LONGITUDINAL WATER PERMEABILITY OF WESTERN HEMLOCK. I. STEADY-STATE PERMEABILITY[1]

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ABSTRACT

Average initial permeability to water of sapwood was found to be 9.6×10^{-10} cm^2, that of wetwood from heartwood was 6.64×10^{-10} cm^2, and that of normal heartwood was 4.4×10^{-12} cm^2. All the specimens were never-dried, approximately 0.95 cm in diameter and 2 cm long, and were embedded in a lucite tube using epoxy resin as binder.

Using polyethylene glycol 1000 as an embedding agent, 23% of sapwood pits, 42% of pits in wetwood from heartwood, and 84% of pits in normal heartwood were found to be aspirated. Scanning electron microscopy revealed that the normal heartwood of freeze-dried heartwood was heavily incrusted, but that of wetwood was relatively free of incrustation. High water permeability of wet heartwood was attributed to a low level of pit aspiration and freedom from incrustation.

Both sapwood and wetwood exhibited deterioration of permeability with time. In sapwood the cause was considered to be time-dependent pit aspiration because of hydrostatic pressure differentials during testing, but in wetwood the deterioration was attributed to extractives transported by water and deposited on pit membranes to form an impermeable coat of film.

A further proposal is that formation of wet pockets during drying of western hemlock lumber is caused by formation of an impermeable zone from the incrustation of pits by extractives during the migration of water, which traps the moisture in lumber.

Additional Keywords: *Tsuga heterophylla*, sapwood, heartwood, wetwood, pit aspiration, transmission electron microscopy, scanning electron microscopy.

INTRODUCTION

Industrial processes such as pulping, preservation, and dimensional stabilization require impregnation of liquids into wood, but drying requires the removal of a liquid from the wood. The operation of these processes is controlled to a great extent by the ease or difficulty with which fluids move through wood. Because information on permeability of wood to liquids should be valuable to these processes, the longitudinal permeability of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) to water was studied.

Western hemlock is one of the western species whose uses and value have increased considerably in the past decade. It also is one of the species containing wetwood[2] or sinker wood in the heartwood zone. Wetwood causes problems in pressure impregnation of wood and drying by forming wet pockets.[3] A few investigations of the longitudinal water permeability of sapwood of western hemlock and the effect of drying and storage on permeability are available,

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[1] Paper 856, School of Forestry, Oregon State University.

[2] Wetwood is heartwood that has a much higher moisture content than normal heartwood in the never-dried condition, appearing as a wet zone to the naked eyes.

[3] Wet pockets are zones of high moisture content remaining in lumber after it has been subjected to normal commercial kiln-drying schedules for the species.

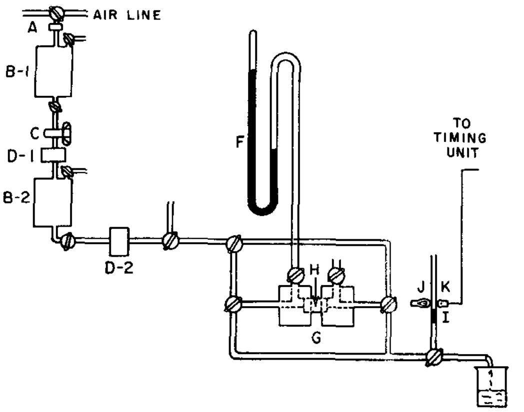

FIG. 1. Schematic diagram of steady-state permeability apparatus. A. In-line filter holder, 2.5-cm diameter. B (1 & 2). Water tank; plexiglass cylinder 16.5 cm outside diameter. C. Water pressure regulator; maximum input, 300 psi; minimum output, 3 psi. D (1 & 2). In-line ultrafilter; Gelman, 47-mm diameter; pore size, 0.45 μm. F. Closed mercury manometer. G. permeability cell. H. Test specimen. I. Wood float (in vertical capillary tube). J. Light source. K. Photoelectric cell.

but they are limited to study at low hydrostatic pressure (Erickson and Crawford 1959; Erickson 1960).

