Treatability and Durability of Heartwood

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Abstract

Reduced treatability in heartwood can cause reduced retention and penetration of preservatives into heartwood. This can reduce the durability of heartwood compared to the treated sapwood. From an anatomical point of view, the factors which contribute to the lower treatability of heartwood include its high extractive content, high rate of aspirated pits, and smaller pore sizes. Generally, in wood members that consists of treated sapwood and untreated heartwood, the durability of treated sapwood is much higher. Untreated heartwood of southern pine, Douglas-fir, Englemann spruce, eastern spruce, red pine, white pine, eastern larch, eastern hemlock, and eastern fir lasts longer in outdoor exposure in the colder northern regions (Wisconsin and Maine) than in warmer southern regions (Mississippi). In the southern regions, the median life of the stakes for these species ranges from about two to four years with the exception of southern pine which ranges from about five to seven years. Eastern spruce and white pine appear to possess lower durability (about two to three years) among all the species studied. In the northern region, the median life of the species range from five to ten years with the exception of southern pine which lasts about eight to fifteen years.

Keywords: heartwood, transition zone, sapwood, preservative treatability, natural durability.

Introduction

The sapwood of most tree species can be successfully impregnated (with some important exceptions such as the spruces), whereas the heartwood is more difficult to treat by conventional methods (USDA Forest Product Lab 1987). From an anatomical point of view, the difficulty in treating heartwood can be attributed to factors such as small pore sizes in the heartwood (Stamm 1970; Petty and Preston 1969), the generally irreversible nature of pit aspiration in the heartwood (Thomas and Nicholas 1966; Thomas and Kringstad 1971), the amount and type of extractives deposited on pit membranes during the formation of heartwood (Hillis 1987; Siau 1984; Cote 1990; Panshin and DeZeeuw 1980), and, in addition, for hardwoods, tyloses formation in the heartwood (Siau 1984; Cote 1990; Panshin and DeZeeuw 1980). For species with naturally durable heartwood such as the cedars or redwood, preservative treatment of the heartwood might not be as critical. However, for wood species with less or no naturally durable heartwood, treatment of the heartwood is necessary for construction of durable timber bridges.

Besides heartwood, in studying the treatability of wood materials, it seems that the emphasis on more understanding of the transition zone between sapwood and heartwood is relevant. In some species, especially softwoods and diffuse-porous hardwoods, a transition zone between the sapwood and heartwood is present (Hartig 1894; Craib 1923). Characteristics of the transition zone include low permeability, pale or white color, lack of starch, and reduced moisture content (Hillis 1987). The width of the transition zone is usually about 1-3 growth rings (Hillis 1987). The implications of the transition zone on treatability of wood articles containing both heartwood and sapwood is not well understood.

In order to treat wood effectively, the treating fluid must be able to penetrate to some given depth into the wood. Generally speaking, there are two broad categories of treating processes: pressure treatment and nonpressure treatment. Of the two kinds of processes, the pressure process is used more often due to its effectiveness, controllability, and speed. In pressure processes, the penetration of the treating fluids is predominantly through bulk flow (Siau 1984). As a first approximation, the parameters which influence the bulk flow, and therefore treatability, can be appreciated through Poiseuille's equation for steady laminar viscous flow (White 1974):

$$V = \frac{\pi r^4 \Delta p}{8 \mu L} t \quad (1)$$

Where

V: Volumetric flow, cm^3
r: The radius of the cylindrical capillary through which the fluids flow, cm
μ: The viscosity of the treating fluids, poise
Δ p: The gradient of the treatment pressure, N/cm^2
L: The length of the capillary pore across which the pressure gradient, Δ p, is applied, cm
t: Processing time, s

Equation (1) was derived for a cylindrically shaped capillary under steady state laminar flow conditions. Solutions also exist for other capillaries with various cross-sectional shapes (Berker 1963). Equation (1) is a much simplified expression for the actual treatment processes. When the unsteady nature of the flow is considered, for example, a different expression was obtained which suggested less dependence of the volumetric flow on the pressure gradient and viscosity (Siau 1970). Aside from their qualitative differences, the principles in these results point to three aspects in examining the treatability of wood materials: 1) the anatomical characteristics of the wood species; 2) the characteristics of the treating fluids; and 3) the parameters of the treating processes.

