CHAPTER 1 - STRUCTURE AND PROPERTIES OF WOOD

Wood is a very important structural material. It has numerous advantages and a few disadvantages ***(Table 1)***. In addition to being a biological material that is both renewable and readily available, it has an excellent strength/weight ratio and good ductile properties. Many species have a high degree of natural resistance to wood degrading organisms and if they don't they can be effectively treated with a wood preservative that is toxic to the wood degrading organisms.

Wood is made up of many cells that were produced by the living tissues in the tree. The manner in which the cells develop and are organized has profound effects on the properties of wood. The anatomy of wood is also the basis for separating wood into categories or species. The following discussion describes some of the major features of wood structure important in understanding biological deterioration in wood.

Table 1. Wood as a structural material

Advantages		Disadvantages
Renewable Resource		Biodegradable
Versatile		High natural variability
Readily Available		Combustible
Good Strength/Weight Ratio		Properties change with changes in Moisture
Ductile Material		Properties are different for each structural direction
Easy to join to other materials		
Pleasing appearance		
Can be treated with chemical to alter (improve) properties		

BASIC WOOD STRUCTURE

Wood is commonly grouped into two categories which are representative of the basic botanical classification of the two families of trees.

- **Hardwoods** - Angiosperms (broadleaf, mostly deciduous), for example: oak, maple, walnut.
- **Softwoods** - Gymnosperms (mostly conifers), for example: pine, Douglas fir, white fir, hemlock, etc.

Hardwoods are generally denser, have a finer texture and are more attractive than most softwoods (although some softwoods are harder than some hardwoods), a direct result of differences in wood structure. For example, hardwoods have specialized cells including a cell type for support, and a cell type for water conduction. Softwoods have one cell type that functions in both support and conduction. Traditionally the major market for hardwoods was furniture, and softwoods were more of a utility wood used in construction and paper manufacturing. Today, softwoods and hardwoods may compete in some of the same markets. However, nearly all of the species used for structural purposes in the construction of buildings are softwoods. The primary construction species, or species groups, used in the western United States are Douglas-fir, true firs, pines and hemlock.

Basic Features Common to All Wood

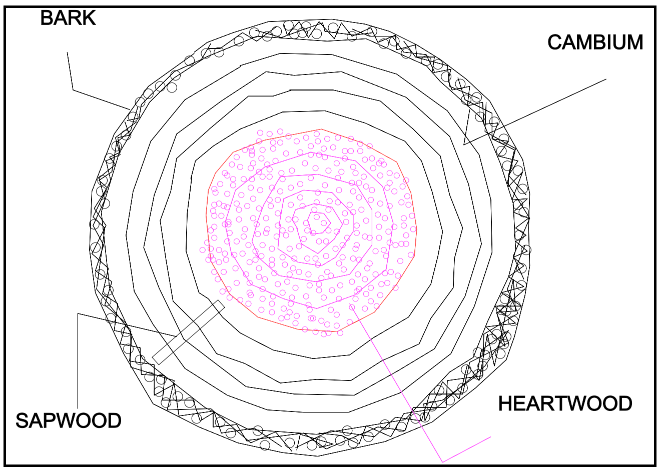

***Figure 1**. Sketch of a tree cross-section*

Bark - Outer layer of protection for the tree, and transport of food from the leaves to the rest of the tree.

Cambium - Thin layer of cells that produces all other cells, xylem (wood) cells towards the center of the tree and phloem (bark) cells to the outside.

Growth rings - Light and dark rings of wood as seen on a cross-section of a tree. The rings are related to the growing conditions (e.g. growing seasons).

Earlywood - Cells formed during favorable growing conditions (spring) forming a light colored band of cells.

Latewood - Cells formed during slow growth periods (summer) appear flattened out forming a thin dark band of cells. Latewood cells are usually denser than earlywood cells.

Sapwood - Zone of wood cells active in transport of water from roots to leaves and the storage of food in the living tree.

Heartwood - Cells in this zone have all died and are no longer active in water transport and food storage. Heartwood is often a different (usually darker) color than the sapwood because of the deposition of extractives, some of which are biocidal. This is the zone of wood most resistant to biological attack in hardwoods.