Longitudinal water permeability of wetwood in western hemlock was given considerable attention in this study because of its slower drying rate when compared to normal heartwood (Kozlik et al. 1972). In addition to having a considerably higher moisture content than normal heartwood, wetwood had significantly higher specific gravity, which was attributed to higher concentrations of extractives in the wetwood (Schroeder and Kozlik 1972), and which possibly hindered the drying rate. A major portion of the extractives in western hemlock heartwood is lignans, and the three found in hemlock are α-conidendrin, hydroxymatairesinol, and matairesinol. Although floccosoids in western hemlock contain large amounts of α-conidendrin (Barton 1963), Krahmer et al. (1970) showed that considerable concentrations of extractives assumed to be lignans lined most tracheid walls as surface films throughout the heartwood and often incrusted the bordered pits of *dried wood.* The lignans are only partially water-soluble, and upon drying, these deposits could be observed migrating to the end surface of the small wood samples.

The purpose of this investigation was to study the longitudinal water permeability of green sapwood, normal heartwood, and wetwood of western hemlock and to find the possible cause of the differences in their permeability.

EXPERIMENT

Material preparation

Pieces of green, freshly cut western hemlock, containing sapwood, normal heartwood, and heartwood with wet pockets, were selected from trimsaw tailings at the Burkland Lumber Company sawmill in Turner, Oregon. Ten blocks prepared from each of these three zones were 5 cm in the radial and tangential directions and 4.5 cm along the grain. Because differentiating sapwood from normal heartwood of western hemlock often is difficult, wood within 5 cm of the vascular cambium was considered sapwood.

Specimens for permeability measurements were round dowels, 1 cm in diameter and 4.5 cm long, cut from each block such that the grain direction of the wood was parallel to the dowel axis. Each dowel was all sapwood, normal heartwood, or wetwood heartwood. The lateral surfaces of the dowels were sanded on a lathe to obtain the smooth surface necessary for tight fit of the assembled test specimens. Each dowel was washed, stored in refrigerated distilled water, and saturated under vacuum.

To assemble the test specimens for permeability measurements, the lateral surface of each dowel was flash-dried with a high-intensity heat lamp, coated with epoxy cement, and carefully inserted into a piece of lucite tubing. After the cement had set, the lucite tube-wood dowel assembly was cut to a length of about 2 cm by removing about 1.3 cm from each end. Each end was trimmed with a new razor blade, and the assembled specimens were stored in dis-

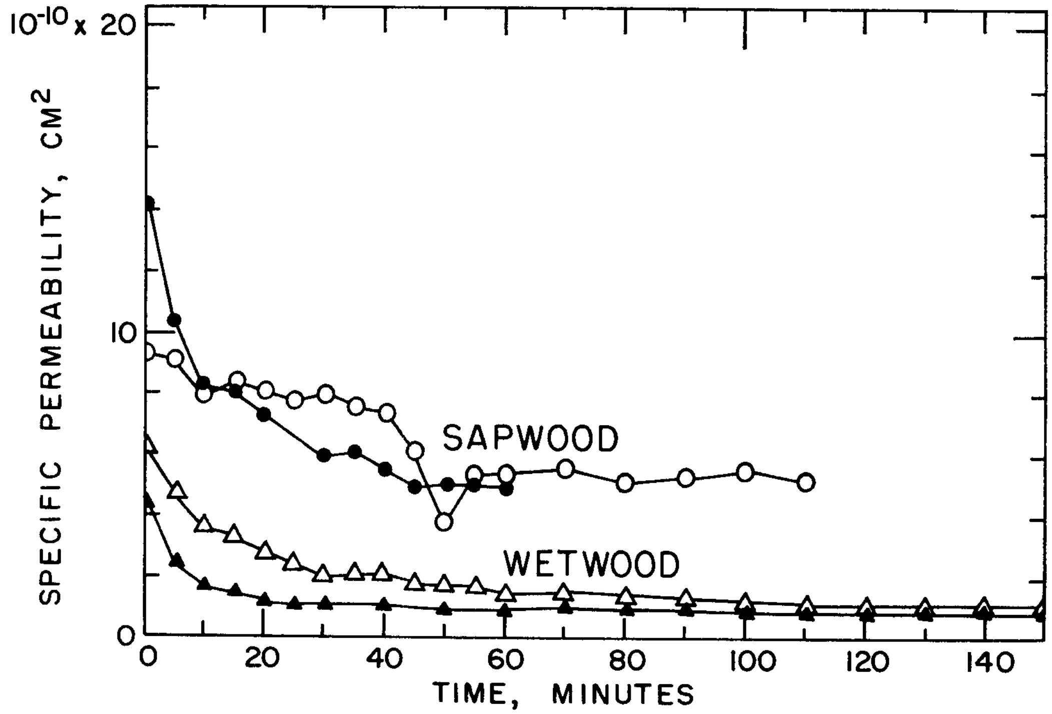

FIG. 2. Typical relation of steady-state longitudinal water permeability of western hemlock sapwood and wetwood to time.

tilled water under vacuum. Immediately before the permeability test, a fresh surface of wood again was exposed on the ends of each specimen by removing a thin section with a razor blade.