Treatability

1. Softwood

A typical softwood species contains about 90 to 94% longitudinal tracheids, 5 to 10% rays, and 0.1 to 1% longitudinal resin canals. The sizes of the longitudinal tracheids in several softwood species are listed in Table 1. The amount of longitudinal parenchyma is negligible (Panshin and deZeeuw 1980). The ends of the tracheids are closed. Communication among tracheids and rays are mainly through the bordered or non-bordered pit pairs. Most of these pits reside on the radial surfaces of the tracheids or rays (Panshin and deZeeuw 1980).

Table l—Average Tracheid Diameters and Lengths of the Selected Softwood Species
(Panshin and deZeeuw 1980)

	Diameter, μm	Length, mm	L/D
Douglas-fir (*Pseudotsuga menziesii*) (4)*	55	3.0	54.5
		3.32	60.4
		3.88	70.5
Eastern hemlock (*Tsuga canadensis*) (2)	50	2.81	56.2
		2.91	58.2
		3.10	62.0
Norway pine (*Pinus resinosa*) (2)	45	2.51	55.8
		2.63	58.4
		2.67	59.3
		2.70	60.0

* Meaning of number in parentheses is the index of heartwood treatability according to MacLean (1935):
1: Easy to penetrate; 2: Moderately difficult; 3: Difficult; 4: Very difficult

Table 2—Radii of the Effective Pit-Pore Openings (mm)
(Stamm 1970; Sebastian et al 1965; Petty and Preston 1969)

Species	Heartwood	Sapwood
E. larch (*Larix laricina*) (4)* [c]**	0.008	0.500
Incense cedar (*Libocedrus decurrens*) [c]	0.012	0.085
E. red cedar (*Juniperus virginiana*) [c]	0.013	0.12
N. white cedar (*Thuja occidentalis*) [c]	0.017	0.170
Douglas-fir (*Pseudotsuga menziesii*) (4) [c]	0.025	0.170
Redwood (*Sequoia sempervirens*) [c]	0.047	0.100
Sitka spruce (*Picea sitchensis*) [d]	0.20 - 0.26	0.74 - 0.98
White spruce (*Picea glauca*) (3) [TEM]	0.58	0.75

* Meaning of number in parentheses is the same as in Table 1
** c: From Stamm (1970) measured using capillary method; d: From Sebastian (1965) using permeability measurement; TEM: From Petty and Preston (1969) using Transmission Electron Microscope.

Because the average diameter of the pit pores is much smaller than that of the tracheid lumens, the treatability of wood is largely dependent on the size and condition of the pit structure. Therefore, parameters such as effective pore size, number of pit openings per unit area, probability of aspiration and deaspiration, encrustation of the pit membranes, and length of the tracheids are directly related to the treatability of softwood species. Besides the pit openings, tiny pores in the cell wall also play a role in the treatability, especially when polar solvents are used for the preservatives (Nicholas and Siau 1973). However, since these pores are much smaller than the pit pore openings, their role in treatability maybe secondary when the pits are effective in transporting fluids.

The size of pit openings has been measured with various techniques: electron microscopy (Cote and Krahmer 1962, Thomas and Nicholas 1966), electro-osmotic flow techniques (Stamm et al 1968; Stamm 1970; Siau 1981), filtration of aqueous suspension of particles of known sizes (Liese 1965; Megraw 1967), and the permeability measurement using the Adzumi equation (Siau et al 1981; Bao, Siau, and Avramidis 1986; Comstock 1967; Sebastian et al 1965). As indicated in Table 2, there is a substantial difference between the pit-pore radii of sapwood and heartwood. The volumetric flow rate is proportional to the fourth power of the pore size. Therefore, one would expect much reduced treatability of the heartwood of these species given the other conditions being constant. For example, as shown in Fig. 1, experimental results from about 100 southern pine specimens indicated that the total retention in preservative treated wood decreases exponentially as the percentage of heartwood increases (Huffman 1996). This is attributable to the fact that heartwood possesses much lower permeability,

Even though the permeability of an unaspirated pit membrane in a softwood is relatively high due to the

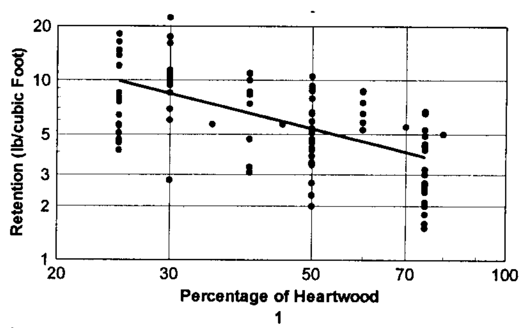

Fig. 1—Relation between amount of heartwood and retention in southern pine (Huffman 1996).

presence of the open margo structure, the function of the open margo can cease upon aspiration of pit membranes (Cote 1990). During drying prior to preservative treatment, the pit membranes aspirate as water is removed from the cell and the air-water meniscus passes through the membrane. The aspirated pit membrane results in a tight seal between the membrane and the pit opening due to hydrogen bonding, capillary forces (Thomas and Kringstad 1971), and, in heartwood, the adhesion of extractives.

