approximate volumetric swelling of wood going from an oven-dry state to the FSP and the approximate volumetric shrinkage of wood going from the FSP to oven-dry. Deviations from this relationship usually occur in species high in natural extractives.

All of the cell wall polymers (cellulose, the hemicelluloses, and lignin) are hydroscopic. The order of hydroscopicity is hemicellulose (**HEMI**) > cellulose > lignin (**K LIG**), as shown in Figure 4.4 (Skaar 1984). The holocellulose isotherm is a combination of the hemicelluloses and cellulose polymers. The sorption of moisture by each cell wall polymer depends on not only its hydrophilic nature but also accessibility of water to the polymer's hydroxyl groups. Most, if not all, of the hydroxyl sites in the hemicelluloses are accessible to moisture and the same is probably true of the lignin. The noncrystalline portion of cellulose (approximately 40%) and the surfaces of the crystallites are accessible to moisture, but the crystalline part (approximately 60%) is not (Stamm 1964, Sumi et al. 1964).

4.6 DISTRIBUTION OF MOISTURE

According to the Dent sorption theory, water is added to the cell wall polymers in monolayers (Dent 1977). This theory is based on a modification of the BET model by Brunauer et al. (1938) that was based on a Langmuir model of 1918. The model also permits more than one layer of water on any particular sorption site. This means that when liquid water or water vapor comes into contact with wood, it does not concentrate in one spot but spreads out over the entire cell wall structure at equilibrium. Uneven swelling does occur when one part of the wood is wetter than another until equilibrium is reached.

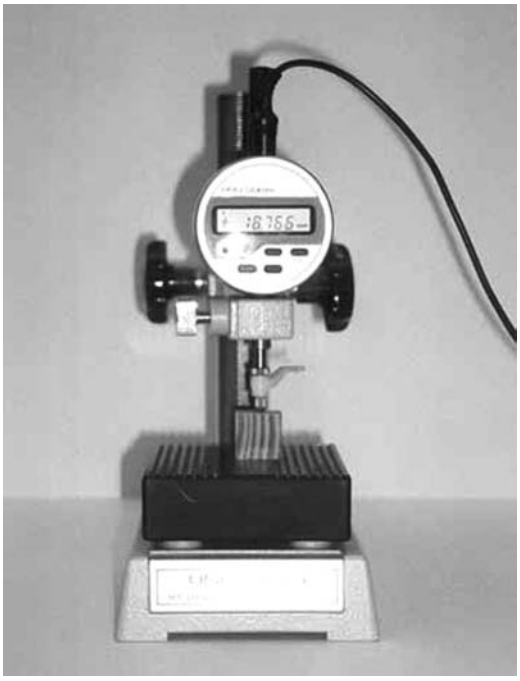


FIGURE 4.5 Measuring wood swelling using a flat-bed micrometer.

4.7 MEASURING SWELLING

There are several ways to measure swelling resulting from interaction with water or other solvents in wood. Some report volumetric swelling, which is a combination of radial, tangential, and longitudinal swelling, and some report just tangential swelling. Since tangential swelling is usually about twice that of radial, tangential swelling alone is representative of the swelling characteristics of each species.

In measuring the rate and extent of swelling in wood using a flat bed micrometer, it is best to cut specimens thin in the longitudinal direction for fast penetration of moisture into the wood with maximum tangential length (see Figure 4.5). It is critical that the tangential grain run parallel to the cut top and bottom edge. If the tangential grain is not parallel to the top and bottom edge, the specimen will go out of square when it swells and will not be measured accurately in the flat bed micrometer.

4.8 RATE OF WATER SORPTION AND ACTIVATION ENERGY

The rate of swelling of Sitka spruce wood at 23ºC is shown in Table 4.4. The specimen size was small (2.5 cm square), but it takes some time for water to penetrate into the wood structure. Table 4.4 shows that more than half of the final tangential swelling occured in the first 15 minutes of liquid water contact with the wood. Since the swelling rate depends on specimen size, the rate of swelling would be faster with a thinner specimen (in the longitudinal direction) but the extent of swelling at equilibrium would be the same. Tangential swelling was determined as follows:

$$\text{Tangential swelling} = \frac{(\text{Swollen dimension} - \text{Oven-dry dimension})}{\text{Oven-dry dimension}}$$

TABLE 4.4
Rate of Tangential Swelling of Sitka Spruce in Water at 23ºC

Time (minutes)	Tangential Swelling (%)
15	5.3
30	7.0
45	7.8
60	8.1
75	8.4
90	8.5
105	8.6
120	8.7
180	8.8
240	8.8
480	9.0
960	9.0

The rate of swelling of wood in water or other solvents is dependent on several factors, for example, hydrogen bonding ability, molecular size of the reagent, extractives content, temperature, and specimen size (Banks and West 1989). In the case of water, there is an initial induction period due to the diffusion of the water into the cell wall structure and then the water penetrates cell wall capillaries and moves from lumen to lumen in the fiber direction.

