CWPA Proceedings, 2001, pp 1-7

WOOD ANATOMY AND PHYSICAL PROPERTIES—AND HOW THEY AFFECT DURABILITY AND TREATABILITY

John Balatinecz
Faculty of Forestry, University of Toronto

Summary

The basic anatomical structure and the properties of wood are discussed briefly in relation to natural durability and treatability. Differences between softwood and hardwood species are considered, as well as those between the sapwood and heartwood of the same species. The most important single factor influencing the natural durability of wood is the type and content of extractives. The heartwood of durable species typically has extractives (usually phenolic in nature) which are toxic to wood-destroying microorganisms and insects. The treatability of wood, which is a function of permeability, is largely dependent on the availability and condition of passage ways to penetrating preservative liquids and/or solutions. In softwoods, it is the condition of inter-tracheid bordered pits which lergely defines permeability. During the process of heartwood formation, bordered pits often close and their membranes become encrusted with flow-blocking deposits. Thus, permeability, and hence treatability, is reduced significantly. Consequently, sapwood is generally more permeable than heartwood. To date very few treatments proved effective and economical for the improvement of permeability. In hardwood species, the condition of vessels has the greatest influence on permeability. Vessels in the heartwood of many species may become blocked by tyloses and deposits, resulting in poor treatability.

Introduction

Long and trouble-free service life is a desirable goal for the use of all wood products. Under favourable service conditions wood can last indefinitely. However, it is often exposed to hazardous environments where biological, chemical and physical deterioration may be a serious problem for safe structural performance. Therefore, knowledge of natural durability and effective wood protection are important issues for the structural utilization of wood.

To insure long service life, one option for designers is to select species with high degree of natural resistance to deterioration, i.e. woods which are naturally durable. Unfortunately ‘natural durability’ is difficult to define, as well as to quantify. Generally, wood scientists define natural durability as the ability of wood to resist attack by foreign organisms, i.e. fungi, bacteria, insects and marine borers. Often natural durability is equated with decay resistance (Panshin and De

Zeeuw, 1980; Cartwright and Findlay, 1958; Mullins and McKnight, 1981). Longstanding experience in wood utilization has shown that certain species exhibit outstanding natural durability, whereas others are prone to rapid deterioration in adverse environments. The concept of natural durability only applies to the heartwood portion of the stem, since the sapwood of all species has negligible resistance to biological deterioration.

Another option to insure long service life for wood products is through the application of appropriate protective and preservative treatments. For preservatives to be effective, they need to penetrate the wood beyond the surface layers. Thus, treatability is essentially a measure of the ease with which liquids and gases can penetrate the inner structure of wood. Treatability can be quantified by measuring permeability.

Good design practice, which can range from good ventilation to the prevention of moisture ingress, can also reduce the hazards of biological deterioration for wood products.

This paper presents an overview of the relationships between natural durability and treatability of wood on the one hand, and its basic anatomical structure and properties on the other. Differences between softwoods and hardwoods, as well as between sapwood and heartwood of the same species are discussed.

Basic structure of softwoods and hardwoods

Chemical composition

The main polymeric constituents of wood are cellulose (40% to 50%), hemicelluloses (20% to 35%) and lignin (15% to 35%). These three macromolecules make up the walls of all wood cells or fibres. When the cells are formed and their wall is synthesized, the cellulose is deposited in the form of microfibrils (which are aggregations of cellulose chains) and is ultimately surrounded by a hemicellulose-lignin matrix. This unique reinforced composite structure is responsible for the excellent strength and stiffness of woody cells and wood itself.

While the amount of cellulose is quite similar in both softwoods and hardwoods, there are significant differences in lignin and hemicellulose content. Softwoods typically have higher lignin (25%-35%) and lower hemicellulose content (20%-25%) than hardwoods (e.g. 15%-25% lignin, and 25%-35% hemicelluloses).

Wood also contains minor amounts of non-structural chemical components. These substances are normally called extractives, because they are removable from wood with neutral solvents. Extractives are a diverse group of organic compounds (they number in the thousands), such as polyphenols, oleoresins, tropolones, fats, waxes, gums, volatile hydrocarbons, etc. Polyphenols, which are one of the largest group, occur in both softwoods and hardwoods. They include such compounds as tannins, flavones, catechins, lignans, and anthocyanins. Extractives may be infiltrated into the cell walls or deposited on to the wall surface (Panshin and De Zeeuw, 1980). The biosynthesis and deposition of extractives is associated with the process of heartwood formation. The amount of extractives in wood is relatively small (1% to 7% of oven-dry mass), however their influence on wood properties is considerable. They are known to affect natural durability, odour, colour, permeability, finishing and gluing characteristics. Considerable variation exists in the type and amount of extractives between different wood species. There is some variation in extractive content even within a single tree.

