WOOD AND FIBER SCIENCE

JOURNAL OF THE SOCIETY OF WOOD SCIENCE AND TECHNOLOGY

VOLUME 21	JANUARY 1989	NUMBER 1

CHARACTERIZATION OF WETWOOD FROM FOUR BALSAM FIR TREES

M. H. Schneider

Professor of Wood Science and Technology
Faculty of Forestry
University of New Brunswick
Bag Service No. 44555
Fredericton, NB E3B 6C2

and

Lei Zhou

Ph.D. candidate
University of California at Berkeley

(Received May 1987)

ABSTRACT

Balsam fir wetwood had lower longitudinal permeability to both water and air than sapwood, but higher than heartwood. Based upon the average initial flow rate of water in sapwood, wetwood, and heartwood, a ratio of 45:6:2 was calculated. The ratio of average air permeability of sapwood to wetwood to heartwood was 50:9:1 calculated at an average mean pressure of 0.5 atmosphere (38 cm Hg). The low permeability of wetwood and heartwood results from pit aspiration and incrustation of bordered-pit membranes. Scanning electron microscopy suggested that deposits on wetwood-bordered pit membranes facilitated greater flow through wetwood than heartwood. Sapwood and wetwood moisture contents were comparable and were higher than heartwood. Extractive content values of green wetwood were between those for sapwood and heartwood.

Keywords: *Abies balsamifera,* air permeability, anatomy, balsam fir, extractive content, moisture content, ultrastructure, wetwood.

INTRODUCTION

Wetwood is unusually wet heartwood or inner sapwood in standing trees. It usually requires relatively long periods for adequate drying. Dokken and Lefebvre (1973) reported that the drying time for balsam fir (*Abies balsamea* [L.] Mill.) wetwood veneer was longer than that of sapwood and heartwood.

Because permeability is generally considered an indicator for drying rate, the permeability of wetwood has been given considerable attention in view of its slower drying in comparison with heartwood. Knutson (1973) concluded that permeability to water flow, parallel to the grain, was much less in wetwood than

Wood and Fiber Science, 21(1), 1989, pp. 1–16

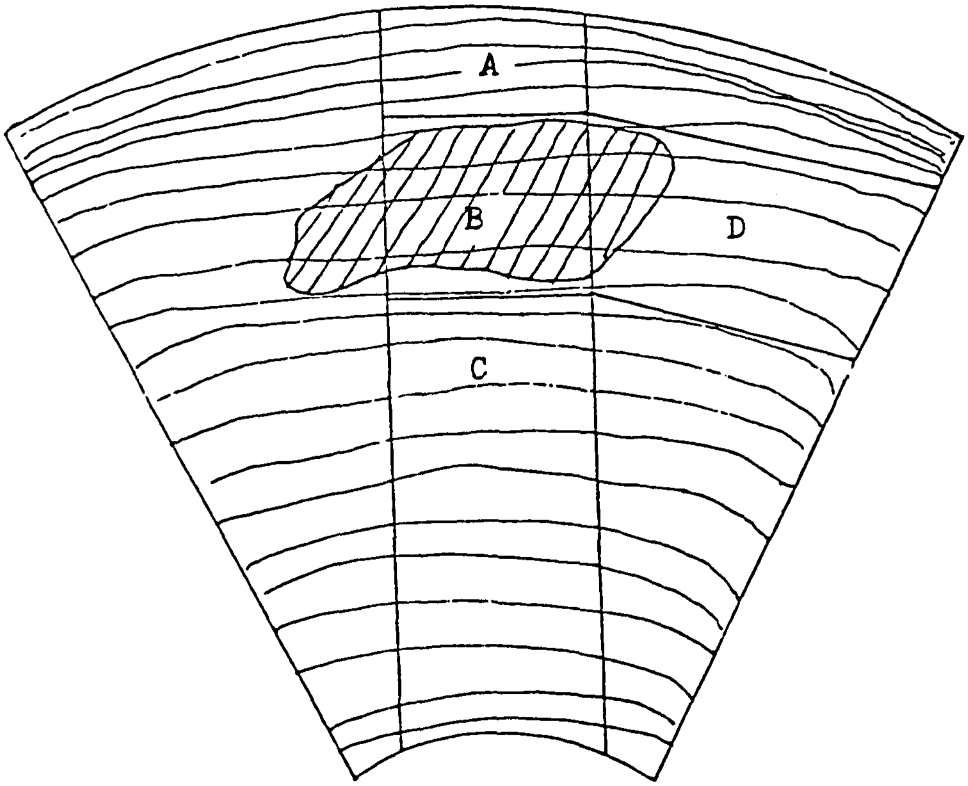

FIG. 1. Schematic diagram of the sample sawing pattern. A = sapwood, B = wetwood, C = heartwood, D = heartwood adjacent to wetwood.

in normal sapwood of trembling aspen (*Populus tremuloides* Michx.). However, Lin et al. (1973), indicated that early in their experiment, the permeability of western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) wetwood was about 150 times greater than that of normal heartwood.

As early as 1935, Lagerberg (1935) reported that air-dried wetwood from Scots pine (*Pinus sylvestris* L.) had higher water absorptive capacity than normal wood.

A study by Arganbright and Wilcox (1969) showed that wetwood in white fir (*Abies concolor* Lindl. [Gord. and Glend.]) absorbed more oil than normal wood although its permeability was somewhat lower. They attributed the greater penetration of oil in wetwood to possible anatomical damage of wood by bacteria. In later papers, this hypothesis was tested by Wilcox and Schlink (Schlink 1967; Wilcox and Schlink 1971). They came to the conclusion that the bacterium from white fir wetwood did not alter wood structure even when present in large numbers. The warty layer was shown to interfere slightly with aspiration, which would allow fluid flow.