Because blockage by air bubbles is the most critical factor causing a decrease in steady-state flow of water through wood (Kelso et al. 1963), care was taken to remove most of the air and foreign materials from the water. This was achieved by boiling freshly distilled water for about 3 hr, filtering it through an ultrafilter, cavitating it under vacuum, and drawing off air bubbles that formed.

Permeability apparatus

The experimental apparatus is shown schematically in Fig. 1. Air pressure of 40 psig was applied to tank B-1, and this pressure was reduced to the desired level for a given experiment with a pressure regulator (C) located beneath the tank. A 0.45 μm ultrafilter, D-1, between tanks B-1 and B-2 eliminated particulate matter from the water and acted as an air trap, as did the second ultrafilter, D-2, downstream from tank B-2.

A manometer (F) attached to the upstream end of the specimen holder (G) was used to measure pressure during each flow determination to assure constant pressure differences across the specimen. The downstream end of a test specimen was open to atmospheric pressure.

The flow rate measuring unit (I, J, K) provided a precise means of measuring the volume of water flowing through a specimen. When the stopcock was positioned correctly, a float (I), which was displaced by a known volume of water, moved up the column and passed between a pinhole light source (J) and a photoelectric cell (K), thereby activating a relay switch that started and stopped a universal counter wired as a precision timer. Timing started

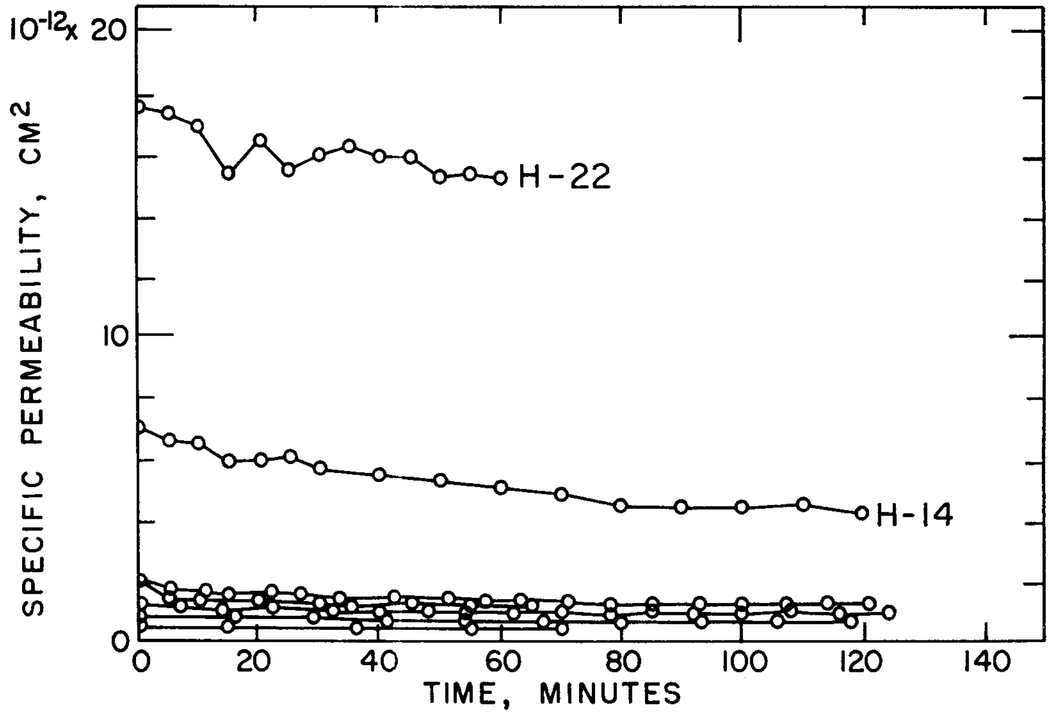

FIG. 3. Relation of steady-state longitudinal water permeability of western hemlock heartwood to time.

when the float rose up the capillary tube and broke the beam of light, and timing stopped when the bottom of the float moved out of the light beam. The time required for the float to pass through the beam was considered equivalent to the time required for the volume of water displaced by the float to pass through the wood specimen.

