A REVIEW OF THE PERMEABILITY, FLUID FLOW, AND ANATOMY OF SPRUCE (*PICEA* SPP.)

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ABSTRACT

This paper reviews the literature discussing some of the qualities and properties of spruce that characterize its refractory nature and influence its treatability. Topics discussed include a review of the permeability of spruce, fluid flow through wood, and the anatomy of spruce.

Permeability and liquid flow through wood are discussed, with an emphasis on differences in flow between sapwood and heartwood and between earlywood and latewood. Literature covering the effects of reversing the direction of flow and decreases in flow with time are also reviewed. Permeability through earlywood and latewood was variable, with neither being more or less treatable than the other. Reversing the direction of flow through wood was shown to increase the rate of flow, which normally tapers off over time.

Discussion of wood anatomy and the path of flow includes a review of longitudinal flow and transverse flow. Pit aspiration and the effects of surface tension, the rigidity of pit membrane, and the adhesion of the torus to pit border are also addressed.

Keywords: Spruce (*Picea* spp.), permeability, refractory, preservative treatment, flow, aspiration, surface tension.

INTRODUCTION

This paper discusses some of the factors that influence the treatability of spruce and was written to provide a background and a summary of the factors that may influence its refractory nature. Many of these factors relate to the anatomical structure of the wood and the path through which preservatives penetrate the material or to the properties of the preservative.

PERMEABILITY AND LIQUID FLOW THROUGH WOOD

Flow in sapwood and heartwood

Preservative treatment of spruce heartwood is a problem because of its nondurable classification and need for treatment to get a long service life. Sapwood is known to be several times more permeable than heartwood (Erickson 1970; Krahmer and Côté 1963), and in conifers, the moisture content (MC) of sapwood is greater than the MC of heartwood (Bamber and Fukazawa 1985). The sapwood in Norway spruce (*Picea abies*) proved readily treatable (Smith 1986). "The primary causes of heartwood and sapwood permeability differences are due to differences in aspiration, and to the amounts and character of the extractives, especially in the heartwood in cases of liquid flow" (Erickson 1970).

Extractives in wood tend to reduce permeability, especially in heartwood (Erickson 1970; Krahmer and Côté 1963), and can have a significant effect on the treating results (Baines and Saur 1985; Nicholas 1982). It is generally agreed that the deposition of extractives in the heartwood of spruce does not confer appreciable durability (Erickson 1970; Krahmer and Côté 1963).

In addition to the general differences between heartwood and sapwood, other anatomical and site influences have been noted to affect treatability. Permeable, treatable spruce (*Picea* spp.) and Douglas-fir (*Pseudotsuga menzeisii*) specimens are known to have longer

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tracheids (Baines 1986; Fleischer 1950; Liese and Bauch 1967), and to have larger lumina (Fleischer 1950). The difference in fiber length has been documented to be as high as 27% (Liese and Bauch 1967). Several studies have found variations in the permeability of Norway spruce (*P. abies*) from different growth sites (Baines and Saur 1985; Peyresaubes 1985). Another study confirms the site influence on the longitudinal treatability of spruce (*P. abies*), but reported it to be of minor importance because it was not seen to affect flow in the radial or tangential directions (Liese and Bauch 1967).

Flow in earlywood and latewood

As with most discussion of the characteristics of spruce, the differences in permeability and fluid flow through earlywood and latewood are also in debate. One study found the lateral movement of preservative in white spruce (*P. glauca*) to be the same in earlywood and latewood (Keith and Chauret 1988). Other authors cite more random variability, where sometimes the earlywood from an annual ring is more permeable than the latewood, and sometimes vice versa (Baines and Saur 1985; Baines 1986). The length of ray tracheids in latewood is about half that of the earlywood cells and is one explanation of why preservative penetration in spruce (*Picea* spp.) is often better in the earlywood than in the latewood (Baines 1986; Liese and Bauch 1967).

The thicker strands and tighter margo texture in latewood pits, their smaller diameter, and the configuration of the pit chamber contribute to their stiffness and resistance to aspiration (Comstock and Côté 1968; Liese and Bauch 1966; Petty 1970). "From observation of dye through the thin sections it seems that the flow was confined to the last-formed earlywood region in which the pits are larger in latewood and have larger gaps between the radial strands in the membranes" (Petty 1970).

