Table 8 Exponents in Hankinson's formula[a]

Property	*n*	A_{90}/A_0
Tensile strength	1.5–2	0.04–0.07
Compression strength	2–2.5	0.03–0.40
Bending strength	1.5–2	0.04–0.10
Modulus of elasticity	2	0.04–0.12
Toughness	1.5–2	0.06–0.10
Average exponent recommended for all properties	2.0	—

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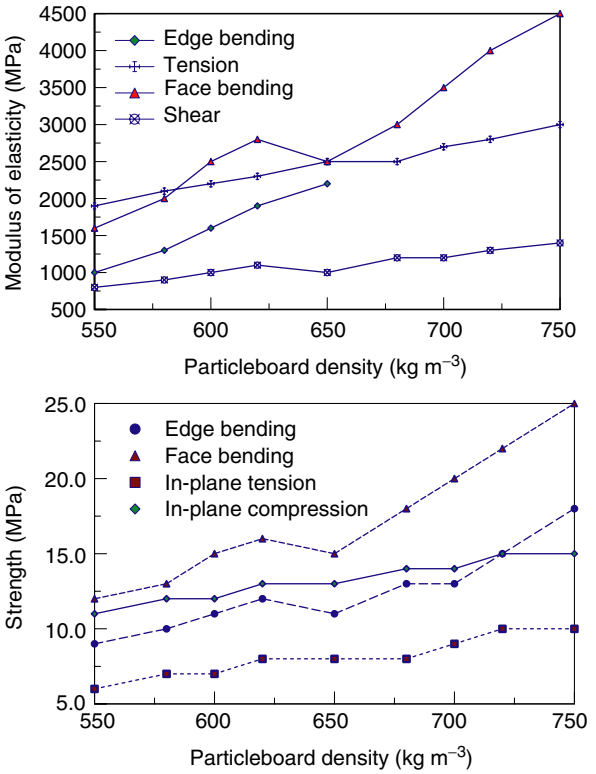


Figure 16 Effect of density on mechanical properties of particleboard. (Data from Niemz P (1993) *Physik des Holzes und der Holzwerkstoffe*. Weinbrenner, Germany: DRW-Verlag.)

features, chemical composition and wood mechanical properties is largely unknown.

Density significantly affects mechanical properties of wood composites and this is shown in **Figure 16**. All mechanical properties will increase with increased density with a linear trend.

See also: **Solid Wood Products**: Structural Use of Wood; Wood-based Composites and Panel Products. **Wood Formation and Properties**: Chemical Properties of Wood; Formation and Structure of Wood; Physical Properties of Wood. **Wood Use and Trade**: History and Overview of Wood Use.

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Physical Properties of Wood

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Introduction

This article addresses the fundamental physical properties of wood (sorptive, fluid transfer, thermal, electrical, and acoustical) that directly affect its processing and service characteristics such as sawing, drying, preservation, machining, gluing, insulation, and mechanosorptive behavior in service as a structural member or as simple panel or piece of furniture. Processing optimization and enhanced design of wood-based products is expected to result from a better understanding of how wood interacts with the environment.

Moisture Content

Wood is a porous, hygroscopic, anisotropic, non-homogeneous biopolymer of cellular structure. Water is always naturally found in freshly cut green wood since it is a necessary component of the living tree. Therefore, when wood is cut from a tree in the form of lumber, veneer, particles, or fibers, it always contains water, the oven-dry basis percentage of which is defined as the green moisture content (M_g). Generally speaking, moisture content, M, is defined as the weight of water in wood (W_w) divided by the oven-dry wood weight (W_o) times 100%:

$$M = \frac{W_w}{W_o} \times 100\% \qquad (1)$$

where W_o is obtained by placing the wood specimen in an oven at $103 \pm 2^{\circ}C$ for 24 h or until constant weight. The nominator of eqn [1] is then obtained by subtracting the W_o from the initial wood weight (W_i). The level of green moisture content is a function of wood species, type of wood (sapwood vs. heartwood, the former always at much higher M_g), and season of tree harvest, and for the temperate zone species it can range between 31% and 250%.