The degree of pit aspiration and encrustation with extractives is closely related to the location of the wood in the tree. After investigating about 200 *Pinus radiata* trees of 27 years old grown in Australia, Harris (1954) concluded that the mean percentage of the aspirated pits in the sapwood, transition zone, and the heartwood are 30%, over 90%, and 96%, respectively. The increase in pit aspiration through these regions is relatively gradual. However, Nobuchi and Harada (1983) found that the percentage of aspirated pits in *Cryptomeria japonica* increased sharply at the border of the sapwood and transition zone from 10% to 60% and with a further slight increase in the heartwood. Similar changes in encrustation percentage have been found in

Table 3—Volume Percentages of the Cells in the Selected Hardwoods
(Panshin and deZeeuw 1980)

Species	Vessels	Fibers	Rays	Parenchyma
Hard maple (*Acer saccharum*)	21.4	66.6	11.9	0.1
Red maple (*Acer rubra*)	18.0	68.0	13.3	0.1
Tulip poplar (*Liriodendron tulipifera*)	36.6	49.0	14.2	0.2
Cottonwood (*Populus deltoides*)	33.0	53.1	13.7	0.2
Red oak (*Quercus rubra*)	21.6	43.5	21.4	13.5
Sweetgum (*Liquidamber styraciflua*)	54.9	26.6	18.3	0.2

Pinus strobus, P. densiflora, and *P. banksiana* (Yamamoto 1982). Yamamoto found that the degree of encrustation of the bordered pit membranes in tracheids was essentially zero in the sapwood, gradually increasing through the transition zone to almost 100% in the heartwood. Not only does the heartwood have a larger percentage of aspirated pits, the reversibility of the pit aspiration is also reduced. In sapwood, pit aspiration is partially reversible under certain conditions such as treating pressure or resoaking in water (Thomas and Nicholas 1966). However, the reversibility is reduced in heartwood due to the adhesion of extractives between the aspirated pit membrane and the pit opening (Thomas and Nicholas 1966). Therefore, it is seen that the reduction in treatability due to pit aspiration and pit encrustation has greater implications in heartwood than in sapwood (Krahmer and Cote 1963; Liese and Bauch 1967).

Because most of the pits are concentrated on the radial surfaces, rays may be the major conduits for radial flow (Erickson 1970; Cote 1963). The function of ray tracheids is especially important for the impregnation of preservatives into poles or flat sawn lumber (Behr et al 1969; Cote 1989). Ray tracheids are constant features of the woods of *Pinus, Picea, Larix, Pseudotsuga, and Tsuga* (Panshin and deZeeuw 1980). Due to the function of these rays, for some wood species in these genera such as *Pinus sylvestris,* the permeability along the radial direction is higher than that along the tangential direction (Banks 1970). It appears that the effectiveness of the ray tracheids depends on their volume percentage in the wood and the condition of their pits. In studying the treatability of spruce wood, it has been suggested that the low ray tracheid content is a major factor contributing the refractory nature of these species (Baines and Saur 1985). Liese and Bauch (1976) concluded that the primary reason for the poor treatability of *Picea abies* is due to the low concentration of the ray tracheids. The refractory nature of *Pseudotsuga menziesii* was also attributed to the pit encrustation and the low volume fraction of the ray tracheids. Ray tracheids are generally more effective for conducting radial flow than the ray parenchyma cells (Buro and Buro 1959; Cote 1963; Erickson and Balatinecz 1964). This may explain why the ray tracheids surrounding the ray parenchyma cells are often impregnated by preservative, while the parenchyma cells are not impregnated (Liese and Bauch 1967).

2. Hardwoods

Most hardwood species contain four major cell types: vessels, fibers, rays, and axial parenchymas. Their volume percentages for selected hardwood species are shown in Table 3.

