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A REVIEW OF THE CONFIGURATION OF BORDERED PITS TO STIMULATE THE FLUID FLOW♣

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ABSTRACT

As the bordered pits have generally been thought to have an influence on the refractory nature of softwoods, structural behaviour of this conducting pathways is discussed according to the published literature. Various theories on the role of bordered pits to axial flow are expounded in respect to preservative treatment. Pit aspiration is also reviewed.

Key Words: Fluid Flow, Bordered Pits, Refractory Nature, Pit Aspiration, Softwood.

INTRODUCTION

It is now generally accepted that conifer wood must be regarded as a heterogeneous medium with respect to axial permeability. Erickson and Crawfort (1959) found that after air-drying, permeability to water was reduced to 1-3 % of its value for green wood. Such large changes of permeability are of great importance in wood preservation and in studies of water conduction in the living tree. In this respect, it is generally acknowledged that interfacial forces are partly responsible for many phenomena in timber drying.

According to Bolton and Koutsianitis (1980), such phenomana include the aspiration of bordered pits in coniferous species, the collapse of wood in lumber drying, the reduction of mass (liquid) flow through intercellular passageways due to the blockage of pores by gas embolisms. Components of the medium have thus been identified as tracheid lumina, bordered pits, and the porous bordered pit membranes (Bolton and Beele, 1981).

BORDERED PITS AND FLUID FLOW

For precise causes of the bordered pits to fluid flow and to clarify the reasons for the differential permeability, many anatomical studies have been carried out by several wood scientists. Literature has been well covered by such reviews as Jane (1970), Panshin and de Zeeuw (1980), Tsoumis (1991), Eaton and Hale (1993), and Langrish and Walker (1993). Some of the published literature were however listed here (see Annex).

In coniferous trees, water in sapwood is known to move longitudinally through the tracheid lumina, passing from one tracheid lumen to the next through the bordered pits. The same pathway is also used by preservative liquids when penetrating wood from a transverse surface. Both longitudinal and tangential flow paths in softwoods are predominantly by way of the bordered pits as illustrated in Fig.1, while the horizontally aligned ray cells constitute the principal pathway for radial flow (Comstock, 1970).

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The longitudinal flow of softwoods is much greater than the tangential flow due to the fact that there are fewer pitted cross walls to transverse per unit length in the longitudinal than in the tangential direction (Siau, 1984). It is therefore widely believed that in longitudinal flow through wood the greatest bulk fluid transport occurs through the bordered pits of the axial tracheids. Because tracheid lumina provide an unobstructed pathway for flow, it follows that the bordered pits will largely control the movement of fluids in conifer wood (Petty, 1970).

The number of pits per tracheid varies from 50 to 300 in earlywood with only 10 to 50 rather small bordered pits in latewood (Stamm, 1970), i.e. latewood is more permeable than earlywood in seasoned material whilst earlywood is more permeable than latewood in green wood (Petty and Preston, 1969). In green wood, water may pass from one pit aperture to the other through the pit chamber and the pit membrane pores. When wood however is dried the structure may be modified by the process of aspiration in which the torus moves across the pit chamber to seal off one of the pit apertures, thus preventing fluid flow through the pit (Fig. 2).