Water in wood can be divided into two types. The first is the water of constitution, which is the water included in the chemical structure of wood, and it is inherent to the organic nature of its cell walls. This type of water cannot be removed without modifying the chemical composition of wood, and the wood therefore losing its natural appearance. The second type comes in three different phases according to the moisture content level. The bound phase comprises the water molecules dissolved or adsorbed by the sorption sites (hydroxyls) mostly in the amorphous areas of the cellulose chains and the hemicelluloses. The free water, which is liquid water, is found in the cell lumina, and the vapor water is also found in the lumina when they are not completely saturated with free water.

In the hygroscopic range ($0\% \leq M \leq 30\%$), all of the water in wood is considered as bound, located within the cell wall. At about 30%, all sorption sites are considered to be saturated with water molecules and the moisture content is then called fiber saturation point (FSP) or M_{fsp}. Any additional water molecules taken up by wood normally appear as free water in the lumina and pits. It is below M_{fsp} where most of the physical and mechanical properties of wood are affected by moisture content, e.g., strength decreases, wood shrinks, electrical resistance increases, and the biodeterioration hazard diminishes as moisture content tends toward 0%.

Owing to its hygroscopic nature, freshly cut wood exposed to ambient conditions will tend to assume a moisture content which is in balance with the water vapor conditions in the surrounding atmosphere. This is a quite slow process (called sorption) that is highly dependent on the ambient temperature (T) and relative humidity (H). When green wood finally reaches the equilibrium state, two things have happened to its original water content: (1) it has lost a considerable amount of water (all of the free plus some bound water) by a process called desorption and (2) its final moisture content, which is then called equilibrium moisture content (M_e), is somewhere within its hygroscopic range. The speed of desorption is proportional to T and inversely proportional to H.

Throughout the hygroscopic range, the relationship between the equilibrium moisture content and relative humidity (or relative vapor pressure in the ambient environment) at constant temperature is represented by a sigmoid curve commonly called the sorption isotherm (**Figure 1**). The M_e values of a green piece of wood exposed to successively decreasing relative humidities (desorption) will always be higher than those of the same specimen exposed to successively higher humidities (adsorption), both cases under the same temperatures (**Figure 1**). This phenomenon is called hysteresis; and the area enclosed between the hysteresis loop represents the difference in free energy between adsorption and desorption.

It must be emphasized here that given enough time, the M_e value after exposure of green wood to the ambient environment always range between 0% and 30%. There is no free water in wood when it has reached equilibrium with the normal ambient environment. This M_e range is maintained during service unless wood comes into contact with liquid water.

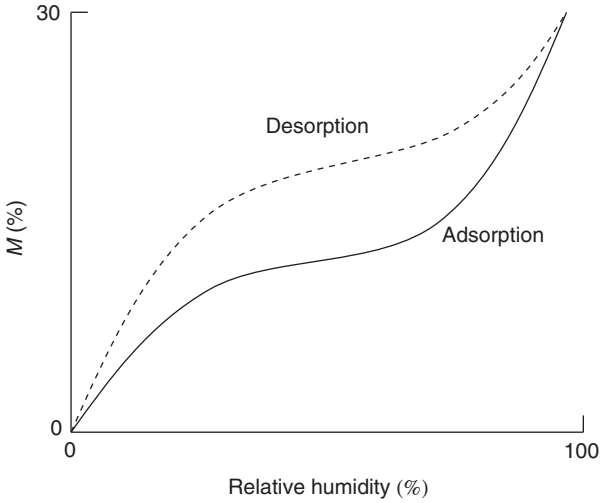


Figure 1 Typical moisture sorption isotherm for wood.

Density, Specific Gravity, and Porosity

Wood is made up of a mix of cells of a tubelike shape connected to each other in parallel and mostly oriented along the length of a tree. The cells are made of a thin wall and an empty area called the lumen. The existence of the cell wall material and the empty space in the lumen are the reasons why wood is classified as a porous material.