During preservative treatment, the treating fluids flow in an interconnected network of these cells as illustrated in Figure 3 (Siau 1984). Therefore, all the components including the conducting channels and their connections contribute to the treatability of hardwoods. However, experimental results in the literature generally show that vessels are by far the major avenue in conducting treating fluids. Therefore, the size, distribution, and condition of the vessels are important factors affecting the treatability of hardwoods. Vessel diameter of the diffuse-porous species is generally between 20 and 100 μ m. Average vessel diameter of the ring-porous species varies conspicuously between the earlywood and latewood. Average vessel diameter in the earlywood ranges between 50 and 400 μ m, while that in latewood ranges between 20 and 50 μ m. The typical concentration of vessels when counted in cross section is on the order of 15,000/cm^2 (Siau 1984).

Vessels are composed of vessel elements connected end to end through perforation plates. The resulting vessels can be long and continuous. For example. vessels up to three meters in length have been reported (Thomas 1981) Tyloses and various gummy, resinous, and chalky exudates often form in the vessel lumens within the heartwood and transition zone (Hillis 1987) The formation of these materials will substantially reduce the treatability of the heartwood and the transition zone (Kumar and Dobriyal 1993; Perng, Brebner, and Schneider 1985) In their pioneer work, Teesdale and MacLean (1918) found that the treatability of hardwood was directly related to whether the vessels contained tyloses and, if tyloses were present, the completeness of the vessel blockage by the tyloses. In a more recent work by Thomas (1976), the role of tyloses in reducing the treatability of hardwood is further confirmed. A practical example of the role of tyloses in blocking fluid flow is the use of white oak to make barrels for wine and whisky (Cote 1990) The vessels in the heartwood of most white oaks me completely blocked by tyloses. Besides tyloses, gummy and chalky extractives can also reduce the treatability of hardwoods (Siau 1984) It worth noting that since tyloses and extractives are more likely to be found in the heartwood (Panshin and deZeeuw 1980), one would expect that these factors are responsible for the reduction of the heartwood treatability.

Rays and fibers occupy about 10 to 20%, and 25% to 75%, respectively, of the total volume of hardwoods. When the vessels are occluded with tyloses and extractives, the literature seems to indicate that the rays and fibers could function as fluid conducting channels. One may also be able to deduce this conclusion from Figure 3. It has been experimentally observed that there is a relatively high concentration of preservatives in the ray tissues when various hardwoods were treated with CCA and creosote (Greaves and Levy 1978; Bosshard 1961). It has also been reported that ray parenchyma cells are important channels for radial flow in some species (Behr et al 1969). However, Teesdale and MacLean (1918) concluded that hardwood rays are not important in transverse distribution of creosote preservatives. Fibers in hardwoods are elongated cells with thick walls and small lumen diameters. The fiber lengths range from 600 to 2,300 μ m with a length to diameter ratio on the order of 100. It has found that the conducting channels in the heartwood of hickory were essentially the fibers (Thomas 1976; Teesdale and MacLean 1918) due to a multitude of factors such as the blockage of pits and vessels, isolation of vessels, and the low volume of vessels. Behr et al (1969) observed that treating fluids are transported from fiber to fiber via pits. In the oaks, the vasicentric tracheids can also function as communication means between the intervessel fluid transport (Wheeler and Thomas 1981).

Fluid transport between cells is through the bordered or half bordered pit pairs (Siau 1984; Perng, Brebner, and Schneider 1985). The pit membranes in hardwoods lack the open margo structure of softwood species. Besides this difference, the hardwood pits are generally smaller with a chamber diameter on the order of 6 μ m (Siau 1984). Studies show that the pit membrane in hardwoods is actually permeable despite the lack of a margo (Siau 1984; Thomas 1876; Cote 1963). Apparently the hardwood pit membrane acts like a filter in that the fluid flows circuitously in the membrane. This type of membrane exists in the intervessel bordered pit pairs, between vessel and fiber tracheids, and also between longitudinal and ray parenchyma.

Similar to softwoods, the pit membranes of hardwoods can also exhibit aspiration and encrustation in the heartwood (Panshin and deZeeuw 1980; Hillis 1987). These factors also contribute to the reduced treatability of heartwood in hardwoods (Cote 1963; Krahmer and Cote 1963).