Structural Planes of Wood

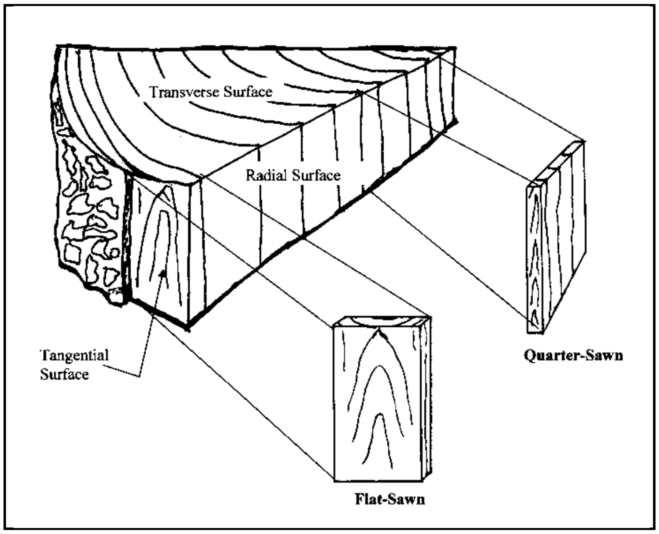

***Figure 2**. Structural Planes of Wood*

Transverse - Surface exposed by cutting across the stem (cross-section).

Tangential - Surface exposed by cutting tangent to the growth rings (flat-sawn).

Radial - Surface exposed by cutting across the growth rings from the pith to the bark (quarter-sawn).

Wood Formation

All the new cells in a growing tree are produced in the cambium. The tissue at the top of the stem, known as the apical meristem, produces new cambial cells as the tree grows in height. Within the stem there are various zones of wood with distinct property differences that are related to how and when the cells are formed. Five distinct zones are apparent in the tree sketch shown in Figure 3.

1. **Juvenile wood** - The cells made during the first 10 - 20 years of a cambial cell's life form the juvenile core of the stem. The juvenile wood cells exhibit excessive longitudinal shrinkage and swelling in response to changes in wood moisture content.
2. **Mature wood** – The cells formed after the first 10 to 20 years of growth.
3. **Knots** - A change in the axial direction of longitudinal cells to form a branch.
4. **Reaction wood** - The wood formed when the tree is forced to grow in a non-vertical aspect. For example, a tree growing on a slope, a tree leaning in a dense forest to find sunlight, or the underside of branches. The reaction wood zones are different in gymnosperms (conifers or softwoods) and angiosperms (hardwoods).
   a. Compression wood - The reaction wood of softwoods. This reaction wood exhibits excessive longitudinal shrinkage and swelling in response to changes in wood moisture content.
   b. Tension wood - The reaction wood of hardwoods; exhibits abnormal dimensional change and abnormally low strength properties.