One important property that characterizes porous materials is density (ρ), defined as the amount of mass per unit volume and is expressed in kilograms per cubic meter. On the other hand, specific gravity (G) is the density of wood divided by the density of water and is dimensionless. Both ρ and G are used by the forest products industry interchangeably without considering the fact that both are highly dependent on moisture content and only in the case 0% moisture content (oven-dry or bone-dry) are numerically equal. This becomes evident from the equations that are used to calculate these two parameters:

$$\rho = \frac{W_M}{V_M}(\text{kg m}^{-3}) \tag{2}$$

$$G = \frac{W_o}{V_M \rho_w} \tag{3}$$

where W_M is the wood weight at moisture content M (kg), W_o is the oven-dry weight of wood (kg), V_M is the volume of wood at moisture content M (m^3), and ρ_w is the density of water ($1000\,\text{kg m}^{-3}$). It is apparent, that eqns [2] and [3] are equal only in the case of oven-dry wood ($M = 0\%$) and above that, their difference increases as M increases (ρ always greater than G). A typical plot of both as a function of moisture content is shown in **Figure 2**. Once G is known, ρ can then be calculated from

$$\rho = G(1 + 0.01M)\rho_w \tag{4}$$

In industry, G is occasionally referred to as basic density. When knowing the specific gravity at one moisture content (M_1), we can calculate the specific gravity at another moisture content (M_2) by

$$G_2 = \frac{G_1}{1 + 0.01(M_2 - M_1)G_1} \tag{5}$$

valid only over the hygroscopic range.

The values for G of temperate zone hardwoods at 12% moisture content ranges between approximately 0.35 and 0.78, and for softwoods, between 0.34 and 0.62. The growth characteristics and age of trees within the same species and the location of wood also affect these values horizontally and vertically within the same tree. Density is a very important physical property since it directly affects dimensional changes, and mechanical, electrical, and acoustical properties, and furthermore the drying and machining characteristics of wood and wood-based products.

Porosity (V_a) is a number between 0 and 1 that indicates the fraction of void volume in wood. For example, a V_a that is equal to 0.6 indicates that $1\,m^2$ of wood is made up of $0.4\,m^3$ of solid cell-wall material and $0.6\,m^3$ of empty space (void volume) due to lumen and pit capillaries. Porosity is an important property because it helps with the estimation of the amount of liquids that can be introduced into the material for protection or for creating polymer-impregnated wood. It also provides an indirect indication of the ease of fluid flow through wood and of the thermal and acoustical insulation properties of wood.

Deriving from its definition, porosity is directly affected by density and moisture content their relationship given by

$$V_a = 1 - G(0.653 + 0.01M) \tag{6}$$

which is valid for all moisture contents above and below M_{fsp}. At full saturation of wood (all lumina are fully saturated with a liquid), porosity is equal to zero.

One of the highest porosity temperate-zone softwoods is northern white cedar with a V_a value of 0.77 and one of the lowest porosity softwoods is longleaf pine with a V_a value of 0.52. For hardwood, these values are 0.73 for black cottonwood and 0.40 for true hickory.

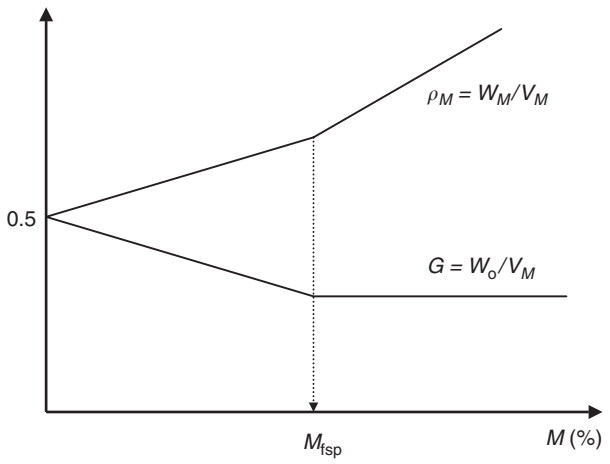


Figure 2 Change of wood density and specific gravity below and above the fiber saturation point.