Physical properties

Of the various physical properties of wood only relative density (i.e. specific gravity) and moisture content will be discussed briefly because they may have a bearing on treatability and natural durability. Wood substance (i.e. cell wall substance) has a density of approximately 1500 kg/m^3. This value does not take into account the fact that wood is a porous solid, with considerable internal voids created by cell cavities. When density is expressed as the ratio of the oven-dry mass of wood to its external volume then a very useful relative density is obtained which provides for a valuable comparison of different species, as well as for the comparison of wood to other materials. The average relative density of different wood species covers a very broad range. For example, balsa, at the low end, has an average relative density of about 150 kg/m^3, whereas lignum-vitae, at the other end, has average relative density of over 1100 kg/m^3. The average density of most commercial wood species is in the range of 300 kg/m^3 to 700 kg/m^3.

Due to its lingo-cellulosic nature, wood is a hygroscopic material; i.e. it has a strong affinity for water from both the liquid and vapour phase. Moisture in wood influences most other properties, including weight, dimensions and strength. Water is also an essential ingredient of fungal decay; i.e. below a certain threshold moisture content (usually 20% MC) wood decay can not take place (Panshin and De Zeeuw, 1980; Wood Handbook, 1999). The most important practical implication of this fact is that wood should be kept dry to endure. If that is not possible, then the choices may be limited to the use of species with high natural durability or the application of appropriate preservative treatments.

Structure of softwoods

Softwoods have a relatively simple anatomical structure. Over 90% of their volume is made up of longitudinal tracheids. These are long, tapered cells which, when viewed on the cross section, are arranged in distinctive radial rows (Figure 1). The length of tracheids ranges from about 2.5mm to 7.0mm, depending on species and the age of tree when the woody tissue was formed. Common softwood species, such as spruces and pines, have average tracheid length between 3.5mm and 4.5mm. Tangential diameter of tracheids is in the range of 30um to 80um, again, depending on species and age (Panshin and De Zeeuw, 1980). Differences in the radial diameter and wall thickness of tracheids gives rise to the distinctive tissue zones of earlywood and latewood within annual rings.

Tracheids serve a dual function in wood. One function is the conduction of sap in living trees, and the second is the provision of strength and stiffness to the woody stem. The conductive function is facilitated by inter-tracheid bordered pits. These are small valve-like structures with a permeable membrane while the cell is part of the sapwood (Figure 2). During heartwood formation the pit membrane usually becomes occluded with deposits that render it impermeable. The strength and stiffness of softwoods emanate from the intricate lingo-cellulosic structure of the walls of longitudinal tacheids.

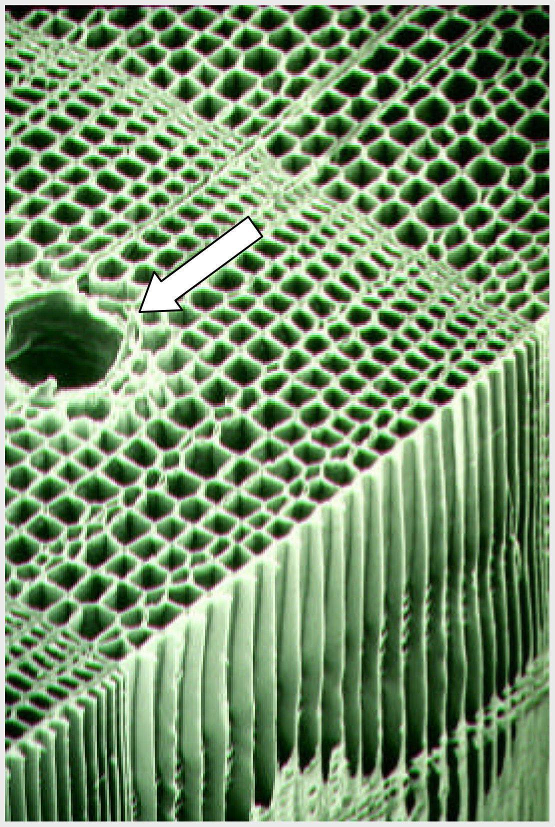

Figure 1. SEM view of pine wood, showing rows of longitudinal tracheids and a resin canal