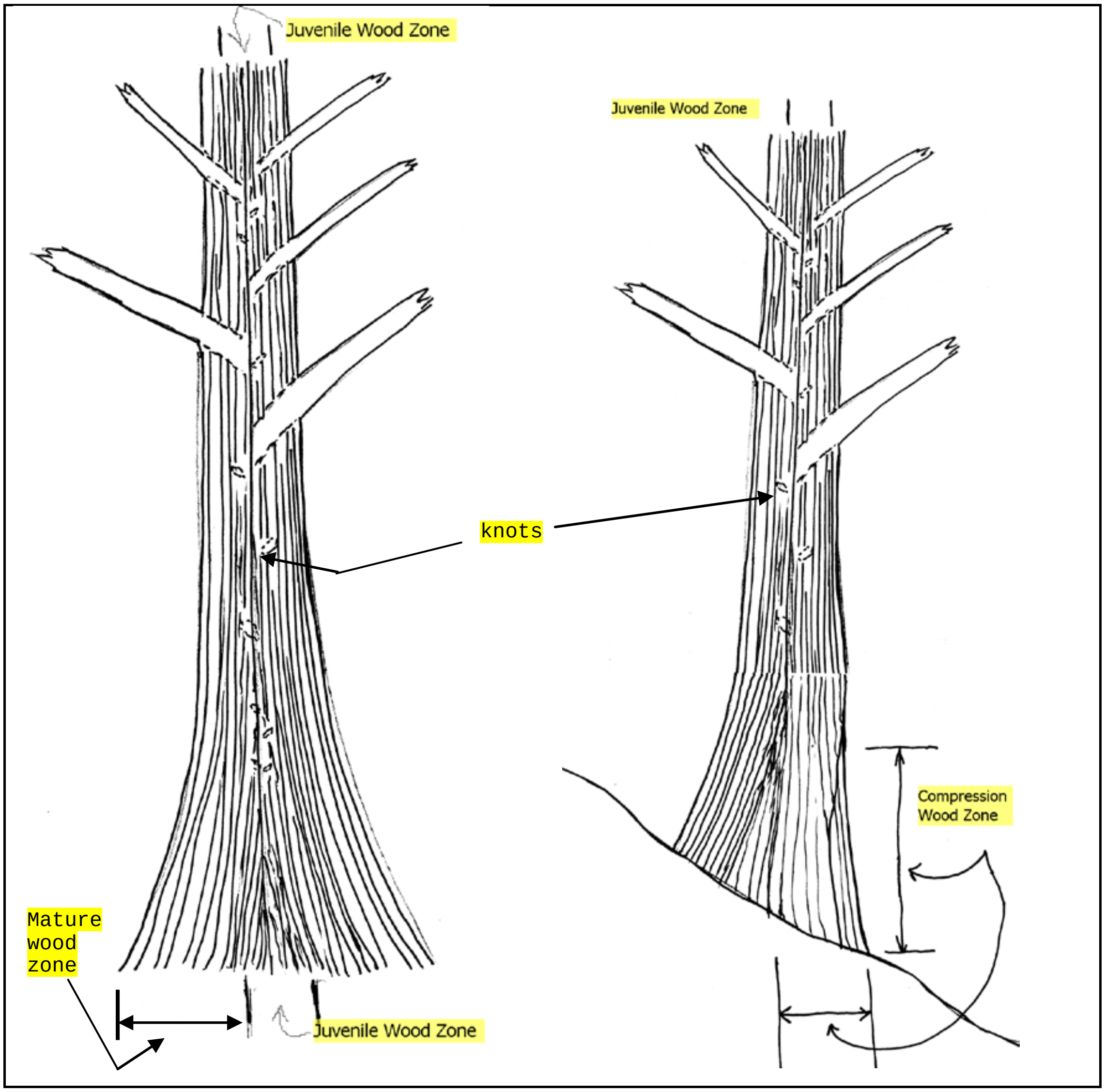

***Figure 3**. Vertical section of coniferous tree showing the various wood zones*

Chemical Composition of Wood

Wood consists of four main chemical groups (Table 2). The cellulose and hemicellulose groups are the carbohydrates (sugar molecules) which make up the majority of the cell wall. Lignin acts as a "glue" to bond the cells together into a stiff/strong material. The extractives are chemicals that are deposited in the cells and provide unique properties to wood, such as the natural resistance to biological deterioration.

Woods with a high degree of natural resistance have a relatively high percentage of biocidal extractives. The total extractive content of some species can be as high as 20 to 30%; these species generally have a high proportion of biocidal extractives. Examples of naturally resistant wood with high extractive contents are cedars and redwood.

Table 2. Chemical Constituents of Wood

Compound	Description	Amount (percent of total mass)
Cellulose	long chain of glucose molecules	40 - 50
Hemicellulose	long chains of sugar molecules other than glucose	25 - 30
Lignin	complex organic compound that helps bond cells together	15 - 20
Extractives	Compounds that are not an integral part of the cell wall	< 5
Ash	Inorganic elements in wood	< 1

Major Cell Types

All cells are similar in composition in that lignin, cellulose and hemicellulose are the compounds which form the cell walls. However, there are many different cell sizes and shapes that form cells designed for specific functions. The three main functions required of tree cells are food storage, mechanical support and the conduction of water, nutrients, and food. The food storage cells in all trees are named parenchyma cells. In softwoods there is one major longitudinal cell type, the tracheid, which provides both the mechanical support and the water conduction functions in the tree (Figure 4). In hardwoods, the cells are more specialized with different cell types performing different functions; vessels function in conduction and fibers function in mechanical support. Cells can be laid down in the longitudinal axis of the tree or transversely. The transverse cells make up the rays.