Dimensional Changes (Hygroexpansion)

Wood is a very unstable material when it gains or loses water molecules as a result of changes in

ambient relative humidity and temperature. This is because the sorbed water molecules are mainly located in the amorphous areas of the microfibrils forming hydrogen bonds with the free hydroxyls (sorption sites). If water leaves wood because the air is quite dry, the cellulose chains tend to move closer to each other and this results in a reduction of the wood volume, i.e., shrinkage. The opposite phenomenon, adsorption, will therefore result in wood swelling.

Since the type of water that causes dimensional changes is bound water, this phenomenon is a characteristic of moisture content changes only in the hygroscopic range. Above M_{fsp}, free water accumulates in the wood pores and does not contribute to further separation of the amorphous chains and consequently, dimensional changes.

The amount of total volumetric swelling (V_{sw}) and shrinkage (V_{sh}) of wood over the hygroscopic range is a strong function of its specific gravity and moisture content and can be calculated from the following equations by assuming $M_{fsp} = 30\%$:

$$V_{sw} = 30G_o \tag{7}$$

$$V_{sh} = 30G_{fsp} \tag{8}$$

and between two moisture contents within the hygroscopic range:

$$V_{sw} = G_1(M_2 - M_1) \tag{9}$$

$$V_{sh} = G_2(M_2 - M_1) \tag{10}$$

The volumetric swelling (V_{sw}) and shrinkage (V_{sh}) between two moistures within the hygroscopic range can be calculated from the following equations:

$$V_{sw}^T = 2/3G_1(M_2 - M_1) \quad \text{and} \quad V_{sw}^R = 1/3G_1(M_2 - M_1) \tag{11}$$

$$V_{sh}^T = 2/3G_2(M_2 - M_1) \quad \text{and} \quad V_{sh}^R = 1/3G_2(M_2 - M_1) \tag{12}$$

where the superscript T denotes tangential direction and R denotes radial direction.

The anisotropic behavior of wood is evident when examining the total linear dimensional changes over the hygroscopic range. The total linear swelling from 0% to 30% moisture content is about 0.1% to 0.3% whereas the radial swelling ranges between 3% and 6% and the tangential between 6% and 12%. It is obvious that wood swells and shrinks very little in the longitudinal direction due to the same direction microfibrillar orientation, a trend that is not observed in the transverse direction (tangential and radial). Furthermore, there is a relationship of 2 to 2.5 between radial and tangential dimensional changes due to the presence of rays (one of the most accepted theories) that are restraining dimensional movement in the former direction. Abnormal and juvenile wood exhibit different levels of swelling and shrinkage, the latter exhibiting excessive longitudinal changes.

Dimensional instability is a major problem with wood that is exposed to wide variations of ambient relative humidity or it is in direct contact with liquid water. This can cause, in combination with anisotropicity, shape distortions and internal stresses that can manifest themselves as fissures through the structure of the wood. This problem can be avoided by dimensional stabilization, namely, the introduction of chemicals that introduce stability to wood at the microscopic level or by alteration and reduction of its hygroscopic nature and water affinity. Both methods have their advantages, disadvantages, and associated costs, and are mostly used for small-sized wood articles and specialty products. Examples of these stabilization processes are coating with film-forming finishes, heat treatment under vacuum or nitrogen, bulking with polyethylene glycol, acetylation, and formaldehyde crosslinking.

Fluid Flow through Wood

In drying and chemical treatment of wood (preservation, stabilization, veneer bolt steaming, pulping), we always have to deal with the flow of fluids (liquids and gases) to the surface of a timber or bolt from either its center or from the outside. In this case, the fluid is transferred mainly under a pressure differential through the interconnected void space of wood. It is important to emphasize here that although porosity is a measure of the scale of void volume in wood, high porosity does not suggest high flow rates. The voids must be connected to each other for this to happen; in other words, the pits should be 'open' to allow fluid flow from one lumen to the next. There are many examples where wood species with very high porosity value have a very low tolerance to fluid flow (refractory species).