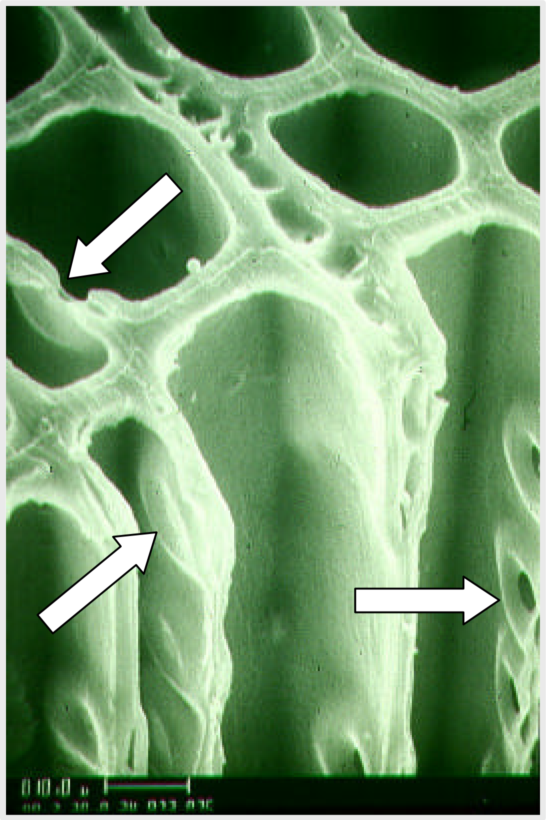

Figure 2. Inter tracheid bordered pits

Wood rays make up only about 10% of the wood volume of softwoods. Their constituent cells are mainly parenchyma, and they serve storage and lateral conductive functions while they are part of the sapwood zone. Ray parenchyma cells play an important role in heartwood formation, a process during which extractives are synthesized and deposited into the woody tissue.

Many softwood species also contain special intercellular structures called resin canals or resin ducts. These canals are surrounded by resin secreting epithelial parenchyma cells (Figure 1). They are typically found in the wood of pines, spruces, larches and Douglas fir, and are absent in other softwood species.

Structure of hardwoods

Hardwood species show considerable diversity in their anatomy, which is reflected in the type and arrangement of specialized cells that make up their structure (Figure 3). The main longitudinal cell types in hardwoods are the vessel elements, fibres and axial parenchyma cells.

Their ratios (relative to one-another), arrangement and distribution in the annual ring account for the significant anatomical diversity between species. Vessels serve for conduction, and, depending on species, make up between 10% to 50% (mostly in the 20%-40% range) of the wood volume. The arrangement of vessels in the annual ring may follow a random diffuse or ring-like pattern. Hence the origin of the terms diffuse porous and ring porous hardwoods.

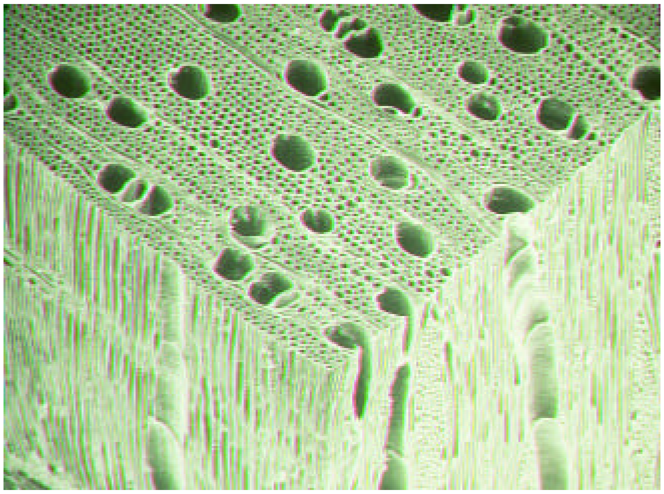

Figure 3. SEM view of birch wood, showing dispersed vessels between small diameter fibres.

Figure 4. Tyloses in vessels of hickory

Depending on species, fibres account for between 30% to 70% (mostly in the 40%-60% range), and axial parenchyma cells for 2% to 12% of the wood volume. The main function of fibres is the strengthening of the stem, whereas parenchyma cells provide storage function. Wood rays are composed entirely of radial parenchyma cells (which also serve for storage), and make up between 10% and 20% of the wood volume (depending on species).