Specific permeability of the wood was calculated from Darcy's law:

$$k = VL\eta/tA\Delta p, \qquad (1)$$

where k is the specific permeability,[4] A is the effective cross-sectional area of the test specimen, L is the length of the specimen, η is the viscosity of water, and t is the time for a volume of water (V) to be displaced at a pressure difference, Δp, across the specimen.

Two calibrated floats permitted measurement of a range of flow rates. Float volumes were determined five times for each float by placing a syringe, calibrated to 0.01 cm³, upstream from the measuring unit and determining the amount of water required for the float to pass across the photoelectric light beam. The large float displaced 0.40 cm³ and was used for permeability measurements of specimens from sapwood and wetwood. The small float displaced 0.02 cm³ and was used to measure the permeability of normal heartwood. The capillary tube in which the float moved was 7 mm inside diameter for the large float and 2 mm for the small float.

During a permeability determination, the flow-rate measuring unit was used to obtain flow readings at about 5-min intervals during the test. For the steady-state measurements, Δp was held constant and each test of permeability was run for about 1 to 2 hr.

Flow direction was not reversed during the study.

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[4] The dimension of k is (cm³ of fluid)/(cm of wood), but the unit of cm² is widely used in practical engineering, and hence was used in this paper.

FIG. 4. Scanning electron micrograph of bordered pit membrane in normal heartwood of western hemlock.

Determination of pit aspiration

Bordered pit aspiration was determined by microscope observation of tangential sections of springwood. Sapwood, normal heartwood, and wetwood heartwood of green material were cut into thin wafers approximately 0.3 cm along the grain. To preserve the natural condition of the pit structure, they were immersed in a 25% aqueous solution of polyethylene glycol 1000 for a week to permit the polyethylene glycol to diffuse into the wood. The solution with specimens then was gradually heated to 50 C and maintained at that temperature for 3 more days to evaporate water, removed, and cooled to ambient temperature. A 10-μm-thick tangential section of the wax-embedded wood was cut with a sliding microtome, flushed with water to remove the wax, stained, and observed for pit aspiration with the light microscope. Partially aspirated pits were those where space could be observed between the torus