Using the data in Table 4.4, the swelling rate constant k can be derived from the slope of a plot of ln k vs. 1/T. From this data, the activation energy Ea can be calculated from the standard Arrhenius equation:

$$k = Ae^{-Ea/RT}$$

where
A = constant
R = gas constant
T = temperature (in Kelvin)

Table 4.5 shows the maximum tangential swelling of wood in water, the swelling rate (k), and the activation energy of swelling (Mantanis et al. 1994a) for Sitka spruce, Douglas fir, and sugar maple. Of these three species, Sitka spruce swells the fastest and has the lowest activation energy. The rate of swelling increased with an increase in temperature (see Table 4.6). The higher density hardwood had greater activation energies as compared to softwoods, which Stamm had found earlier (1964).

The presence of extractives also has a great effect on the rate of swelling of wood in water and other liquids. Stamm and Loughborough (1942) discuss two types of extractives in wood: extractives deposited in the coarse capillary structure and extractives deposited in the cell wall structure. The extractives deposited in the cell wall structure have a great influence on the rate of swelling. The effect of extractives on swelling rate as a function of temperature is shown in Table 4.6. Extractives were removed using 80% ethanol in water for 2 hours at room temperature. In the case of Sitka spruce, the swelling rate greatly increases with the removal of extractives but the removal of extractives from Douglas fir and sugar maple has less effect.

TABLE 4.5
Rate of Swelling, Maximum Tangential Swelling, and Activation Energy of Wood in Water

	Maximum Tangential Swelling (%)		
Temp (C)	**Sitka Spruce**	**Douglas Fir**	**Sugar Maple**
23	6.5	7.6	10.0
40	6.9	7.7	10.8
60	6.9	7.7	11.5
80	7.2	8.0	11.5
100	7.3	8.1	12.3
Swelling Rate, k			
23	1.3	0.3	0.3
40	3.3	0.9	1.1
60	6.5	1.8	3.6
80	10.8	4.7	6.6
100	14.8	6.9	7.6
Activation energy, A_e, kJ/mole	32.2	38.9	47.6

TABLE 4.6
Rate of Swelling and Activation Energy for Unextracted and Extracted Woods

	Sitka Spruce		Douglas Fir		Sugar Maple	
	Unextracted	**Extracted**	**Unextracted**	**Extracted**	**Unextracted**	**Extracted**
Max Tangential Swelling (%) at T (C)						
23	6.5	7.4	7.6	9.0	10.0	10.7
40	6.9	7.5	7.7	9.1	10.8	11.6
60	6.9	7.7	7.7	9.1	11.5	11.4
80	7.2	7.7	8.0	9.1	11.5	11.2
100	7.3	7.7	8.1	9.2	12.3	11.3
Swelling Rate, k, at T (C)						
23	1.3	7.2	0.3	0.2	0.3	0.9
40	3.3	14.9	0.9	1.2	1.1	4.0
60	6.5	25.6	1.8	1.4	3.6	7.1
80	10.8	32.4	4.7	3.2	6.6	16.7
100	14.8	36.2	6.9	3.4	7.6	20.7
Activation Energy, Ea (KJ/mole)	32.2	23.3	38.9	41.5	47.6	42.3

TABLE 4.7
Water-Repellent Effectiveness, Contact Angle, and Time for Contact Angle to Fall to 90°

Treating Solution	Concentration (%)	WRE (%)	Contact Angle (θ)	Time for θ to Fall to 90 (Min)
Alkyd resin	10	78	130	425
Paraffin wax	0.5			
Hydrocarbon				
Resin	10	64	131	416
Paraffin wax	0.5			
Rosin ester	10	68	136	460
Paraffin wax	0.5			

Source: Rowell and Banks, 1985.

4.9 CELL WALL ELASTIC LIMIT

The orientation of the cell wall polymers in the S_1 layer determines the extent of swelling of wood in water or other solvent. Swelling from the dry state to the water saturation state continues until the cross banding of the cell wall polymers in the S_1 layer restricts further swelling. This point is defined as the elastic limit of the cell wall. In many cases, data on swelling in solvents other than water is given relative to the swelling in water so that the value of water is set at a value of 1, 10, or 100 and all other solvents are reported above or below this value. Some solvents do swell wood greater than water due to several factors, including extractive removal, plasticization, softening, or solubilization of one or more of the cell wall polymers (usually lignin or hemicelluloses) (see Tables 4.7, 4.8, and 4.9).