Darcy's law governs the flow of liquids and gases through wood and the equations that describe this process under steady-state conditions are:

$$k_l = \frac{VL}{tA\Delta P}\left(\mathrm{m}^3(\text{liquid})/\mathrm{m\,Pa\,s}\right) \tag{13}$$

$$k_g = \frac{VL}{tA\Delta P}\left(\frac{P}{\overline{P}}\right)\left(\mathrm{m}^3(\text{gas})/\mathrm{m\,Pa\,s}\right) \tag{14}$$

where k_l and k_g are the superficial permeability coefficients to liquids and gases, respectively; V is the

volume of flow (m^3); L is the length of wood (m); t is time (s); ΔP is the pressure drop across wood (Pa); and $\bar{P}$ is average pressure between the two ends of wood (Pa). The superficial permeability coefficient is a measure of how fast fluid will flow through various wood species, but as it can be seen in eqns [13] and [14], it is highly affected by the compressibility of the fluid (gases vs. liquids). A better way of expressing permeability levels is by excluding the effect of the fluid and converting this property to one that is only affected by the structure of wood, i.e., specific permeability (K), which is calculated by:

$$K = \mu_l k_l = \mu_g k_g \qquad (15)$$

measured in $m^3\,m^{-1}$, where μ is the viscosity of the measuring fluid (Pa s). It is obvious from eqn [15] that K is independent of the type of measuring fluid and once the superficial permeability is measured by, e.g., dry air the specific permeability can then be calculated.

Although Darcy's law is mainly used to measure the permeability coefficient of various species so that fluid flow under different pressures can be predicted, it must be emphasized here that the law applies to laminar flow which is not always the case in wood. Further to laminar or viscous flow, in wood with such small pore sizes, we may have turbulent flow, nonlinear flow due to kinetic energy losses at the entrance of short capillaries (i.e., pits), and slip flow or Knudsen diffusion due to mean free path of gases being larger than the size of a pore (i.e., margo membranes). Total levels of volumetric fluid transfer can then be a combination of two or more of the above types of flow.

Permeability is also a physical property that is greatly affected by the anisotropic nature of wood. Longitudinal permeability coefficients are 15 to 50 000 times larger than the transverse ones due to the orientation of the wood fibers. Not much difference exists between radial and tangential direction; however, the K values of the former are slightly higher due to the extra flow path provided by the rays. Sapwood is normally more permeable than heartwood and the species anatomy will also affect K. An example very commonly cited is the difference between red oak and white oak. Both have the same density and porosity, but red oak is more permeable by a factor of 10 000 due to the lack of tyloses which are very pronounced in white oak and greatly reduce fluid flow.

Aspiration and embolism are two phenomena that also reduce permeability. The former is the result of moving the torus/margo system of the bordered pits due to capillary forces during drying and permanently attaching them by hydrogen bonds to the cell wall thus closing any capability of communication between two adjacent lumina. The latter is the result of air bubbles plugging the pits thus not allowing further fluid flow through them. Both significantly reduce the value of K and hence reduce the uptake of liquid preservatives and pulping chemicals during wood processing.

Molecular Flow (Diffusion)

Molecular flow or diffusion is a mass transfer mechanism involved in processes such as drying below M_{fsp}, mechanosorptive behavior of wood in service, and flow of moisture through wall systems, amongst others. The flow of molecules is by activation and random and spontaneous 'jumps' from one sorption site to another under the influence of a concentration (or moisture) gradient. Bound diffusion through the cell walls is quite pronounced during drying and sorption, but also diffusion through the lumina (inter-gas) is also an important component of the total diffusive flux.

Fick's law describes the process of steady-state diffusion as follows:

$$D = \frac{wL}{tA\Delta C} \qquad (16)$$

where D is the diffusion coefficient ($m^2\,s^{-1}$), w is the weight of fluid transferred (kg), and ΔC is the driving force for diffusion, namely, the concentration difference ($kg\,m^{-3}$), and the other terms are the same as in eqn [14]. Since moisture diffusion is probably the most important for wood processing, ΔC can be substituted in eqn [16] by ΔM, which in turn will make more sense from the calculation point of view. After this, eqn [16] becomes

$$D = \frac{100wL}{tA\rho_w G_M \Delta M} \qquad (17)$$

The gross wood diffusion coefficient is a composite of bound water and inter-gas vapor diffusion and it is highly affected by moisture content, temperature, species and type of wood, and last but not least, direction. Specifically, D is directly proportional to moisture content and temperature since higher moisture levels will swell the cell walls thus creating new paths of flow and the higher temperature will provide the extra thermal energy required for faster molecular movement. The wood species and type (heartwood vs. sapwood) have an effect on D through density and chemical composition, which affect accessibility to sorption sites. Finally, longitudinal D values are higher that transverse

ones at low moisture content values in the hygroscopic range, but the difference decreases by increasing moisture content toward the fiber saturation point.