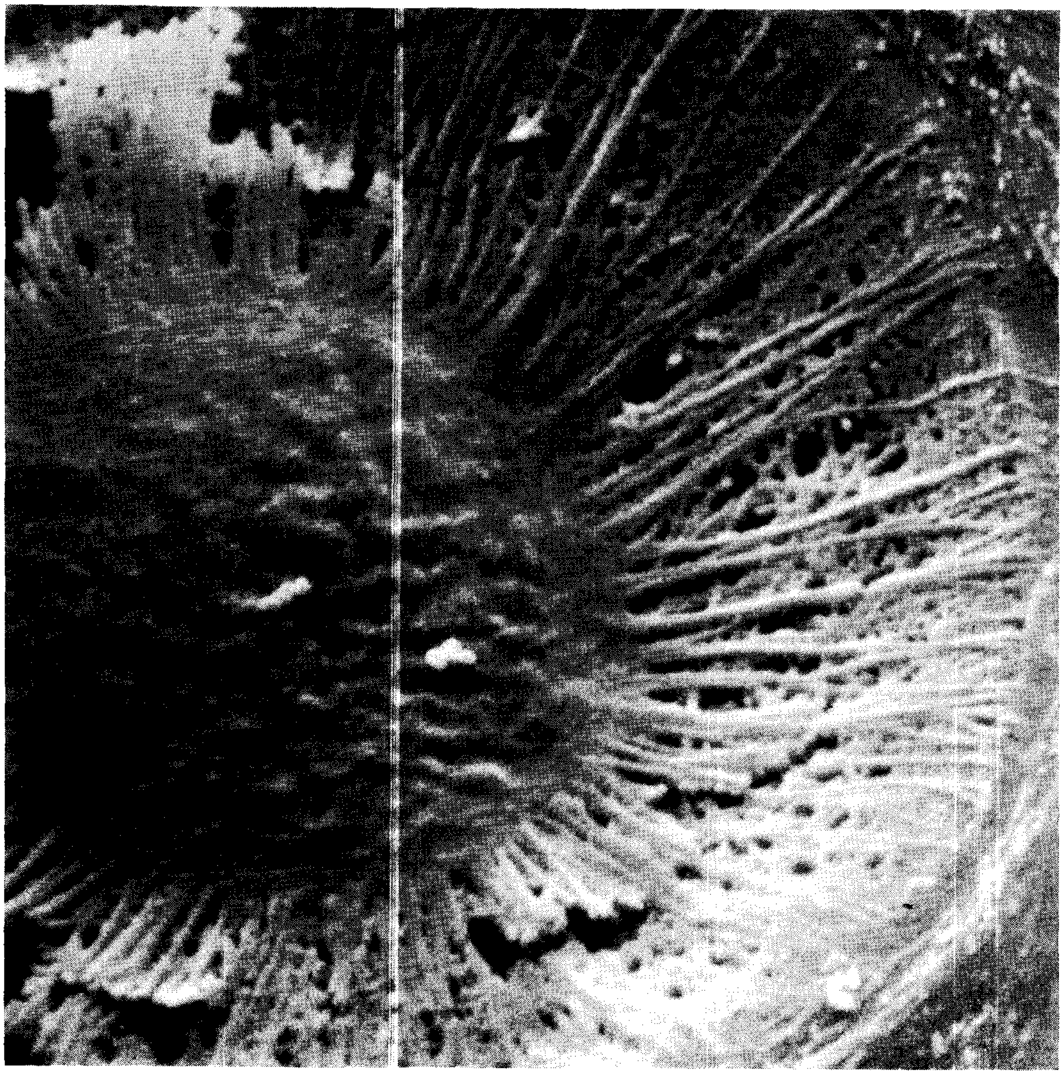

FIG. 5. Scanning electron micrograph of bordered pit membrane in wetwood of western hemlock.

and the pit aperture, but the torus was not in the central position between the two apertures.

Electron micrography

One green sample each of wetwood heartwood and normal heartwood about 0.5 cm along the grain was immersed in liquid nitrogen. The frozen specimens were freeze-dried under vacuum for 48 hr. Specimens were split to expose radial surfaces, which then were metal-coated for scanning electron microscope observations (Collett 1970). Because only replicas were used for transmission electron microscopy, the direct-carbon replica method was followed for specimen preparation (Côté et al. 1964).

RESULTS

Permeability decreased with time for eight of the ten sapwood specimens. Duration of tests ranged from 25 to 120 min at a pressure of 10 psi. The initial permeability of sapwood ranged from 3×10^{-10} cm^2

FIG. 6. Electron micrograph of bordered pit membrane in *air dried* wetwood of western hemlock. (This picture is supplied by Allen Doerksen, School of Forestry, Oregon State University.)

to 16 × 10^{-10} cm^2 and averaged 9.65 × 10^{-10} cm^2 (Table 1, Fig. 2). The final permeability of sapwood ranged from 1.5 × 10^{-10} cm^2 to 15.0 × 10^{-10} cm^2 and averaged 7.59 × 10^{-10} cm^2.

Of ten normal heartwood specimens prepared for testing, seven were suitable. The epoxy seal on the other three appeared inadequate. Five of the seven specimens exhibited constant flow rates with time, but the other two showed a slight decrease with time. Those specimens exhibiting constant flow had initial permeabilities in the range of 0.5 × 10^{-12} to 2 × 10^{-12} cm^2, but the initial permeabilities of the two specimens (H-22 and H-14) showing decreasing flow were considerably higher at 7.0 × 10^{-12} cm^2 and 17.6 × 10^{-12} cm^2 (Fig. 3). Test times for normal heartwood ranged from 60 min to 124 min. A differential pressure (ΔP) of 6.9 × 10^5 dynes/cm^2 (10 psi) was applied to relatively permeable specimens, and 1.7 × 10^6 dynes/cm^2 (25 psi) was applied to relatively impermeable specimens.