4.10 SWELLING PRESSURE

The maximum swelling pressure of wood has been measured (Tarkow and Turner 1958). It was measured by inserting wooden dowels into steel restraining rings equipped with a strain gage. The wooden dowels of different densities were then wetted with liquid water and the swelling pressure was measured as a function of density. Extrapolation of the curve of swelling pressure vs. density to the density of the cell wall (1.5) gave a value of 91 MPa (13,200 psi). A theoretical value based

TABLE 4.8
Antiswell and Antishrink Efficiency of Wood Treatments

Treatment[a]	Antiswell Efficiency 1st wetting	Antishrink Efficiency 1st drying	Antiswell Efficiency 2nd wetting	Antishrink Efficiency 2nd drying
Methyl Methacrylate 65 WPG	15	20	13	20
Polyethylene Glycol	85	15	10	10
Phenol-formaldehyde	83	80	82	81
Acetic Anhydride 21 WPG	82	85	83	85

[a]WPG = weight percent gain.

TABLE 4.9
Volumetric Swelling Coefficients for Southern Pine Sapwood in Various Solvents

	V	V
Solvent	**120°C, 1 hour**	**25°C, 24 hours**
Methyl isocyanate	52.6[a]	5.1
n-Butylamine	15.5	15.2
Piperidine	13.3	0
Dimethyl solfoxide	13.3	11.7
Dimethyl formamide	12.8	12.5
Pyridine	11.3	13.1
Formaldehyde	12.3	12.3
Acetic anhydride	12.3*	1.5
Acetic acid	11.1	8.8
Aniline	11.0	0.5
Cellosolve	10.6	10.2
Methyl cellosolve	10.3	10.0
WATER	10.0	10.0
Methyl alcohol	9.0	9.3
Epichlorohydrin	6.9	5.9
Acrolein	6.7	7.0
1,4-Dioxane	6.5	0.6
Tetrahydrofuran	5.4	7.2
Propylene oxide	5.2	5.0
Acetone	5.1	5.6
Diethylamine	5.0	11.0
Acrylonitrile	4.6	4.5
Butylene oxide	4.1	0.7
Dichloromethane	3.8	3.3
Methyl ethyl ketone	3.6	5.0
N-Methyl aniline	2.6	0.8
Ethyl acetate	2.4	4.2
Cyclohexanone	2.3	0.5
N-Methylpiperidine	2.2	1.6
4-Methyl-2-pentanone	0.4	1.5
N,N-Dimethylaniline	0.3	0.5
Xylenes	0.1	0.2
Cyclohexane	0.1	0.1
Triethylamine	–0.1	2.1
Hexanes	–0.2	0.2

[a]Reaction occurred.

on an osmotic pressure theory gave a theoretical value of 158 MPa at room temperature. The difference between the actual and the theoretical values was thought to be due to hydroelastic factors. These factors are associated with the fact that restrained wood has a lower moisture content than unrestrained wood.

The best example of using the swelling pressure of wood to practical use goes back to the Egyptians. On a trip to Egypt in 2001, the author saw the evidence first hand. On the edge of a shear granite cliff, holes about 15 cm long, 5 cm wide and 10 cm deep had been chiseled into the rock. Dry wooden wedges the size of the cavities were driven into these holes. Water was then



FIGURE 4.6 Evidence of holes cut in wood to split the rock (Egypt 2001).

poured onto the dry wood and allowed to swell. The swelling pressure caused the granite to split down the chain of holes resulting in a giant obelisk or other large building blocks. Figure 4.6 shows the series of holes that were chiseled into a large rock and Figure 4.7 shows the result of the splitting process.

4.11 EFFECTS OF MOISTURE CYCLES

Drying and rewetting causes increases in both the rate of swelling and the extent of swelling. The degradation and extraction of hemicelluloses and extractives as well as some degradation of the cell wall structure during wetting, drying, and rewetting cycles results in more accessibility of water to the cell wall. This is especially evident in hot or boiling water extraction of wood, where significant amounts of cell wall polymers can be lost. A similar effect occurs with wood that is exposed to high relative humidity in repeated cycles. Even though no cell wall polymers are extracted, repeated humidity cycles result in a slight increase in moisture content with each cycle.



FIGURE 4.7 Rock split by using the swelling pressure of wood (Egypt 2001).