Reversal of flow

Reversal of flow direction is a known method of improving the rate of flow through wood. It works even after flow in the original direction has tapered off (Anderson et al. 1941; Erickson and Crawford 1959; Hudson and Henriksson 1956; Nicholas 1982), and the effect has been seen in both hardwoods and softwoods and in filter media (Anderson et al. 1941). One study of Douglas-fir permeability found a hysteresis effect with flow rates (Bailey 1965). The general reasons cited for this change in flow rates include blockage of the pathways by particles or air bubbles and movement of the torus, so that it blocks the opening of the bordered pit.

This increase in flow has been seen in both directions (Anderson et al. 1941; Hudson and Henriksson 1956), and "The efficacy of reversal of the flow in re-establishing the original high rate of flow in permeable woods is a well established fact, which has tended to strengthen the belief that the use of fluctuating pressures would improve penetration in woods that are difficult to treat by ordinary means" (Hudson and Henriksson 1956).

Decrease in flow with time

There are many scenarios suggested to account for the decrease in flow through wood with time. Wood can act as a filter, with small particles or air bubbles in the water gradually blocking the pathways; or polar liquids can cause swelling of the wood fibers. An obvious factor appears to be the fact that "the permeability of spruce (*P. abies*) is related mostly to the structure and condition of the bordered pits in the tracheids" (Liese and Bauch 1967), and that "most of the pits of (black and white) spruce (*Picea* spp.) heartwood are aspirated and therefore cannot be bulged" (Anderson et al. 1941). Various theories have reportedly been eliminated as causes, while others are supported in various conflicting studies.

Many studies agree that entrapped air in wood complicates the measurement of liquid permeability (Anderson et al. 1941; Sebastion et al. 1965; Stamm 1963). Air is believed to be trapped in small openings, such as pits, in the wood structure and block flow (Bailey 1965; Erickson 1970; Sebastion et al. 1965; Stamm 1963). High pressures are required to over-come surface tensions at liquid-air menisci that form in these openings. "These pressures may range from tens to hundreds of pounds per square inch depending on the sizes of the pit openings" (Stamm 1963).There has been some discussion regarding the theory that "entrapped air does not materially affect flow once it is established, although it is relevant in the initial stages of penetration" (Bailey 1965).

"If air is dissolved in the liquid under pressure so that when the pressure is reduced as the liquid traverses the wood a supersaturated condition results, air may be released into the pores in the wood" (Anderson et al. 1941; Erickson 1970; Jagels 1984; Petty 1970). An observation that supports the air blockage theory is that filtering the air out of liquid to be impregnated into the wood has been shown to improve treatment (Erickson and Crawford 1959; Nicholas 1982; Petty 1978).

"Non-polar liquids flow faster than polar liquids of equal viscosity" (Jagels 1984). A study that failed to take into account the effect of moisture gradients reports that "One possible explanation for the difference in penetrability of polar and non-polar liquids is the fact that the permeability of wood decreases with an increase in moisture content (and the resultant swelling effects)" (Nicholas 1982). Another study refutes the observation about swelling as a factor, reporting that once penetration started, "further swelling, if it did occur, would continue for a time after penetration ceased so that when flow was resumed the rate would have decreased still more. This was not found to be the case, rates of flow through softwoods being more frequently increased by standing" (Anderson et al. 1941).This study further states "Electrokinetic changes, swelling, plugging by particles, blocking by air, and pit aspiration have been eliminated as important factors in producing decreasing rate of flow" (Anderson et al. 1941).

WOOD ANATOMY AND THE PATH OF FLOW

Refractory wood is influenced by many interrelated factors including: wood density; earlywood/latewood differences; heartwood formation; the structure of rays, tracheids, resin ducts, bordered pits, and the cell walls. "At relatively high average moisture contents, the moisture content in the outer millimeters (of Norway spruce, *P. abies*) can be much lower, and the more or less completely aspirated pits close to the surface prevent penetration" (Johansson and Nordman-Edberg 1987). "On logs felled during seasons of botanic activity penetration of preservative is poor" (Dahlgren 1985).

The CCA preservative in pressure-treated material is located in several regions along the main path of penetration. Deposition of high preservative concentrations is evidence of preservative flow. Longitudinal fluid flow through coniferous wood has been shown to include passage through the tracheid lumen, the pit aperture (and chamber), and the pit membrane pores (Bolton and Petty 1977; Keith and Chauret 1988; Petty 1970).