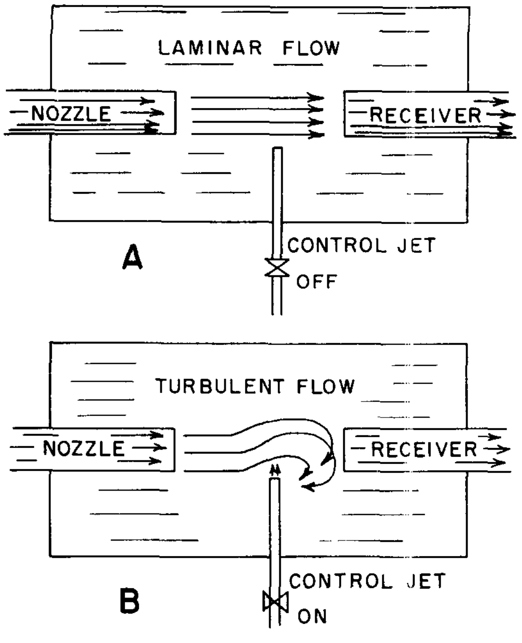

FIG. 7. A schematic of a fluid turbulence amplifier (Henke 1966).

Initial longitudinal water permeability of wetwood was close to that of sapwood, but the permeability values at the end of the tests had decreased markedly. The initial permeabilities ranged from 1.4×10^{-10} cm^2 to 17.5×10^{-10} cm^2 and averaged 6.64×10^{-10} cm^2, and the final permeabilities ranged from 0.2×10^{-10} cm^2 to 8.0×10^{-10} cm^2 and averaged 1.6×10^{-10} cm^2 (Fig. 2).

The results of observations on pit aspiration also are shown in Table 1. Of the bordered pits from normal heartwood, 84% were aspirated. For sapwood and wetwood, the amount of pit aspiration was 22% and 42%, respectively.

Electron micrographs of bordered pit membranes from normal heartwood and wetwood are shown in Figs. 4, 5, and 6. In freeze-dried normal heartwood, incrustation is generally observed on the pit membrane (Fig. 4). The freeze-dried specimen of wetwood appears to be relatively free of heavy incrustation (Fig. 5). In air-dried samples of wetwood, heavy incrustation has been observed (Fig. 6).

DISCUSSION

Several factors generally considered to influence the flow of water through wood are blockage by air bubbles, aspiration of bordered pits, and incrustation with extractives. In the sapwood samples and the wetwood samples, a decrease in permeability was observed during the initial period of flow under steady-state conditions. Work by Kelso et al. (1963) indicated that air blockage was the predominant cause of a decreasing flow rate of water through wood under uniform pressure. The influence of air blockage was considered negligible in our study, however, because of the precautions taken to remove air from the water and the observation that although bubbles appeared downstream from the first ultrafilter (D-1, Fig. 1), none was observed beyond the second ultrafilter (D-2) or the test specimen. Furthermore, the flow rate of normal heartwood, which has lowest pore-size distribution, did not deteriorate with time. Therefore, other factors were considered responsible for the observed changes in permeability.

In sapwood, extractives normally are not present in longitudinal tracheids, and decreasing permeability during testing might be attributed to aspiration of bordered pits. Bordered pits frequently aspirate during

TABLE 1. *Longitudinal water permeability and degree of pit aspiration of green western hemlock wood*

	Permeability (10^{-10} cm^2)				No. of pits observed	Pits (%)		
	Initial		Final					
Type of wood	Range	Avg	Range	Avg		Aspi-rated	Partly aspi-rated	Unaspi-rated
Sapwood	3-16	9.65	1.5-15	7.59	48	22.9	14.6	62.5
Normal heartwood	0.005-0.02	0.014	0.005-0.02	0.014	226	83.9	13.1	3
Wetwood heartwood	1.4-17.5	6.64	0.2-8.0	1.6	886	41.8	18.2	40.0