4.12 EFFECTS ON VIBRATIONAL PROPERTIES

Moisture has a great effect on vibrational properties of wood. Because wood is a viscoelastic material, vibrational properties are highly dependent on the elasticity of, as well as the internal friction within, the cell wall polymers and matrix. One way of studying the viscoelastic properties of wood is through vibrational analysis. A simple harmonic stress results in a phase difference between stress and strain. The ratio of dynamic Young's modulus (E') to specific gravity (γ) (i.e., E'/γ = specific modulus) and internal friction (tangent of the phase angle, tan δ) measurements can be used to study the viscoelastic nature of wood. The E'/γ ratio is related to sound velocity and tan δ to sound absorption or damping within the wood.

The sorption of water molecules between the wood cell wall polymers acts as a plasticizer to loosen the cell wall microstructure. This affects the tone quality of wooden musical instruments because as moisture content increases, the acoustic properties of wood, such as specific dynamic Young's modulus and internal friction, are reduced or dulled (James 1964, Sasaki et al. 1988, Yano et al. 1993). The decrease in cohesive forces in the cell wall also enhances the deformation of wooden parts under stress.

In practical terms, as the moisture content of a wooden musical instrument, such as an oboe, clarinet, or recorder, increases, the quality of the sound, the brightness of the tone, and the separation of sound between notes decreases.

4.13 EFFECTS ON BIOLOGICAL PROPERTIES

The ability of microorganisms to attack wood depends on the moisture content of the cell wall. The old saying, "dry wood does not rot," is basically true. Ten thousand year-old wood from tombs in China that has remained dry through the years is essentially the same wood today as it was when it was first used (Rowell and Barbour 1990). Termites may seem to attack dry wood, but, in fact, they bring their own moisture to the wood. White-rot fungi need the least water to attack, brown-rot fungi require more, and soft-rot fungi require the highest water content. But all of them require moisture at or near the FSP to be able to degrade wood (see Chapter 5).

4.14 EFFECTS ON INSULATION AND ELECTRICAL PROPERTIES

Thermal and electrical conductivity is very low in dry wood. Early log cabins were warmer in the winter and cooler in the summer due to the insulation properties of wood. Thermal conductivity increases with increasing moisture content. Heat transmission through dry wood is slow but heat transfer is much faster in moist wood using the water as the heat conduit.

The electrical resistance of wood is extremely sensitive to the wood's moisture content. Moisture meters that determine the moisture content of wood are based on this sensitivity. There is also a strong increase in resistance with a decrease in wood temperature. Moisture meters measure the resistance between pairs of pin electrodes driven into the wood to various depths. The meter is calibrated by using data obtained on a given species at room temperature. Meter readings are less reliable at moisture contents above about 25% and read high when used on hot wood and low on cold wood.

4.15 EFFECTS ON STRENGTH PROPERTIES

Changes in moisture content of the wood cell wall below the FSP have a major effect on the mechanical properties of wood (see Chapter 11). Mechanical properties change very little at moisture contents above the FSP. Mechanical properties increase with decreasing moisture content with compression parallel to the grain being the most affected.

4.16 WATER REPELLENCY AND DIMENSIONAL STABILITY

The terms water repellency and dimensional stability are often used interchangeably as if they were the same. They are very different concepts. Water repellency is a rate phenomenon and dimensional stability is an equilibrium phenomenon (Rowell and Banks 1985). Confusion over these two concepts has led to some product failures in service, costing contractors or owners considerable money.

A water repellent treatment is one that prevents or slows down the rate that moisture or liquid water is taken up by the wood. Examples of water repellents include coating, surface applied oils, or lumen filling. A dimensional stability treatment is one that reduces or prevents swelling in wood no matter how long it is in contact with moisture or liquid water. Examples of dimensional stability treatments include bulking the cell wall with polyethylene glycol, penetrating polymers, or bonded cell wall chemicals, or cross-linking cell wall polymers (Rowell and Youngs 1981).

An attractive force exists between a solid and a liquid in contact with it. The net value of this force is governed by the relative magnitudes of the cohesive forces within the liquid and the adhesive forces generated between the liquid and solid. Where the adhesion of liquid to solid is equal to or greater than the cohesion of the liquid, a drop of liquid in contact with the solid spreads spontaneously. That is, the angle between solid and liquid at the solid/liquid/air interface, the contact angle, is zero. If the liquid/solid adhesion is less than the liquid cohesion, an applied liquid droplet does not spread but stands on the surface making a finite contact angle with it (see Figure 4.8). The magnitude of the contact angle increases as the magnitude of the adhesive forces relative to the cohesion of the liquid decreases (Adam 1963). These relationships are expressed algebraically as the Young equation:

$$\gamma_S = \gamma_{SL} + \gamma_L \cos\theta$$

where

γ_S = surface tension of the solid
γ_{SL} = liquid/solid interfacial tension
γ_L = surface tension of the liquid
θ = contact angle between liquid and solid