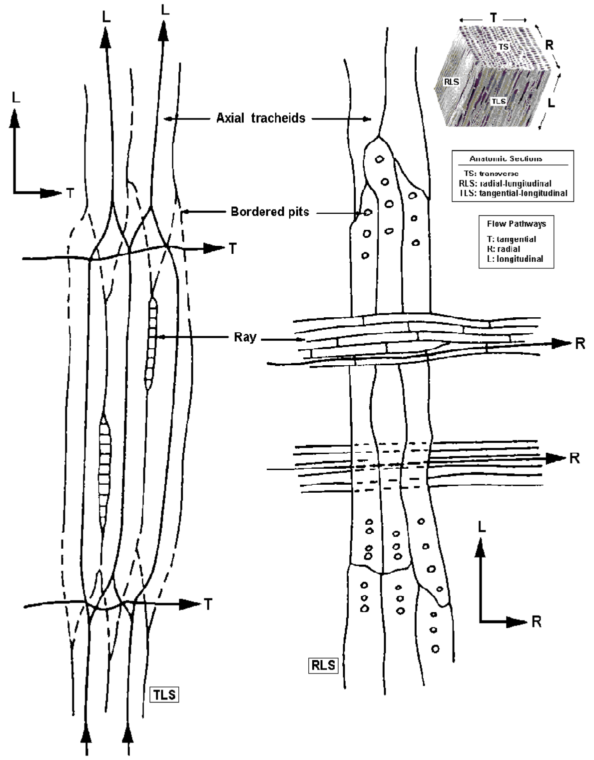

Fig. 1. On the left, a representation of the cellular structure of a softwood in a (TLS) tangential-longitudinal section illustrating the significance of the bordered pits in both longitudinal and tangential flow. On the right, softwood timber in the (RLS) radial-longitudinal section indicating the role of the ray cells in defining the principal pathway for radial flow (after Comstock, 1970).

PIT ASPIRATION

As mentioned by Eaton and Hale (1993), in green softwood sapwood, longitudinal flow is favoured in the earlywood due to a number of factors, i.e. larger lumen diameters, more and larger bordered pits and larger cross-field pits. However, when dried, earlywood bordered pits aspirate due to surface tension forces and permeability is reduced. As mentioned by Tsoumis (1991), a common modification of bordered pit-pairs is the lateral displacement of the membrane. This phenomenon, called aspiration, usually occurs when sapwood is transformed into heartwood or when wood dries. Apparently, it results from high tension forces set up by menisci formed in pit apertures and in pit membrane openings through which water (sap) is moving out. In softwoods, the torus seals one of the pit apertures and, therefore, blocks the passage through the pit. Aspiration makes the wood of fir, spruce, and Douglas-fir difficult to impregnate with preservatives.

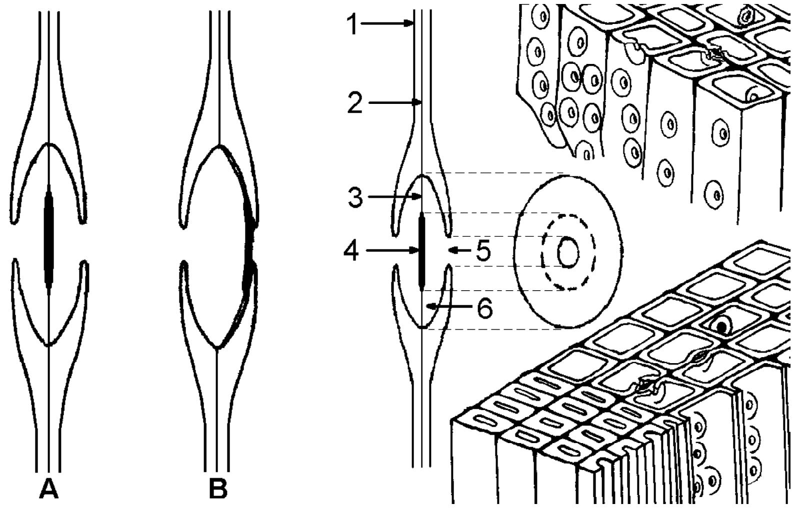

Fig. 2. The diagrammatic representation of an earlywood bordered pit in section transverse to the pit membrane. On the left, (A) Aspect in unaspirated situation, (B) Aspiration of a bordered pit during drying, i.e. the torus is pulled across the pit chamber by surface tension forces. On the right, the structure of a typical dimensions of an earlywood bordered pit: 1 tracheid wall (secondary wall), 2 middle lamella (and primary wall), 3 margo strands, 4 torus, 5 pit aperture, 6 pit chamber (after Petty, 1970).

In 1933, Phillips made what appears to be the first comprehensive study of pit aspiration. He found that drying sapwood caused a gradual increase in the number of aspirated pits with loss of moisture down to the vicinity of the fibre saturation point. At this point, virtually all the earlywood pits became aspirated, whereas about one-third of the latewood pits remained unaspirated. He described the greater tendency of latewood pits to resist aspiration to the greater rigidity of the latewood pit membrane. Liese and Bauch (1967) reported observing the same phenomena.