In Douglas-fir there is some suggestion that "the transient cell wall capillary network contributes significantly to flow from cell to cell" (Bailey 1965) and that "it appeared that the treating chemicals had existed in the wood not as deposits within the cell cavity (as in the case of creosote), but as relatively uniformly distributed material throughout the cell wall" (Fleischer 1950). Preservative has also been located on the surface of the cell wall or cell lumen of other coniferous species (Fleischer 1950; Hosli 1986; Kumar and Jain 1978), especially at high retention levels where it has been found in tannins (Hosli 1986). A study using X-ray absorpton has shown that "the middle lamella region is generally much more porous than the secondary wall" of Douglas-fir (Bailey 1965). Other sources note that the preservative is concentrated in the middle lamella-primary wall region of spruce (*Picea* spp.), southern yellow pine (*Pinus* spp.), and other softwoods (DeGroot and Kuster 1986; Greaves 1974). "In general between 60% and 65% of the CCA material is fixed to the lignin components" of South African pines (Knuffel 1985).

Longitudinal flow

Three mechanisms are effective in reducing the capillary size of the pit pairs, and any combination of these may be present in a wood species. The mechanisms are pit aspiration, pit occlusion with extractives, and pit incrustation.

Most research has supported the theory that the bordered pit is the primary structure governing the permeability of softwoods (Comstock 1967; Erickson 1970; Keith and Chauret 1988; Krahmer and Côté 1963; Kuroda and Siau 1988; Petty 1970; Sebastion et al. 1965). "Liquid flow in softwoods is primarily through cell lumens and pits" (Jagels 1984). Bordered pits, especially the torus, receive heavy treatment (DeGroot and Kuster 1986; Greaves 1974; Liese and Bauch 1967). "Bordered pits occur mainly on the radial walls of the tracheids of spruce and can be larger than the pits on the tangential walls" (Baines 1986). The largest decrease in permeability occurs in the bordered pit component (Bolton and Petty 1977; Comstock and Côté 1968; Petty 1970) where pit pores contribute more than 90% of the total resistance to liquid flow (Petty 1970). The hypothesis of membrane displacement helps to explain this phenomenon (Petty 1970), but research shows that permanent membrane displacement alone cannot account for the observed reduction of permeability (Bolton and Petty 1977; Comstock and Côté 1968). "Permeability is determined by the interfibril spaces of the margo in the bordered pit" (Liese and Bauch 1967). "The margo (E. Hemlock) is seen to have a very high porosity" (Comstock and Côté 1968).

The number and location of bordered pits have generally been thought to have an influence on the refractory nature of red spruce. The number of conducting pathways has been discussed, with Sebastion et al. (1965) estimating the number of bordered pits in the region of overlap of two tracheid ends (of white spruce, *P. glauca*) to cover a range of 5 to 20, and Petty (1970) reporting that the mean number of 250 (s = 30) pit pores per conducting tracheid (in Sitka spruce, *P. sitchensis*) is very much larger than any of the previous estimates, which were all about one pore per tracheid. Only at the edges of the growth rings do bordered pits exist on tangential walls (Bailey 1965; Panshin and DeZeeuw 1980). This may not matter because Liese and Bauch (1967) report that the number of pits in longitudinal tracheids reportedly has no significant influence on the treatability of spruce (*P. abies*). Many attempts to correlate porosities with permeabilities found there is no general relationship (Bailey 1965).

"The presence of resin canals has no recognizable influence on the permeability" (Liese and Bauch 1966). One source disputes this statement, speaking of some degree of penetration through resin canals and intercellular spaces (Erickson 1970).

Transverse flow

Tangential fluid flow is primarily through longitudinal tracheids and intertracheid bordered pits (Erickson 1970; Keith and Chauret 1988). "In tangential flow the pits in the center regions rather than the ends of the tracheids will be the most effective. The total number of pores being used for tangential flow is approximately 10^3 times smaller than the number for longitudinal flow" (Petty 1970). In a study of Sitka spruce (*P. sitchensis*), the conducting ray tracheids were found mainly in the latewood (Petty 1970); but in white spruce (*P. abies*), the "radial movement of CCA was definitely restricted in the latewood" (Keith and Chauret 1988).

Samples of spruce with good treatability by soaking were found to have a higher percentage of ray area (Liese and Bauch 1967). Lateral penetration in spruce (*P. glauca*) was higher in the radial direction than in the tangential direction (Keith and Chauret 1988).

Ray cells (including ray tracheids) are known to be much better treated than longitudinal tracheids (DeGroot and Kuster 1986; Greaves 1974; Liese and Bauch 1967), and crossfield pit membranes are also well treated (DeGroot and Kuster 1986; Greaves 1974). Liese and Bauch (1967) suggest that the main reason for the limited radial penetration (of spruce, *P. abies*) is the relatively small proportion of ray tracheids, which they regard as the main radial pathways. "The ray tracheids of spruce have unaspirated bordered pits even when air dry, but they are heavily encrusted in the heartwood, which limits fluid penetration" (Baines and Saur 1985; Baines 1986).