3. Flow Characteristics

Under given treating conditions, the penetration depth of a preservative also depends on its flow characteristics in the interconnected wood cells. Depending on the Reynolds number, the flow of the preservative undergoes in the wood cell network could manifest in three forms: 1) laminar flow, 2) nonlinear flow, or 3) turbulent flow. For flow in a circular tube, the Reynolds number can be expressed as (White 1974, Siau 1984):

$$Re = 2ru\rho/\eta \qquad (2)$$

Where

- Re: Reynolds number
- r: A characteristic dimension of the flow pathway, which depends on the shape of the cross section of the flow pathway. For circular cross-section, r is the radius, cm
- u: The average linear fluid velocity, cm/s
- ρ: The density of the fluid, g/cm^3
- η: The viscosity of the fluid, poise

In laminar flow, the preservatives flow along well defined streamlines. Laminar flow generally occurs when a fluid flows in a long tube at a moderate velocity. In laminar flow, the flow rate is proportional to the pressure gradient, Δp. However, if the length-to-diameter ratio of the capillary is small, flow could become nonlinear. In this case, there will be kinetic energy loss due to the end effects when fluid enters or exits the short tube. Due to the energy loss, flow rate is proportional to $\Delta p^{0.57}$ (Siau 1984). Turbulent flow is due to the breakdown of the laminar flow at high velocity. In turbulent flow, there will be heat energy dissipation due to friction. Due to this energy loss, the flow rate is proportional to $\Delta p^{0.5}$ (Siau 1984). Therefore, in both the nonlinear and turbulent flows, the flow rate would be reduced at a given pressure gradient due to energy losses. The criterion at which each flow occurs can be expressed as (Siau and Petty 1979; White 1974):

Laminar flow	$Re < 0.8\ L/r$	(3)
Nonlinear flow	$Re > 0.8\ L/r$	(4)
Turbulent flow	$Re > 2000$	(5)

Where

L: The length of the capillary, cm
r: The radius of the capillary, cm

The above discussions are based on the assumption that the inside wall of the capillary is smooth. However, it is known that the inside walls of the longitudinal or transverse cells are generally not smooth. For example, the inside walls of the tracheids in Douglas-fir contain spiral thickenings (Panshin and deZeeuw 1980). These thickenings impart spiral "ridge and valley" features on the inside wall of the tracheids. Due to this roughness, the flow characteristics inside the tracheids will be affected. For example, the turbulent flow may develop at a lower velocity than in the otherwise smooth walls. The study of the roughness effect on the flow behavior was not found in the literature.

Durability

In two FPL studies, untreated solid wood stakes, nominally 2" X 4" X 18" (5 X 10 X 45 cm) in dimensions, were vertically set into ground to a depth of half of their length in three locations: Mississippi, Wisconsin, and Maine. The species included southern pine, Douglas-fir, and Englemann spruce installed in December, 1975 and May, 1976 (Gutzer and Crawford 1995); and white pine, red pine, eastern spruce, eastern hemlock, eastern larch and balsam fir (Gjovik and Schumann, 1992) installed in Mississippi and Maine in 1985. The southern pine 2" x 4" (5 X 10 cm) source material contained some sapwood, but an attempt was made to eliminate all sapwood when cutting stakes from that material. The other species were almost entirely heartwood.

In a study at the University of Florida, stakes, nominally 2" X 4" X 24" (5 X 10 X 610 cm), were installed near Gainesville, Florida. Stakes contained both heartwood and sapwood. Before installation, the Florida stakes were treated with 1% of copper naththenate in mineral spirit in a steaming and soaking procedure (Huffman 1996).

From Fig. 2 and Fig. 3, it is seen that stakes of all wood species survived longer in the northern regions than in the southern Mississippi. In southern Mississippi, virtually all heartwood stakes failed within a decade of exposure. Only one southern pine heartwood stake survived for more than ten years. It is known that the ideal fungi growth condition is at a temperature of around 20 to 30 °C and a relative humidity of 80 to 100%. Therefore, apparently, the Mississippi weather is more suitable for the fungi to grow, thus accelerating the degradation process. From Fig. 3, southern pine species possesses better natural durability than other species, while that the heartwood

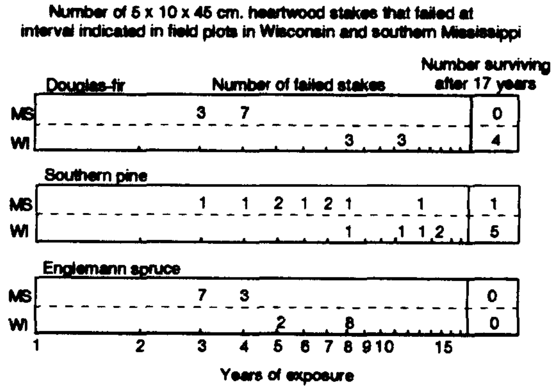

Fig. 2—Natural durability of Douglas-fir, southern pine, and Englemann spruce in Mississippi and Wisconsin.