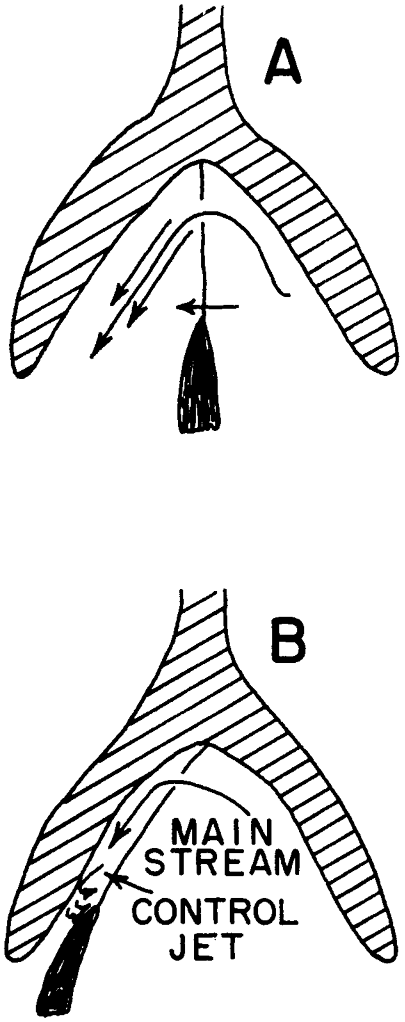

FIG. 8. Proposed model for turbulence amplification in a bordered pit. (A). In an unaspirated pit with membrane in median position, flow through small pores near the torus has little effect on the main stream, but (B) in an aspirated pit with membrane deflected, the mainstream is influenced so that turbulence is amplified.

drying. Bailey and Preston (1970), however, show that pit aspiration can occur by applying pressure to a pit membrane, which indicates that a difference in hydrostatic pressure across a bordered pit-pair can cause the torus to deflect toward the downstream border. The amount of deflection depends upon the magnitude of the pressure drop as well as the number and thickness of supporting strands in the margo of the pit membrane. They calculated that pressures from just above zero to over 100 psi can cause aspiration—the more delicate membranes in the springwood pits are displaced by relatively low pressures, and the thicker membranes of summerwood pits are displaced by higher pressures.

The supporting strands of the pit membrane suspended across the pit chamber might be compared to a wooden plate fixed at both ends. Loading of such a plate would result in a deflection that is time-dependent and is governed by the rheological behavior of wood. When water is forced through wood and through the bordered pits, the unaspirated pit membranes should be loaded as a beam because of the pressure differential across the pit chamber. As creep strain occurs, flow paths through the pit become more restrictive to the passage of water, and a decrease in flow rate accompanies the corresponding deflection. Therefore, if deformation of membranes toward the pit-aspirated condition is time-dependent, a decreasing flow rate should be observed under steady-state conditions in wood with initially unaspirated bordered pits when the pressure drop is large enough to cause appreciable deflection of the membrane during the period of testing.

In addition to the deflection of the pit membrane influencing the nature of the flow through the bordered pit, another factor, turbulence amplification, which is itself dependent upon the rheological nature of the membrane, might cause further depression of the flow rate. A turbulence amplifier is illustrated schematically in Fig. 7 (Henke 1966). When the velocity of the liquid jet issuing from the nozzle is below the threshold value required for laminar flow, a uniform stream exists between the nozzle and the receiver (Fig. 7, A). If a disturbance is introduced, the flow will become turbulent, and the flow rate reduces (Fig. 7, B).

On the basis of the models for turbulence amplification, rheological nature of cell-wall substances, pit aspiration, and structure of pit membranes, the following concept is proposed (Fig. 8). Openings or pores through the outer edges of the bordered pit membranes generally are larger than those nearer the torus because of the radiating nature of the fiberlike strands making up the margo. Before flow begins and during the very early stages of flow, the unaspirated pit membrane would occupy a median position in the pit chamber (Fig. 8,A). Flow paths for liquid would be provided by both the larger pores near the edge of the membrane, because they would offer less resistance to the passage of water, and the channel between the downstream side of the membrane and the pit wall. Little water would pass through the smaller pores of the membrane near the torus at this time. These pores could be compared to the control jet of the turbulence amplifier model, as water issuing from them would enter perpendicularly to the main stream from the large pores. The large pores are analogous to the nozzle, and the pit aperture is equivalent to the receiver in the model.

Once pressure is applied to the pit membrane, creep strain commences and the membrane begins to deflect toward the downstream pit aperture. As this occurs, the amount of liquid passing through the larger pores with respect to the volume of liquid moving through the smaller, more central, pores decreases (Fig. 8-B). Because of the shape of the pit chamber, a deflection of the membrane results in a restriction of the flow paths near its edges. This deflection causes more water to flow through the central pores and the result is similar to "turning on" the control jet shown in Fig. 8-B. Localized turbulence is introduced on the downstream side of the pit membrane, which would tend to depress the flow rate further. As the membrane continues to deflect, turbulence conceivably would become greater until some maximum level is reached and flow rate becomes constant. Localized turbulence in bordered pits affects the flow rate, but may not influence the laminar nature of flow of liquid through wood as observed at the macroscopic level.