Ray parenchyma cells are noted as often lacking preservative treatment because of "the structure of ray cells where ray-parenchyma cells communicate with each other only through small channels of a few microns in diameter with a separating membrane through which only very small plasmodesmata lead" (Liese and Bauch 1967). Ray parenchyma have small, simple pits connecting them to the tracheids, and the ray cells are connected by small plasmodesmata and not by the pits, which could explain why the ray tracheids surrounding the ray parenchyma cells are often penetrated by the preservative, while the parenchyma is not penetrated (Baines and Saur 1985; Baines 1986). "The impermeability of the parenchyma cells is said to be due to the impervious protoplasmic debris which lines the walls" (Bailey 1965). Contrary to other studies, Krahmer and Côté (1963) suggest "Forced penetration parallel to the rays indicated that penetration proceeded to a greater extent in ray parenchyma cells than in ray tracheids."

Rows of ray tracheids are generally interrupted by a parenchyma cell at the border of annual rings in spruce, and this interruption can affect the treatability of the wood (Baines and Saur 1985; Baines 1986; Liese and Bauch 1967).

Pit aspiration

"Three factors are commonly regarded as being involved in pit aspiration: (1) surface tension, (2) rigidity or stiffness of the pit membrane, and (3) adhesion of the torus to the pit border" (Comstock and Côté 1968).

Capillarity and the related surface tension of the withdrawing liquid water force the pit membrane and torus against the pit opening, causing aspiration (Bamber and Fukazawa 1985; Hart and Thomas 1967; Johansson and Nordman-Edberg 1987; Liese and Bauch 1966). Hydrogen bonding between the pit opening, the margo, and hydrophobic extractives contributes to the irreversibility of pit aspiration (Bamber and Fukazawa 1985; Johansson and Nordman-Edberg 1987).

Due to differences in structure, in latewood the forces necessary for closing the pits are higher, so that even the high surface tension of water is not sufficient to bring about aspiration of many of the pits in these tracheids (Liese and Bauch 1966; Comstock and Côté 1968). "The relative rigidity of the pit membrane compared to the surface tension forces will determine whether the torus is displaced sufficiently from the central position to come into contact with the pit border" (Comstock and Côté 1968).

Latewood cell walls have greater thickness (Comstock and Côté 1968; Liese and Bauch 1966), a correspondingly deeper pit structure (Comstock and Côté 1968; Liese and Bauch 1966), and a more rigid pit membrane (Comstock and Côté 1968; Liese and Bauch 1966). The torus is lens-shaped in latewood (Liese and Bauch 1966), often encrusted (Petty 1970); and the aperture of the pit is elliptical in shape, making it difficult for the torus to seal it (Bailey 1965). Latewood pits are known to have a smaller diameter (Comstock and Côté 1968; Liese and Bauch 1966) with one study finding latewood pits to be "about 10 micrometers in diameter, whilst those of earlywood are in the range 15 to 20 micrometers" (Petty 1970).

Some studies have concluded that pit aspiration is an irreversible process (Krahmer and Côté 1963; Johansson and Nordman-Edberg 1987) because "an increased adhesion might occur after pit aspiration due to hemicellulose or pectic-like substances producing a gluing effect" (Liese and Bauch 1967).

"The role of water in the adhesion process appears to be an overriding factor which provides the molecular forces necessary for adhesion to occur" (Comstock and Côté 1968). Forces involved are thought to include hydrogen bonding and Van der Waals-forces.

Some regions of a specimen may be less susceptible to aspiration than others. "A torus aspirated against a wart-covered pit border could reduce the permeability of the pit, but possibly not stop it completely" (Krahmer and Côté 1963).

SUMMARY

Permeability through earlywood and latewood is variable, with neither being more or less treatable than the other. Reversing the direction of flow through wood has been shown to increase the rate of flow, which normally tapers off over time. The major problems in the treatment of spruce relate to the anatomical structure of the material. The bordered pit is normally considered the most important structure regulating the permeability of softwoods, but the rays have also been proven influential. The presence of an abundance of aspirated bordered pits, small ray size, and a high percentage of heartwood contribute to the refractory nature of spruce. Because of these factors, and the many failed attempts to effectively treat many of the different species of spruce, attempts to improve treatment may best be left to the use of physical modifications to the material, such as laser incising, and to the development and use of diffusible preservatives, which are fixable.

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