Wood is a capillary porous medium. The pore structure is defined by the lumina of the cells and the cell wall openings (pits) interconnecting them. The primary routes for liquid penetration into wood are by these two routes. Except in the case where the contact angle is equal to 90º ($\cos\theta = 0$), any liquid contained in a cylindrical capillary of uniform bore has a curved surface. The pressure difference (Pc), often called the capillary pressure, across this curved surface is given by the following relationship, derived from the Kelvin equation:

$$Pc = \frac{-2\gamma_L \cos\theta}{r}$$

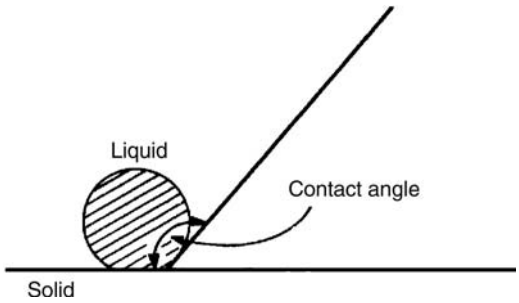


FIGURE 4.8 Contact angle of a water drop on wood.

where

γ_L = surface tension of the liquid
θ = contact angle between liquid and solid
r = capillary radius

The pressure gradient set up by the pressure difference acts in the sense that liquid is forced into the capillary spontaneously for values of θ less than 90º. Conversely, where θ is greater than 90º, external pressure larger than Pc must be applied to force liquid into the capillary. Although wood structure departs significantly from a simple cylindrical capillary model, the general principles of capillary penetration into its structure hold, and the magnitude of Pc remains functionally related to the cosine of the contact angle.

In systems involving water as the liquid phase, surfaces forming contact angles less than 90º are said to be hydrophilic, whereas those with a contact angle greater than 90º are said to be hydrophobic or water repellent.

The chemistry of surfaces giving rise to these properties is fairly well understood. Those surfaces presenting polar functional groups, especially those capable of forming hydrogen bonds with water, tend to be hydrophilic. In contrast, surfaces consisting of nonpolar moieties tend to be strongly hydrophobic.

Water repellent effectiveness (WRE) is also measured as a time dependent function of swelling as follows:

$$\text{WRE} = \frac{D_c - D_t \times 100}{D_c}$$

where

D_c = Swelling (or weight of water uptake) of control during exposure in water for t minutes
D_t = Swelling (or weight of water uptake) of treated specimen for the same t time.

For a given exposure time, considerable variation in WRE may result from variations in specimen geometry and in permeability to water of the wood species. To ensure good reproducibility of swelling or water uptake tests, conditions must be closely specified and carefully adhered to.

As was stated before, water repellents are applied to wood principally to prevent or reduce the rate of liquid water flow into the cellular structure and do not significantly alter the dimensions or water sorption observed at equilibrium. Usually the treatments involve the deposition of a thin layer of a hydrophobic substance onto external and, to some extent, internal cell lumen surfaces of wood. The measured WRE varies between 0 and 100 percent depending on the time the test specimens are exposed to water. In some cases, the time to reach equilibrium may be weeks, months, or even years but eventually, maximum swelling will be reached at equilibrium. Generally, the equilibrium moisture content is not altered by the water repellent treatments.

Water repellent treatments, such as impregnation with a wax, may fail due to a failure of the bond formed between the wax and the wood cell wall. This is usually due to degradation of the wood (Banks and Voulgaridis 1980). Wood flooring that has been treated with methyl methacrylate or a similar monomer and polymerized in situ also give a very high WRE. Moisture is physically blocked from entering lumens and penetration of the water must proceed by wicking through the cell wall. Moisture pickup can take a very long time so this type of treatment can be confused as a treatment for dimensional stability.

Table 4.7 shows the results of three resin/wax treatments on WRE, contact angle and the time it takes for the contact angle to fall to 90º. The data indicates that the hydrophobic effect (contact angle) only partly controls the water resistance of specimens treated with the resin/wax systems.

In contrast to water repellency, which is a measure of the rate of moisture pickup, dimensional stability is the measure of the extent of swelling resulting from ultimate moisture pickup. A variety of terms have been used to describe the degree of dimensional stability given to wood by various treatments. The most common term, antishrink efficiency or ASE, is misleading because it seems to apply to shrinking and not to swelling. The abbreviation is acceptable because ASE might also stand for antiswelling efficiency; this usage requires a statement whether the values were determined during swelling or shrinking, and, in addition because both are possible, whether they were obtained in liquid water or water vapor.