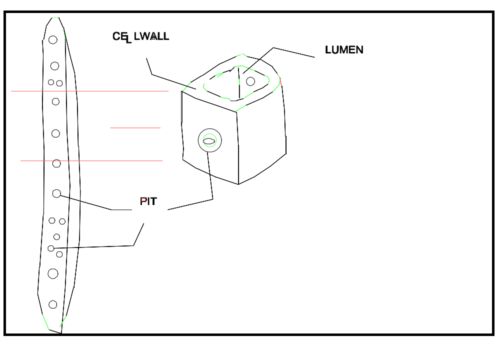

***Figure 4**. Sketch of a typical Softwood Tracheid*

Cell wall - strands of cellulose and hemicellulose embedded in a lignin matrix.

Lumen - Hollow center of cell.

Pits - Openings through side walls of cells to allow for transport of water in transverse direction.

Cell Types

Softwood - One cell type provides support and water conduction, tracheids.

Longitudinal cells

Tracheids - Long (1/4"), thin cells that function in both water transport and support in the tree.

Epithelial cells - These cells exude resin into longitudinal canals (resin canals); resin helps wounded tissue to heal and provides protection against insect and decay attacks.

Radial cells (rays)

Ray parenchyma - Their function is to store food.

Ray tracheids - Their function is to transport water in the radial direction.

Hardwood - Different cell types for conduction and support.

Longitudinal cells

Vessels - Thin-walled, large lumens (pores). Function mainly in water transport.

Fibers - Thick-walled, small lumens. Function in support.

Parenchyma - Function in food storage.

Radial cells

Ray parenchyma - Food storage.

Dimensional Change

Dimensional changes in response to changes in **temperature** are negligible in most cases. The linear expansion coefficient (thermal) for wood is approximately 2×10^{-7} per ^{o}F, a value low enough that it can be ignored for most uses. However, moisture induced dimensional change cannot be neglected. The dimensions of wood change with changes in wood **moisture content** (MC) in the range from oven-dry (0% MC) to the fiber saturation point (approximately 25-30% MC). Within this range, an increase in the moisture content causes wood to swell, and a decrease causes shrinkage. Changes in MC above the FSP do not induce dimensional change.

- As a general rule, denser woods exhibit more dimensional change than less dense woods, for a given change in moisture content.
- Dimensional change in the **tangential** direction is approximately two times greater than the dimensional change in the **radial** direction. Dimensional change in the **longitudinal** (axial) direction is normally very small (<0.5%) and can be neglected in most cases. Juvenile and reaction wood are an exception; longitudinal dimensional changes can be as high as 3% in wood from these zones of the tree.
- The ratio of tangential dimensional change to radial dimensional change (T/R) is a good indicator of the tendency of a species to warp in service. The lower the T/R values the less the tendency for warp.

Table 3. Shrinkage from Fiber Saturation Point to Oven-Dry Moisture Content*

SPECIES	TANGENTIAL	RADIAL	T/R
Redwood	4.9%	2.2%	2.2
Douglas fir	7.6	4.8	1.6
N. Red oak	8.6	4.0	2.2
Albizia	3.7	1.6	1.1
Acacia koa	6.2	5.5	1.1
E. saligna	12.1	6.5	1.9
E. robusta	7.7	2.7	2.8
Fraxinus uhdei	7.4	3.5	2.1
Toona australis	9.8	4.3	2.3

Source:
Wood Handbook: Wood as an Engineering Material. USDA Agriculture Handbook No. 72.
Skolmen, R. G. 1974. Some Woods of Hawaii. USDA General Technical Report PSW-8.