It must be emphasized here that the process of diffusion is very slow when compared to bulk flow or heat transfer, and thus it is the controlling mechanism in drying where total processing time is concerned. Unfortunately, there are no reliable methods of improving the diffusion coefficient of wood at an industrial scale so that the drying speed of timbers can be increased. Attempts have been made with presteaming, hot water and surfactant solution dipping, ultrasonic field exposure, and freezing as possible methods with some success, more in improving permeability than diffusion.

Thermal Properties

Wood is always exposed to thermal loads either during processing, i.e., drying, heat stabilization, preservation, finishing, etc., or in service, i.e., as part of a wall system or a structural component, due to changing environmental temperatures. The amount of thermal energy absorbed and transferred through wood is affected by its thermal properties, namely, specific heat and thermal conductivity.

The specific heat of wood is defined as the amount of heat required to raise the temperature of 1 gram of wood by 1°C. The specific heat can be calculated from the following empirical formula:

$$c_p = \frac{1176 + 5859m}{1 + m} \qquad (18)$$

where c_p is the specific heat (kJ kg^{-1} K^{-1}); and m is the fractional moisture content between 0.05 and 0.30. Equation [18] is valid at $T = 30°C$. It is apparent that c_p is a strong function of moisture content, but it also is a function of temperature and wood species. Values of c_p will range between 1.3 and 1.9 (kJ kg^{-1} K^{-1}) at 30°C and between 0% and M_{fsp}.

Transfer of thermal energy through wood by conduction takes place by molecular interaction in the cell walls. Fourier's law describes steady-state flow of heat as follows:

$$K_\theta = \frac{HL}{tA\Delta T} \qquad (19)$$

where K_θ is the thermal conductivity coefficient (W m^{-1} K^{-1}); H is the quantity of heat transfer (J); and ΔT is the driving force, temperature difference, that drives heat flow (°C). K_θ will range between 0.08 and 0.17 W m^{-1} K^{-1} for oven-dry hardwoods and 0.08 and 0.14 W m^{-1} K^{-1} for oven-dry softwoods. For moisture content of 12%, the ranges are 0.10 to 0.21 W m^{-1} K^{-1} and 0.09 to 0.17 W m^{-1} K^{-1} for hardwoods and softwoods, respectively. For comparison, the K_θ of water is 0.59, and of dead air, 0.024 W m^{-1} K^{-1}.

Wood is a good thermal insulator; however, K_θ increases as wood density and moisture content increase. Furthermore, it is also affected by the anisotropic behavior of wood, that is, K_θ is greater in the fibers direction (longitudinal) than across (transverse) the timber.

Wood can also be a source of thermal when it burns (exothermic reaction) and this heat release per kg of wood is called heat of combustion (Q_c) measured in kJ kg^{-1}. During combustion, gases are released by thermal decomposition of wood that ignite and burn and ash is left as a solid byproduct. Spontaneous combustion can take place when wood is heated to 275°C in the presence of oxygen. This temperature is highly affected by the moisture content of wood, the species (anatomy), extractive types, and content, density, and wood dimensions. Fire resistance of wood can be increased by partially filling the lumina with special chemicals (fire retardants) that either increase its ignition point or delay its burning rate.

The Q_c value between species does not differ much and is about 19 600 kJ kg^{-1} when wood is oven-dry (no moisture present). When water is adsorbed in the wood cell walls, Q_c tends to decrease and when free water is present in the lumina ($M > 30\%$), Q_c normally drops to about 15 000 kJ kg^{-1}.