Accordingly, the condition of bordered pits have significant influence on permeability of softwoods. In this case, the amenability of fluid flow is usually greater in green conditions of wood than in its dried conditions. During drying, capillarity and the related surface tension of the withdrawing liquid force the pit membrane and torus against the pit opening, and hence, causing aspiration effectively.

To sum up, the mechanism of the pit aspiration could be outlined as follows:

a) the liquid transport from one tracheid to another takes place through the bordered pits quite easily in the green condition make facilitation to fluid flow: greater permeability,

b) drying can aspirate the bordered pits and cause cessation to flow: lower permeability which was due to pit membrane deflection and this phenomenon is found to be higher in earlywood than in latewood.

Structural Components

The most of the earlier studies were designed to observe the experimental findings to understand what extent the decrease in axial permeability is caused by aspiration and consequent reduction in the number of conducting pits, by changes in the number and size of the pit membrane pores, or by changes in the proportion of the tracheids which are conducting. Whilst decreases in the permeability of wood to liquids may be attributed to pit aspiration, little or no investigation has been made in which all are measured for the same wood specimen to study the effects of drying. In this case, Stamm (1964) described the seperate methods which exist for the estimation of all these characteristics. Petty (1969), however, developed a method which allows the pit membrane pore radius, the total number of conducting pit pores, the tracheid lumen radius and the total number of conducting tracheids to be evaluated for a single specimen from measurements of gaseous permeability at various mean pressure.

At one time it was thought that all significant resistance to flow was generated by the pit margo pores in the longitudinal tracheids. However, Petty and Puritch (1970) were able to show that at least two structural components offered resistance to flow: these components were idendified as the tracheid lumina and pit margo pores. Similarly, Smith and Banks (1970) considered that two components offered resistance to flow, but in this case the components were identified as the tracheid lumina and the entire bordered pit system. Bailey and Preston (1970) suggested that the annulus bounded by the pit border (on one side), and the torus (on the other) should offer finite and significant resistance to flow. Bolton and Petty (1975) were able to show that parts of the bordered pit system other than the pit margo pores contributed to the total resistance to flow. These authors were of the opinion that this third structural component was the pit aperture.

Surface Tension

Aspiration of the bordered pits of softwoods is considered to occur because of pressure differences between adjacent tracheids which develop when the wood is drying (Jane, 1980). Liese and Bauch (1967) however showed that if water was replaced with liquids of lower surface tension, aspiration did not occur and concluded that pit membrane closed as a result of surface tension. It was further shown by Thomas and Kringstad (1971) that although surface tension was responsible for displacing the pit membrane, closing of the membrane was dependent on hydrogen bonding between the pit membrane and interior surface of the pit chamber. They concluded that, as well as having the appropriate surface tension, the evaporating liquid must be able to form hydrogen bonds possessing both hydrogen donor and acceptor properties. The liquid must also have the ability to swell wood as much as water.

The percentage of aspirated bordered pits in the transition wood of *Cryptomeria japonica* was determined by Nobuchi and Harada (1983). Non-aspirated pits in the sapwood rapidly became aspirated at the boundry of the transition wood whose moisture content remained high and parenchyma cells alive. Yamamoto (1982) examined the incrustation of the bordered pit membrane at the transition wood of *Pinus* species with UV absorbing substances (heartwood substances) and showed that it began in the innermost sapwood and preceded the decrease of moisture content. He also reported that peroxidase activity of the bordered pit membrane disappeared at the same, while its activity in ray parenchyma cells increased at the transition wood only during the growing season. Saka and Goring (1983) investigated the distribution of inorganic constituents in different morphological regions across the stem of *Picea mariana*. All of the elements were concentrated and localized in the tori and half-bordered pit membranes and some elements as Na, Cl, K, S and Al were only deposited in the transition wood. These results showed the screening function of bordered pit membranes and the blockage of transported water in the transition wood by the incrustation. Incrustation or aspiration of bordered pits in the innermost sapwood or outer part of the transition wood preceding the moisture decrease obviously are key factors in the explanation of the nature of heartwood formation.