Changes in wood dimensions are a result of moisture uptake and can be measured as a single dimensional component, i.e., usually tangential alone, but can also be measured volumetrically taking into account all three dimensional changes. Calculations for dimensional stability are as follows:

$$\frac{S = V_2 - V_1 \times 100}{V_1}$$

where

S = Volumetric swelling coefficient
V_2 = Wood volume after humidity conditioning or wetting in water
V_1 = Wood volume of oven-dried wood before conditioning or wetting

Then

$$\frac{ASE = S_2 - S_1 \times 100}{S_1}$$

where

ASE = Antishrink efficiency or reduction in swelling resulting from a treatment
S_2 = Volumetric swelling coefficient of oven-dried after treatment
S_1 = Volumetric swelling coefficient of oven-dried before treatment

The test conditions for determining the efficiency of a treatment to reduce dimensional changes depend on the treatment as well as the application of the treated product. For a water-leachable treatment, such as polyethylene glycol, a test method based on water vapor is usually used. Humidity tests are also applied to products intended for indoor use. Nonleachable treatments and products intended for exterior use are usually tested in liquid water. For changes in wood dimensions resulting from changes in humidity, the test must be continued long enough to ensure that final equilibrium swelling has been reached.

For a series of humidity cycles, the specimens are placed back and forth in the different humidity conditions and the swelling coefficients are determined. The cycles can be repeated many times to show the efficiency of the treatment when exposed repeatedly to extremes of humidity.

If a liquid water test is used on a leachable chemical treatment, then a single water-swelling test may be run. Because the treating chemicals are leached out during the swelling test, cyclic water tests cannot be done.

Nonleachable treatments are usually tested for dimensional stability by water soaking. The swelling coefficients are determined on the first swelling, again on the first drying, and again on the second wetting. A series of water soaking and drying cycles give the best indication of the durability of the treatment (Rowell and Ellis 1978). This repeated water soaking and oven-drying test is very severe and may result in specimen checking and splitting. It should only be used to determine the effectiveness of treatments for outdoor applications under the harshest of conditions.

Since determination of dimensional stability is based on a comparison between an untreated and a treated specimen, it is critical that the treated specimen come from the same source as the control. Usually, specimens are cut from the same board, taking every other specimen for treatment and the other as controls. To illustrate this point, the S value for southern pine earlywood is 6 to 9, whereas southern pine latewood is 17 to 20. The average swelling coefficient for a sample, therefore, depends on the proportion of latewood and earlywood. If a control is used to compare with a treated sample that differs in percent of latewood, then the values obtained for ASE are nearly useless.

Treatments that have been used for improving dimensional stability include lumen filling (methyl methacrylate), non–cell wall bonded-leachable (polyethylene glycol), non–cell wall bonded-nonleachable (phenol-formaldehyde), and cell wall bonded (reaction with acetic anhydride). Table 4.8 shows the ASE values for these treatments. More information on the chemistry of these treatments is found in Chapter 14.

Complete dimensional stability of wood, i.e., ASE of 100, has only been accomplished through the process of petrification. Chemical treatments are unlikely ever to achieve this level of stabilization.

4.17 SWELLING IN WOOD COMPOSITES

The swelling that occurs in wood composites, such as flake-, particle-, or fiberboard, is much greater than in the wood itself. This is due to the release of compressive forces as well as normal wood swelling. The compressive forces are a result of the physical compression of the wood elements during pressing of the board. This type of swelling is known as irreversible swelling and is the release of the compressive forces during the first wetting of the composites. It is known as irreversible swelling because it is not reversible upon redrying. Reversible swelling also occurs during wetting, which is the swelling of wood elements as a result of moisture pickup. It is known as reversible swelling because the wood shrinks again as a result of redrying.

Most of the irreversible swelling occurs early in the wetting of a composite but the rate can be slow due to the presence of waxes or other chemicals added to retard the rate of moisture pickup.

4.18 SWELLING IN LIQUIDS OTHER THAN WATER

The maximum swelling of wood in various organic liquids is mainly influenced by three solvent properties: the solvent basicity, the molar size, and the hydrogen bonding capacity of the liquid. In addition to these are the extractives content, temperature, and specimen size. An increase in molecule size not only decreases the swelling rate but the swelling equilibrium is also decreased due to the larger molecule slow diffusion into the fine capillary structure of the wood. Swelling of wood in organic liquids is closely associated with the swelling of cellulose alone (Stamm 1935, 1964, Stamm and Tarkow 1950, West 1988, Banks and West 1989, Mantanis et al. 1994a,b).