This explanation does not contradict the findings of Kelso et al. (1963), whose work was done on seasoned material. Our study on sapwood was carried out on green, saturated material in which most bordered pits are unaspirated (Table 1), and the pit membrane is in a pliable condition and would deflect as a result of applied hydrostatic pressure.

Comstock's (1968) findings suggest that the water permeability of sapwood is independent of pressure, provided that sufficient air and foreign matter are removed from the wood and water. The pressure used on sapwood specimens in our investigation, however, was about 8 times higher than that used by Comstock, and therefore creep might not have been a significant factor in his tests.

Unseasoned sapwood contains few aspirated pits, but unseasoned heartwood has many (Table 1). The constant permeabilities observed for the majority of the heartwood specimens (Fig. 3) could be attributed to the high degree of natural pit aspiration in green heartwood, which is considered to be irreversible under normal conditions. The effect of closure of unaspirated pits in the heartwood by creep under hydrostatic pressure might be reduced greatly because of the low percentage of unaspirated pits in the heartwood and because of the nature of heartwood pit membranes to resist creep. The naturally incrusted pit membranes in heartwood are thicker and therefore likely to be stronger than the pit membranes in sapwood.

Two normal heartwood specimens exhibited decreasing flow rates and were more permeable than the other specimens. Possibly these had fewer aspirated pits or smaller amounts of incrustation to allow for the higher flow rates.

Specimens from wet pockets in the heartwood exhibited initial permeability values approaching those for normal sapwood. As shown in Table 1, only 42% of the bordered pits in wetwood were aspirated, compared to 84% in normal heartwood. Also, the pit membrane of freeze-dried wetwood appeared relatively free of incrustations (Fig. 5), and water should flow easily through these pits during the initial stage of liquid flow through the specimens.

Under the steady-state conditions, a sharp decrease in permeability of wetwood specimens was observed. During the experiment, water that had passed through wetwood specimens contained a milky-appearing suspension and had higher foaming tendencies. Apparently, some of the heartwood extractives could change the viscosity and surface tension of the water and influence the permeability determination; however, changes in the surface tension and viscosity of the water were not measured. Krahmer et al. (1970) also observed that lignans move through green western hemlock wood. Therefore, along with the high permeability of wetwood, extractives could be transported by the water and deposited on pit membranes to form a coating that would greatly reduce the flow rate and consequently the high initial permeability. According to Poiseuelle's Law, flow rate of water through capillaries should decrease as a function of the fourth power of the decrease in capillary radius. Occlusion of the pit membranes during the permeability experiment could account for the rapid decrease in permeability observed for wetwood material under steady-state conditions. Occlusion of pit membranes by extractives is shown clearly in electron micrographs of air-dried specimens, but freeze-dried wetwood hemlock is quite free from occlusion.

Very slow drying rates have been observed for western hemlock lumber containing wet pockets (Kozlik et al. 1972). The movement of extractives that become deposited on the bordered pit membranes eventually could trap free moisture by forming an impermeable zone in and around the wet pocket. The drying rate of these wet pockets then would be determined by the diffusion coefficient of moisture through the impermeable zone.

CONCLUSIONS

Longitudinal permeability of western hemlock to water was highest in sapwood, being about 200 times greater than for normal heartwood, and the permeability of material from wetwood in hemlock heartwood was about 150 times greater than for normal heartwood during the initial stages of permeability. The cause of low permeability for normal heartwood was likely incrustation of bordered pit membranes and a high degree of pit aspiration.

Both sapwood and wetwood from the heartwood exhibited sharp decreases in permeability with time. Time-dependent pit aspiration in sapwood was theorized as taking place during testing because of hydrostatic pressure. Migration of extractives that effectively occlude pit membrane openings was considered the cause of the time-dependent change in permeability of wet heartwood.

From the electron micrographs and permeability study, the formation of wet pockets in western hemlock lumber during commercial kiln drying is theorized as caused by incrustation of extractives on pit membranes to form impermeable zones in lumber.

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