COMPARITIVE STUDIES

Aspiration makes the most of the softwood species difficult to impregnate with preservative solutions under pressure, and hence this species became refracted, i.e. resistant to fluid flow and require a long period of treatment (EN 350, 1994 part 2). In this case, spruce sapwood is generally regarded as being very permeable to fluid before drying (Erickson, 1970) but after drying it is much less permeable (Baines and Saur, 1985) and is classed as resistant to preservative treatment (Siau, 1984). It is generally believed that the cause of loss of permeability is axial tracheid bordered pit aspiration in the earlywood where the pit margo and torus are displaced when air bubbles move past the membrane as would typically occur during drying (Petty, 1972).

According to Phillips (1933), the degree of pit aspiration in Norway spruce as in the region of 97 % while in Scots pine (which is known as a permeable species) it was in the region of 93 per cent. Although permeability is an extremely variable property of wood between the species, it is unlikely that this totally accounts for the differences in longitudinal permeability of these two softwood species.

Liese and Bauch (1967) examined the In the air-dried sapwood samples of the *Pineceae*, and observed that in the earlywood all bordered pits were closed, whereas in the latewood differences between species were noticed. In *Abies alba*, the bordered pits in the radial cell wall are mostly aspirated as in the earlywood,whereas the tangential pits, especially present in the last cell-rows of the annual rings, were open. However, in the latewood of *Picea abies* 20-25% of the pit membranes were found to be unaspirated. In *Pinus sylvestris* even up to 50% of the pits remained open. These observations provide an explanation for the differential penetrability of tracheids in earlywood and latewood of one species, and of the latewood alone between the species.

ALTERNATIVE SEASONING METHODS: SOLVENT DRYING

According to Comstock and Cote (1968), it is evident that the permeability of the wood (*Abies grandis*) was affected markedly by the method of drying, i.e., specimens dried after solvent exchanging water for ethanol, acetone, benzene and ethyl were examined and the invariable result was that the majority of the pits were unaspirated, which corresponds to the permeability. That the earlywood remains conducting after solvent-drying is in agreement with the findings of other workers (Erickson and Crawford, 1959; Liese and Bauch, 1967), and may be attributed to the pit aspiration of earlywood bordered pits being prevented by the absence of water at the time of drying. In Comstock and Cote's work (1968), Red pine was reduced to about 15 percent of its original permeability and Eastern hemlock was reduced to less then 1 percent of its original permeability. There does not appear to be any trend in permeability with either surface tension or swelling of the liquids, so it seems unlikely that the higher permeability is produced by evaporation of the solvent from the wood.

In Petty and Puritc's work (1970), the solvent dried specimens show much less variation in gas permeability than the air-dried ones. This may be explained by the presence of a varying proportion of latewood in the specimens, which does not affect the permeability of solvent-dried specimens in which virtually all of each growth ring is conducting.

Decreases in the permeability ow wood to liquids with respect to time can be attributed to the growth of gas embolisms in the flow paths. Bolton and Petty (1978) stated that, such embolisms develop in the presence of particulate gas nuclei, or where the pressure gradient in the wood is large enough to cause gas in the liquid to come out of solution. With this knowledge, many researchers have been able to obtain flow rates more nearly constant with respect to time, by subjecting their test liquids to such treatments as microfiltration, boiling or distillation, shock-cavitation, and storage under vacuum.

CONCLUSIONS

The bordered pits governing the longitudinal permeability of softwoods has been discussed according to the published literature. Although this review covers mainly the period from 1913 to 1987, some later studies are also included as background material.

This review will interest wood scientists concerning with wood preservation both in research institutes and at universities, and that it will suggest to some of them possible lines for research.

NOTE

♣This paper was originally presented at the 36th Annual Meeting of the International Research Group on Wood Protection held in Bangalore, India, 24-28 April 2005 (Document No: IRG/WP 05-40315) but it has been revised.

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