Table 4.9 shows the decreasing volumetric swelling coefficient order of pine sapwood in various liquids at two different temperatures (Rowell 1984). Several organic liquids swell wood greater than water. It is believed that this is due to a partial softening and solublization of the lignin in the cell wall that allows the wood to swell to a larger volume than in water (Stamm 1964). The largest swelling occurs in methyl isocyanates at 120ºC but this is due to a noncatalyzed reaction of the isocyanates with the wood cell wall hydroxyl groups forming a urethane bond. The reacted wood is much larger than the green volume resulting from cell wall rupture due to excess bonded chemical in the cell wall (see Chapter 14). Acetic anhydride also reacts with cell wall hydroxyl groups at 120ºC but there is no rupture of the cell wall occurring with this reaction.

Table 4.9 also shows swelling coefficients at a high temperature (120ºC) for one hour versus room temperature (25ºC) for 24 hours in various liquids. Solvents such as *n*-butyl amine, dimethyl sulfoxide, dimethylformanide, pyridine, formaldehyde, cellosolve, and methyl cellosolve swell wood to the same extent at both the high and low temperature. Piperidine, aniline, 1,4-dioxane, and butylene oxide swell wood to a much greater extent at the high temperature as compared to

TABLE 4.10
Maximum Tangential Swelling of Wood at 23°C, 100 Days

Solvent	Sitka Spruce	Douglas Fir	Sugar Maple
Water	8.4	8.8	10.6
n-Butylamine	14.5	16.4	19.3
Dimethyl sulfoxide	13.9	13.7	14.5
Pyridine	12.2	11.4	13.3
Dimethyl formamide	11.8	11.5	13.2
Formamide	11.2	9.6	16.8
2-Methylpyridine	10.8	11.6	11.9
Diethylamine	10.1	10.4	11.0
Ethylene glycol	9.5	9.1	10.4
Acetic acid	8.7	7.6	10.2
Methyl alcohol	8.2	7.3	8.7
Pyrrole	7.6	6.9	12.0
Butyrolacetone	7.2	7.5	9.6
Ethyl alcohol	7.0	6.3	6.9
Propionic acid	6.4	6.3	10.0
Acetone	5.0	4.6	7.1
Dioxane	5.7	7.5	8.4
Furfural	5.5	5.4	7.6
Methyl acetate	5.0	4.7	5.6
Propyl alcohol	4.9	5.1	5.3
Nitromethane	4.5	4.0	5.4
2-Butanone	4.3	4.1	5.1
Benzyl alcohol	2.9	2.6	8.9
Ethyl acetate	2.6	2.7	3.7
Propyl acetate	2.2	1.4	3.1
Ethylene dichloride	2.1	2.1	4.6
Toluene	1.6	1.5	1.5
Isopropyl ether	1.5	1.3	1.0
Chloroform	1.4	1.5	3.9
Dibutylamine	1.3	1.0	0.8
2,6-Dimethyl pyridine	1.3	1.0	6.3
Carbon tetrachloride	1.2	1.3	1.1
Benzaldehyde	1.0	0.9	2.1
Benzyl benzoate	1.0	0.9	1.0
Piperidine	0.9	0.2	4.3
Octane	0.9	0.7	0.6
Butylaldehyde	0.7	0.7	1.2
Nitrobenzene	0.5	0.4	0.7
Quinoline	0.4	0.3	0.6

the low temperature. Pyridine, tetrahydrofuran, and diethylamine swell wood to a greater extent at the low temperature as compared to the high temperature. Liquids such as trithylamine and hexanes cause a slight shrinkage of the wood at the high temperature.

Table 4.10 shows the maximum tangential swelling of Sitka spruce, Douglas fir, and sugar maple at 23ºC (Mantanis et al. 1994b). The three different woods swell to different extents in the same organic liquid. For example, 2-methyl pyridine swells sugar maple almost twice as much as it does Douglas fir. Sugar maple also swells greater than Douglas fir or Sitka spruce in acetic acid, pyrrole, propionic acid, benzyl alcohol, and 2,6-dimethyl pyridine.