Continuous and long exposure of wood to elevated temperatures can also result in thermal degradation. This phenomenon is manifested by chemical breakdown of mostly hemicelluloses and cellulose with time and a loss of mass and strength. The rate of thermal degradation varies between wood species and increases with temperature and time of exposure. Controlled thermal exposure in the absence of oxygen can result in crosslinking reactions in the amorphous areas of cell walls, thus resulting in improved dimensional stability.

Electrical Properties

Wood, when dry, is an excellent electric insulator. However, this advantage diminishes when moisture content increases within the hygroscopic range and above the fiber saturation point (**Figure 3**). At a moisture content of 7%, the Douglas-fir's electrical resistance, a measure of the ease with which electric current flows through wood under the influence of a voltage differential, is 22 400 MΩ but it decreases to 0.60 MΩ at 24% moisture content. This dramatic

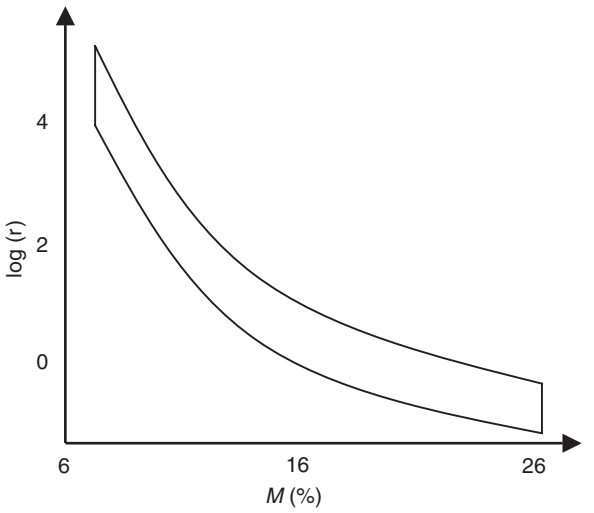


Figure 3 Curves of logarithm of electrical resistance against moisture content for most North American wood species.

drop as a function of moisture content is used by the industry to measure the amount of bound water present in wood with a specially designed piece of equipment call pin-type resistance moisture meter (or *M*-meter). The *M*-meter directly measures electrical resistance between the tips of two metal pins and through a conversion formula, calculates and displays the moisture content of the wood matter between the pins.

The electrical resistance is a strong function of species, temperature and fiber direction (anisotropicity). This is why when resistance *M*-meters are used, they need to be calibrated for species and temperature and also the pins should be placed parallel to the fiber direction. Density has no clear effect on electrical resistance.

When wood is placed within an alternating field, thermal energy is produced within the piece of wood due to the friction of the water molecules in the cell walls and lumina. The friction is the result of their dipolar nature and thus the rotation, vibration, and linear motion of ions when under an electric field of high frequency. This phenomenon is called dielectric heating. The amount of heat generated is predicted by the loss factor of wood that is one of the material's dielectric properties. The loss factor is strongly affected by moisture content (proportional relation), field frequency, species, and, to a lesser degree, wood temperature. This is a complicated dielectric property of wood that is quite difficult to measure directly. However, dielectric heating has served the wood processing industry in accelerated gluing and drying processes such as radio-frequency vacuum drying.

Wood also has piezoelectric properties, like quartz crystals, where electric polarization appears under compressive or tensile stress or mechanical strain develops under the application of electric field. The intensity of piezoelectricity in wood depends on its degree of crystallinity and the degree of orientation of crystallites. This phenomenon has been used in the development of nondestructive methods of evaluating local wood strain and the influence of knots, density, fiber angle, etc., on a dynamic system.

Acoustical Properties

The acoustical properties of wood relate to the production of sound with direct impact, and to the behavior of wood in relation to sound produced by other sources that is transmitted through air impacting wood in the form of sound waves.