IMPORTANT CHARACTERISTICS AND PROPERTIES OF WOOD

The Hawaiian hardwood lumber industry is currently a fragmented industry with many sole proprietorships and a raw material mix including trees from non-industrial timberland, woodland regions, as well as native and exotic trees in the urban landscape. Based on a knowledge of wood properties and the experience of local artisans and woodworkers, successful markets for high value wood products made from this resource are deemed possible, but special manufacturing techniques and innovative marketing strategies may be required to do so economically. In this environment, a wide range of species is likely, the amount of resource available may be limiting, and operating costs are high. In combination, these factors suggest that the only reasonable venture is a small to moderate-sized mill with low overhead costs that manufactures a high value product for a custom or niche market. This is very similar to what is happening in the California hardwood industry. The California hardwood industry consists of producers (primary manufacturers), suppliers, and secondary manufacturers of finished goods. The producers are concentrated in northern California near the timberland hardwood resource. The current total estimated annual production of 2 million bd. ft. well positioned to compete in the hardwood market of more than 100 million bd. ft annual consumption.

When considering the use of a non-commercial species, it is important to understand the limits of the raw material and manufacturing processes, and the expectations and demands of the market. These are common concerns for all types of business structures (small business, cooperative, large company). As a general rule, most urban trees will present more manufacturing difficulties than forest grown conifers and low-density hardwoods. This does not mean that valuable products are unattainable from high-density species, but rather that extra processing steps and great care are necessary. In many situations, the extra effort and care required to deal with these difficulties may not pay for low-value products, but higher-value uses are feasible. Obviously, some species are better suited for particular products than other species. Factors such as ecological concerns, resource availability, cost of production, and quality of the end product are important in determining the long-term utilization potential of urban species.

Important to any manufacturing operation is the target market for the product being produced. The major wood markets include:

- Structural Lumber and Timber.
- Lumber Graded to Industry Standards -- Such as WWPA (Western Wood Products
- Association) for softwoods and NHLA (National Hardwood Lumber Association) for
- hardwoods.
- Lumber for Remanufactured Goods – Specially sized lumber produced for secondary manufacturers, including: furniture, flooring, cabinetry, and numerous consumer goods such as picture frames, jewelry boxes, toys, etc.
- Specialty Lumber.

The first three are primarily commodity markets that demand large volumes of lumber that are readily available at a competitive price and manufactured to existing industry standards. It is unlikely that the urban wood source is reliable enough to provide entry into these commodity markets. However, within each of these categories there is a niche market, which is more flexible because a specific product or customer is targeted and the product is tailored to the customer’s needs. For example, lumber used in structural applications must be graded accordingly. However, an engineer could approve the use of timbers by evaluated strength on the basis of grain angle, presence and location of knots, and reported species strength values or laboratory tests. This approach would provide unique (niche market) structural timbers that could be extremely valuable in custom construction. Another example is residential flooring. The primary requirement for hardwood flooring is that the wood be able to resist mechanical damage such as scratches and dents; softwood floors, on the other hand satisfy a "distressed" market that prefers the added character of scratches and dents. The hardness property (the force required to imbed a steel ball into wood) is a good indicator of the ability of wood to resist mechanical damage. Generally, a hardness value above 1,000 lbs. is required for a satisfactory hardwood floor. In general, all of the high-density hardwoods (specific gravity above 0.5) are acceptable as a flooring material.

Producing specialty-use lumber is the most common product for most non-industrial sawmill operators because only a simple agreement with the customer is needed. However, because this lumber usually does not meet the recognized quality standards of the national grading rules, it may have a low value, unless it is marketed for its uniqueness or unusual character (niche marketing). An emerging niche market that has real potential for urban trees is that of "certified" or "environmentally friendly" products made from wood obtained from a sustainable source that is sensitive to environmental concerns. Diverting wood from landfills may well meet these requirements. Although it is unclear how much more consumers are willing to spend for these certified products, it is certainly an area that should be investigated in any niche marketing approach.

Wood Characteristics.
Trees outside of natural timberland regions grow in a variety of settings, from tree farms and plantations, to “open-grown” in fields and parks, to heavily pruned street trees. Trees grown in open settings often are a spreading tree form with much branching, resulting in high grain wood character but also many knots and other defects. A summary of important physical and woodworking properties is presented in the following discussion. This information is a compilation from a variety of sources in which property measurements were often not performed in a standard or comparable manner. An attempt was made to standardize this information and is offered as a starting point for understanding these woods.