Generally, vessels have large diameters (e.g. up to 300 μm) and thin walls, whereas fibres have small diameters and thick walls. Therefore, the relative ratio of vessels to fibres in a species has a profound influence on wood density and hardness. For example, oak, ash, hickory, maple and birch typically have higher proportion of fibres than vessels, therefore their wood is dense and hard.

Heartwood formation brings about two major changes in hardwoods, which have important consequences for treatability and natural durability. First, the conductive function of vessels ceases, and in many species (especially in ring porous woods, with large earlywood vessels) foam-like structures called tyloses form in the vessel cavity (Figure 4), effectively rendering the wood impermeable. Gummy materials may also be deposited into vessel elements. The second process that accompanies heartwood formation is the synthesis and deposition of extractives into the wood structure. Stored substances of living parenchyma cells (both axial and radial) in the sapwood zone are the sources of extractives. Extractives are responsible for the range of colour variation in wood.

Natural durability and treatability

Natural durability

As mentioned earlier, the natural durability of wood is rather difficult to quantify. Based on longstanding experience and research, various rankings have been constructed to categorize the natural decay resistance of different wood species. Table 1 lists some common woods according to their relative durability ranking (Wood Handbook, 1999). It is interesting to note that most of the species listed under the 'very resistant' category have dark coloured heartwood.

Table 1. Ranking of various wood species for natural decay resistance

Resistant to very resistant	Moderately resistant	Slightly or Nonresistant
Western red cedar *Yellow cedar* *Redwood*	*Douglas fir* *Western larch* *Tamarack*	*Spruces* *True firs* *Pines*
Black locust	*Eastern white pine*	*Poplars*
Black cherry	*Longleaf pine*	*Birches*
White oak	*Chestnut oak*	*Maples*
Black walnut	*Red oak*	*Beech*
Sassafras		*Basswood*

The single most important factor determining the natural durability of wood is the presence or absence of toxic extractives. The wood of durable species invariably contains extractives which are toxic to fungi and often to insects as well. For example, western red cedar, one of the most durable domestic woods, contains thujaplicin, which has natural fungicidal properties against a broad range of fungi. Many other phenolic extractives are known to enhance the natural durability of species in which they are present (e.g. pinosylvin, taxifolin, tannins). It should be noted, however, that not all extractives have fungal toxicity.

There is no general agreement among experts about the possible influence of other wood characteristics (other than toxic extractives) on natural durability (Cartwright and Findlay, 1958; Panshi and De Zeeuw, 1980). For example, density, growth rate and permeability have been mentioned as properties that may have slight effects on durability.

Since natural durability is an inherited trait, it is possible that with the application of biotechnology, molecular biology and genetics, the decay resistance of species prone to rapid deterioration may be enhanced.

Treatability
The treatability of wood, which is a function of permeability, is largely dependent on the availability and condition of passage ways to penetrating liquids and/or solutions (Panshin and De Zeeuw, 1980). In softwoods, it is the condition of inter-tracheid bordered pits that effectively defines permeability. During heartwood formation, bordered pits often close (i.e. become 'aspirated') and their membrane become encrusted with flow-blocking deposits. Consequently, sapwood is generally more easily treatable than heartwood. There are also significant differences between species. For example, pines may be treated more easily by pressure processes than spruces. This is attributed to the impermeable inter-tacheid pits in spruce wood.

In hardwoods, the size, distribution and condition of vessels has the greatest influence on permeability. Vessels in the heartwood of many species may become blocked with tyloses (Figure 4) and gummy deposits, resulting in poor treatability.

Permeability in the longitudinal direction is much greater than in the lateral direction (reportedly more than 1000 times greater). This is because of the large numbers of cell walls which must be crossed by the penetrating liquid in the lateral direction.

References

1. Cartwright, K. S. G. and W. P. K. Findley, 1958: *Decay of Timber and its Prevention*, Her Majesty's Stationary Office, London
2. Mullins, E.J. and T.S. McKnight, eds.1981: *Canadian Woods—Their Properties and Uses,* University of Toronto Press, Toronto
3. Panshi, A.J. and Carl De Zeeuw, 1980: *Textbook of Wood Technology*, McGraw-Hill Book Company, New York
4. *Wood Handbook—Wood as an Engineering Material*, 1999, Forest Products Laboratory, USDA Forest Service, Madison, Wisconsin