Wood is seldom used as a direct source of sound. The pitch of sound produced is dependent on the frequency of the wood vibration. This frequency is a function of the wood dimensions, moisture content, density, and stiffness. When sound waves are produced by another source, they impact the surface of wood and a portion of their acoustic energy is absorbed by wood whereas the rest is reflected. Of the absorbed sound, some will be converted to thermal energy and some will be transmitted through the piece of wood. The density and thickness of the wood substrate and the frequency of the sound waves affect the amount of sound absorbed. The transmission of sound is quite fast, namely, 3500 to 5500 m s^{-1} in the longitudinal direction and 2300 to 3200 m s^{-1} in the transverse direction, as compared to 340 m s^{-1} through air and 1400 m s^{-1} in water. Sound velocity level is strongly affected by density, direction in relation to fiber, wood defects and abnormal growths, and moisture content.

Industry has used the strong relationship of sound transmission to various wood attributes in order to develop nondestructive evaluation techniques that estimate stiffness and strength of wood, internal decay in trees and timbers, fiber angle and the presence of juvenile and reaction wood, among other attributes, with variable level of success.

See also: **Tree Breeding, Practices**: Biological Improvement of Wood Properties. **Wood Formation and Properties**: Formation and Structure of Wood; Mechanical Properties of Wood; Wood Quality. **Wood Use and Trade**: History and Overview of Wood Use.

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Chemical Properties of Wood

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Introduction

The chemical properties of wood are inextricably associated with and dependent upon its chemical composition. Fortunately, the major wood components are not numerous, and with only minor variations are found across all woody species. The chemical behavior results from the interaction of the structural features known as functional groups with either other chemical entities or physical factors such as heat and light. After a description of the chemical components of wood including their relevant functional groups, the most important chemical interactions will be discussed.

Composition of Wood

The chief components of woody plant cell walls are cellulose, hemicelluloses, and lignin. In bark these structural components may be exceeded by suberins and phenolic acids. The final category of wood components is known as extractives. These materials are much less abundant, variable in structure or quantity, usually soluble, and often species or genus specific.

Cellulose

Cellulose is the chief cell wall component, and comprises 40–45% of the wood. It is a long chain polymer of glucose units linked together by glycosidic bonds, a type of acetal ether linkage (O–C–O–C). The other, and most important, functional group in cellulose is the hydroxyl (–OH). Each glucose unit in the chain has three free hydroxyl groups that are capable of reacting with others in a neighboring chain or with water to form hydrogen bonds (H–O–H—H–O–C). Unlike starch which is also a glucose polymer, but with an α-configuration leading to an amorphous structure, the β-configuration in cellulose leads to stiff and straight chains that can form highly ordered crystalline regions. Cellulose contains disordered or amorphous regions as well.

Hemicelluloses

Associated with the cellulose in the cell wall are carbohydrate polymers known as hemicelluloses. They consist for the most part of sugars other than glucose, both pentoses and hexoses, and are usually branched and of much lower molecular weight than cellulose. In softwoods they comprise 25–30% of the wood in decreasing abundance as mannose, xylose, glucose, galactose, and arabinose. In hardwoods the hemicelluloses account for 20–35% as xylose, mannose, glucose, and galactose. The functional groups as in cellulose are glycosides and hydroxyls, with the addition of acetyl ester groups formed by the reaction of acetic acid with hydroxyls.

Lignin

Lignin is the third major wood cell wall component (20–30%). It serves as a cement between wood fibers, as a stiffening agent within the fibers, and as a barrier to the enzymatic degradation of the cell wall. Lignins are three-dimensional network polymers of phenylpropane units. More than two-thirds of the linkages are ether bonds, the rest are carbon–carbon bonds. Some free phenolic hydroxyls are found on the phenyl groups, but most have been etherified with methanol to methoxyl. Softwood and hardwood lignins differ in methoxyl content and in the degree of crosslinking. Hardwood lignins have more methoxyls, but these groups block potential reactive sites and reduce crosslinking. There is evidence that covalent linkages exist between lignin and the hemicelluloses.

Bark Components

Bark fibers contain cellulose, hemicelluloses, and lignin, but in much lower concentration. The cellulose content may be as low as 20–30%. Two other components unique to bark, suberins and phenolic acids, account for this. Suberins consist of long-chain esters. Their content varies from 2–8% in pine, fir, and oak to 20–40% in birch, and 35–40% in cork oak. Phenolic acids are high molecular weight