Appearance properties. The properties of many non-commercial species are not well known; however, some general comments about their properties can be made on the basis of tree form, genus characteristics, and wood density. Most hardwoods would likely be manufactured into finished products that highlight appearance. This means that in addition to how well the wood can be worked with machine tools (machinability), the appearance characteristics such as color, texture, figure, and how well the wood finishes are also important considerations. Color and texture are inherent species-related characteristics, but figure is related to the pattern of growth rings exposed on the wood surfaces and is influenced by how the tree grows as well as how the lumber is cut from a log with respect to the grain aspect. Grain deviations around knots and tree growth irregularities have a major influence on figure. Lumber surfaces that tend to expose the surface that is tangential to growth rings (i.e. flat-sawn) will show more figure than the quarter-sawn surface (perpendicular to the growth rings). An excellent review of figure in wood is found in the book, “Understanding Wood” (Hoadley, 1980).

In general, the fine textured, high-density woods will yield surfaces with a uniform appearance. The relative importance of these properties is dependent on the specific requirements of the finished product and the market place value. Often a positive characteristic for one product can be a negative characteristic in another. For example, the variable color in mango or the high figure of curly koa may be very desirable in a piece of custom made furniture, but it is often undesirable in a mass produced furniture or cabinet line where a uniform appearance is expected by the customer.

Physical properties. Knowledge of physical properties provides a basis for predicting how wood reacts to manufacturing forces and how it will perform in service. Density is the wood property that has the greatest effect on the manufacturing and performance characteristics of wood. Density is the mass of wood per unit volume and is often given in g/cm3. Specific gravity is a unitless ratio of the density of wood at standard conditions (usually ovendry mass/green volume) to the density of water at ambient conditions. Specific gravity is a measure of relative density.

Machining, surface quality, drying, finishing, and dimensional stability are all directly related to density. Most of the hardwoods, and softwoods with a specific density greater than 0.5 (measured on the basis of an oven-dry mass and a green volume), yield a high quality surface when machined with woodworking tools. However, these high-density woods are more difficult to dry and exhibit less dimensional stability than the lower density woods, that is, those below 0.4. But, the easier drying and improved stability of these lower density woods is off set by their poorer machining and finishing qualities.

Wood Property Definitions

Anisotropic - The properties of wood are different in each of the structural directions. For example, dimensional change in response to changes in the moisture content of wood (shrinking/swelling) is much less in the longitudinal (axial) direction than it is in the transverse directions (tangential and radial), and the dimensional change in the tangential direction is typically about twice as great as in the radial direction.

Orthotropic - A specific type of anisotropy, with 3 orthogonal planes of symmetry.

Hygroscopic - Wood has an affinity for water, meaning that it readily picks up (adsorbs) moisture from and loses (desorbs) moisture to the atmosphere.

Density - Measure of the amount of wood substance, defined as the weight per unit volume (units of $lb/ft^{3,}$ g/cm^3, or Kg/m^3). Both the weight and volume of wood vary with the moisture content of wood. Therefore, when density is measured the moisture content of the wood must be noted.

Specific Gravity (SG) - The density of a material relative to the density of water. The scientific convention is to base the SG on the oven-dry mass and the volume at a saturated moisture content, also known as the green moisture content. In some literature SG is also reported as based on an overn dry mass and a volume at 0% MC or 12% MC.

- **Mechanical Properties -** Strength and stiffness are the main mechanical property categories (Table 2). They are a measure of the load (force) wood can carry before it is permanently deformed or it fails (units of psi or Kpa).
- **Strength** decreases with increases in temperature. The effect is small and reversible at temperatures below 100°C. Above 100°C thermal degradation of the wood occurs and dramatic reductions in strength are possible (time dependent).
  - Toughness - Measure of the capacity of a material to absorb shock

energy (that is, the ability to resist impact loading). Toughness is the strength property most sensitive to decay.
    - Compression Strength – Measure of how much load wood can support when stressed in the direction parallel to the grain.
    - Tension Strength – Measure of the capacity of a wood to resist a tension stress applied parallel to the grain.
    - Modulus of Rupture, MOR (Bending Strength) – The strength of a member loaded in bending.
- **Stiffness –** Measure of flexibility
    - Modulus of Elasticity, MOE (Bending Stiffness) – Measure of the load on a beam that will cause a deflection of 1 inch (units of psi).