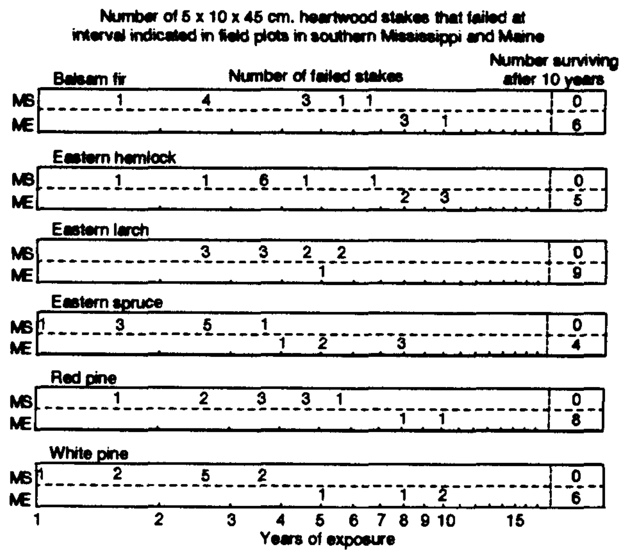

Fig. 3—Natural durability heartwood of the indicated softwood species in Mississippi and Maine.

of white pine and eastern spruce is much less durable than that of other species.

Fig. 4 shows the results from the Florida stakes which installed in ground for about 32 years (Huffman 1996). As seen from these treated stakes, the heartwood is less durable than the sapwood. For example, after 32 years of exposure, almost all the heartwood was degraded. However, at higher retention levels, only a fraction of the sapwood was degraded. For sapwood, the percentage of decay decreased as the retention level

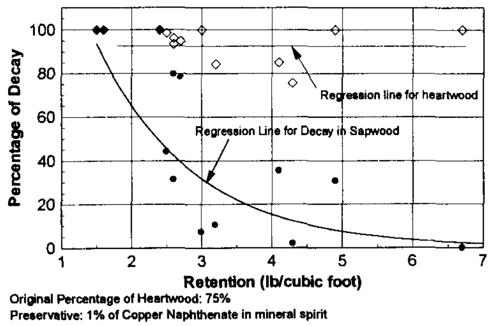

Fig. 4—Percentage of decay in heartwood and sapwood of southern pine after 32 years of field test (Huffman 1996)

increased. As the retention reached 7 pcf treating solution, the decay in sapwood is nearly zero while the decay in heartwood is about 100%. The retention in Fig. 4 reflects the uptake of the preservative solution, which was 1% of copper napthenate in mineral spirits (Moody 1952).

Conclusions

Heartwood treatability is much lower than the sapwood treatability. The factors attribute to the lowered heartwood treatability include the higher extractive content in heartwood, the increased rate of irreversible aspirated pits in heartwood, and, in addition, in hardwood, the tyloses formation in the heartwood. These anatomical factors result in the reduced apparent pit-pore sizes in heartwood and the associated low permeability in heartwood. As a result of these physiological reasons, the treatability of heartwood is much lower than that of the sapwood.

Besides the heartwood region, it seems that the transition zone in some species is also less permeable than the sapwood and less durable than heartwood. This perception makes the transition zone a more sensitive zone in terms of preservative treatment and decay behavior. However, there is no known research has been found which addresses this important anatomical region in terms of its durability and treatability. Therefore, further research in this area is warranted.

Untreated heartwood, with moderate or less natural decay resistance and exposed in ground contact anywhere within the temperate climatic zone, cannot be expected to last more than two decades. In environments of severe biological challenge, such as that of southern Mississippi, untreated heartwoods, exposed to ground contact, cannot be expected to last for a decade.

Climate is an important factor that affects the rate of decomposition of wood exposed in contact with the ground. It is of more importance in affecting the rate of decay in unprotected heartwood than is the degree of natural resistance for heartwoods with moderate or less resistance to decay.

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