TABLE 4.11
Maximum Tangential Swelling of Wood at 23ºC, 100 Days

	Sitka Spruce		Sugar Maple	
Solvent	**Unextracted**	**Extracted**	**Unextracted**	**Extracted**
WATER	5.9	6.3	9.5	10.6
n-Butylamine	11.1	13.3	17.7	19.6
Dimethyl sulfoxide	8.6	9.1	15.7	16.0
Pyridine	8.4	8.6	12.3	14.3
Dimethyl formamide	8.0	8.2	12.5	14.4
Formamide	8.1	8.0	13.3	13.9
2-Methylpyridine	7.8	10.8	11.6	13.2
Diethylamine	7.9	8.6	11.1	11.6
Ethylene glycol	6.9	7.1	10.0	10.8
Acetic acid	5.6	5.7	9.4	11.4
Methyl alcohol	5.8	6.1	9.2	10.2
Butyrolacetone	5.0	6.5	8.3	10.0
Ethyl alcohol	5.0	5.6	8.2	9.7
Propionic acid	4.1	5.3	7.9	9.5
Acetone	4.6	4.7	6.4	8.0
Dioxane	5.3	6.7	8.3	9.9
Furfural	4.0	5.7	7.6	9.4
Methyl acetate	3.7	4.2	5.2	6.9
Propyl alcohol	4.3	4.4	5.6	6.7
Nitromethane	2.7	2.8	5.3	6.6
2-Butanone	4.2	4.2	5.2	7.0
Ethyl acetate	2.8	3.1	4.0	6.1
Propyl acetate	1.1	2.0	2.3	4.6
Ethylene dichloride	2.2	2.1	3.3	4.6
Toluene	1.2	1.3	1.5	2.3
Isopropyl ether	1.7	1.9	1.4	1.8
Chloroform	2.6	3.4	4.3	6.4
Dibutylamine	0.8	0.8	0.5	0.5
2,6-Dimethyl pyridine	1.1	1.9	1.7	10.0
Carbon tetrachloride	1.1	1.5	1.4	1.7
Benzaldehyde	1.6	2.2	1.7	8.5
Benzyl benzoate	1.4	1.5	1.0	1.6
Piperidine	1.3	2.3	1.2	10.6
Octane	1.1	1.2	0.7	0.8
Butylaldehyde	0.4	0.6	1.0	2.2
Nitrobenzene	1.8	1.9	1.7	3.7

Table 4.11 shows the effects of the extractives on the maximum tangential swelling of Sitka spruce and sugar maple at 23ºC in various organic liquids (Mantanis et al. 1995a). Swelling is usually larger in the extracted wood. In the case of sugar maple in 2,6-dimethyl pyridine and piperidine, the swelling is much greater in the extracted wood as compared to the unextracted wood.

Table 4.12 shows the effect of the organic liquid basicity, hydrogen bonding potential, molar volume, and molecular weight on wood swelling (Mantanis et al. 1995b). Nayer (1948) and Stamm (1964) speculated that only hydrogen bonding ability alone could explain the relative swelling of wood in different organic liquids. There are, however, several significant exceptions to this correlation, including di-*n*-butyl amine, tri-*n*-butyl amine, and benzaldehyde (Mantains et al. 1994b).

TABLE 4.12
Properties of Swelling Solvents Affecting Wood Swelling

Solvent	Basicity[a] Kcal/mole	Hydrogen Bonding[b]	Molar Volume[c] (cc)	Molecular Weight
Butyl amine	57.0	16.8	98.80	73.10
Pyridine	33.1	18.1	80.40	79.10
Dimethyl sulfoxide	29.8	7.7	71.00	78.10
Dimethyl formamide	26.6	11.7	77.00	73.10
Acetic acid	25.0	9.7	57.10	60.00
Formaldehyde	24.0	21.5	39.90	45.04
Ethyl alcohol	20.0	18.7	58.50	46.07
Methyl alcohol	19.0	18.7	40.70	32.04
Ethylene glycol	18.0	20.6	55.80	62.10
WATER	18.0	39.0	18.05	18.02
Propyl alcohol	18.0	18.7	75.00	60.10
Propyl acetate	17.4	8.6	115.7	102.10
Ethyl acetate	17.1	8.4	98.50	88.10
Acetone	17.0	9.7	74.00	58.10
Methyl acetate	16.5	8.4	79.70	74.10
Dioxane	14.8	9.7	85.70	88.10
Chloroform	7.0	1.5	80.70	120.40
Nitrobenzene	4.4	2.8	102.30	123.10
Carbon tetrachloride	3.0	0.0	97.10	153.80
Toluene	3.0	4.5	106.40	92.10
Octane	0.0	0.0	162.50	114.20

[a]*Source:* Gutmann 1976.
[b]Wave number shift × 10, Crowley et al. 1966; Gory 1939, 1941.
[c]Robertson 1964, Handbook of Chemistry and Physics, 2003–4.

Swelling of wood in organic liquids can be predicted much more accurately using the four parameters of basicity, hydrogen bonding ability, molar volume, and molecular weight.

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Edited by
Roger M. Rowell



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