Factors that influence mechanical properties include:
- Moisture Content – Wood is strongest when completely dry, as the moisture content of wood increases, the strength of wood decreases.
- Density – As a general rule, high density woods are stronger than low density woods.
- Structural Direction – Strength varies depending on the direction relative to the grain in which the load is applied.
- Time or Duration of Load - Wood gradually changes shape over time when it is loaded. This deformation is named creep and it may become permanent if the load continues for a long time. The duration of load factor used in timber design is related to the creep phenomenon. Strength decreases with duration of loading. Long term loading (10+ years) may reduce strength in bending as much as 60%.

Table 4. Select Mechanical Properties of a few Hawaiian Woods

Species	SG (lb/in^2)	MOE at 12 % MC (lb/in^2)	MOR at 12 % MC (lb/in^2)	Side Hardness (lb_f)
Redwood	0.34	1,100,000	7,900	420
Douglas fir	0.45	1,560,000	7,700	500
N.Red oak	0.56	1,350,000	8,300	1,000
Albizia	0.38	1,280,000	8,400	870
Acacia koa	0.54	1,570,000	13,300	870
E. saligna	0.75	2,059,000	16,400	1,360
E. robusta	0.75	1,800,000	15,600	1,330
Fraxinus uhdei	0.55	1,660,000	12,800	860
Toona australis	0.43	1,300,000	10,600	550

Source:

Keating, W.G, and E. Bolza. 1982. Characteristics, Properties and Uses of Timbers: Southeast Asia, Northern Australia and the Pacific.

Skolmen, R. G. 1974. Some Woods of Hawaii. USDA General Technical Report PSW-8.

- **Permeability** – A measure of the ease with which fluids flow through wood. Wood is much more permeable in the longitudinal direction than in the radial or tangential direction. Exposed end grain readily takes up water whereas water penetrates very slowly through side grain.

- **Electrical Conductivity** – Wood is a good insulator when it is dry but not when the moisture content is above 30%. The electrical conductivity of wood increases as the moisture content of wood increases.
- **Thermal Conductivity** – Wood is a good thermal insulator. Thermal conductivity of wood is approximately 0.75 Btu/hr-ft^2/^{o}F/in (steel is approximately 300). The thermal conductivity of wood is in part dependent on the amount of void spaces in wood. High density woods are more conductive than low density woods because the high density woods have fewer void spaces. If the void spaces contain moisture rather than air the thermal conductivity will also be higher, hence thermal conductivity also increases with an increase in wood moisture content.
- **Variability** – Properties vary because of genetic factors, growth factors and manufacturing methods. Examples of these factors include:
    - Between species - different anatomical characteristics including the amount of cell wall substance (which defines density)
    - Between trees of the same species - genetic and growth factors
    - Between boards of the same tree - grain orientation, knots, relative amounts of heartwood and sapwood
    - Within one board - juvenile and reaction wood zones, and changes in annual ring orientation

Natural Durability – The resistance of wood to the biological degradation of certain insects and decay organisms is termed durability. This natural durability of wood is directly related to the type and proportions of chemicals within the heartwood zone of a tree.. These **heartwood extractives** are formed when the living tissue of the sapwood dies to form the heartwood. Some extractives have biocidal properties. The exact nature of the extractives formed in the heartwood is very species dependent; therefore the degree of resistance to biological degradation varies with species. The sapwood of all species is devoid of these biocidal chemicals and thus has no resistance to biological degradation. In the living tree the resistance to biological degradation is dependent on the protective boundary provided by the bark. Once the bark layer is compromised than the sapwood is susceptible to both insect and decay attacks.

Species are usually grouped into three durability categories based on the make up of the heartwood extractives. Table 4 shows the groups for a selection of temperate, North American and tropical species.

Table 5. Natural Durability of Select Wood Species

Moderate to Very	Slight to Moderate	Non to Slight
Cedar	Douglas fir	Pine
Redwood	Southern Pine	Fir
White Oak		Red oak
Walnut		
		Albizia
		Acacia koa
	E. saligna	
	E. robusta	
		Fraxinus uhdei
	Toona australis	

Source:

Keating, W.G, and E. Bolza. 1982. Characteristics, Properties and Uses of Timbers: Southeast Asia, Northern Australia and the Pacific.

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