Scanning electron microscopic (SEM) observations in poplar by Sachs et al. (1974) indicated that the membranes of vessel-ray pits were eroded by bacteria, while the membranes of vessel-vessel and vessel-fiber pitting remained intact and were apparently not weakened even in the advanced stages of wetwood formation.

Lin et al. (1973) discussed the influence of drying methods upon the pit mem-

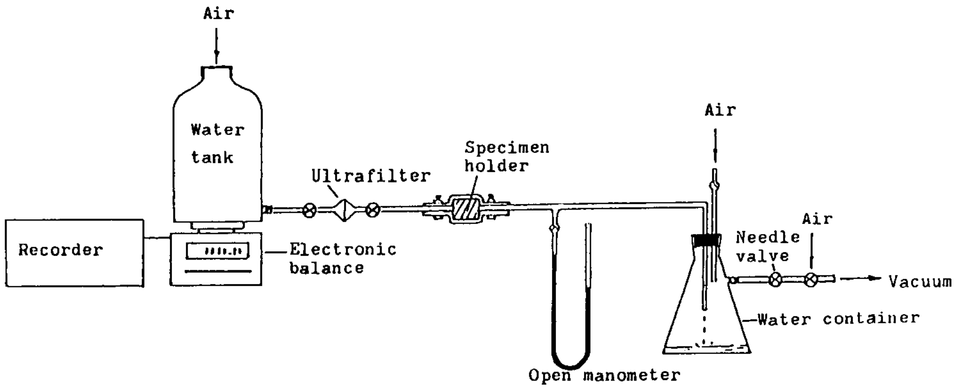

FIG. 2. Schematic diagram of the apparatus used for determining permeability to water.

brane structure of western hemlock, and concluded that the causes of low permeability of normal heartwood appeared to be incrustation of bordered pit membranes and a high degree of pit aspiration.

Ward (1986) measured gas permeability and drying rates of normal sapwood, heartwood, and wetwood in white fir and aspen. The fir wetwood dried at a slower rate and had longer overall drying times than normal wood and it had lower gas permeability (between that of sapwood and heartwood). Electron micrographs revealed bacteria and incrustations that may block moisture movement. Some bordered pit tori were eroded, which would allow easier gas movement.

The objectives of the present work were to obtain information on balsam fir wetwood and compare it to normal heartwood and sapwood. Water and air permeability, pit ultrastructure, and extractive content were studied.

MATERIALS AND METHODS

Longitudinal flow of water and air permeability

Four straight balsam fir trees were felled from a single stand near the Maritime Forest Ranger School, Fredericton, NB, in June 1985. All trees were alive and

TABLE 1. *Moisture contents at three heights in four balsam firs.*

Tree no.	P[1]	Moisture content (%) Sapwood	Wetwood	Heartwood
1	C	157.3 [16][2]	183.7 [5]	84.5 [9]
	M	192.5 [28]	268.8 [7]	91.4 [29]
	B	180.1 [30]	205.5 [7]	70.6 [46]
2	C	196.7 [8]	N/A	84.6 [12]
	M	202.0 [13]	143.6 [5]	82.7 [19]
	B	177.3 [20]	151.0 [4]	65.8 [28]
3	C	215.8 [8]	N/A	117.7 [10]
	M	193.9 [16]	193.2 [4]	93.3 [12]
	B	198.8 [17]	173.7 [5]	93.3 [21]
4	C	173.1 [8]	N/A	88.7 [13]
	M	150.7 [24]	167.6 [7]	96.9 [19]
	B	128.7 [22]	105.6 [4]	70.0 [27]

Note: [1] P = height level in the tree; C = crown; M = mid-stem; B = butt.
[2] Number in square brackets is the number of specimens.

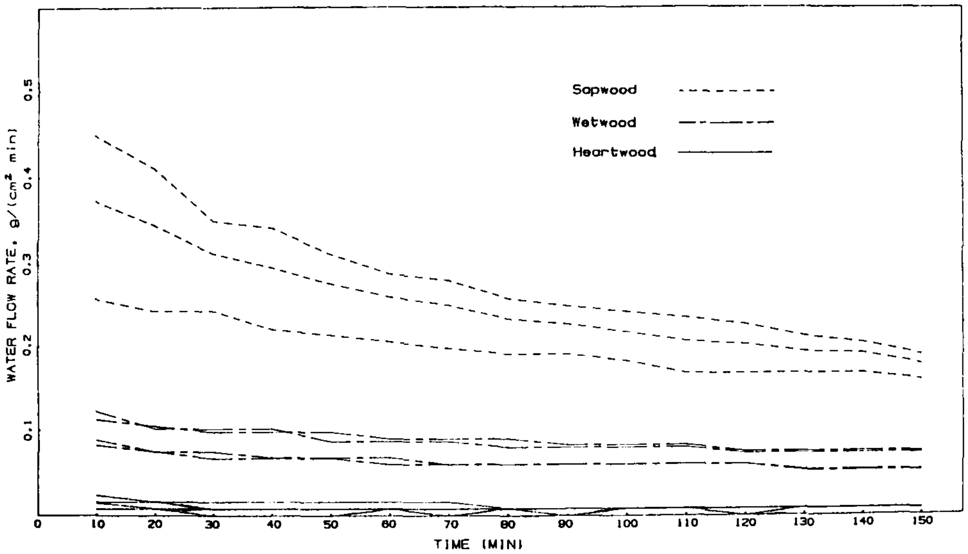

FIG. 3. Longitudinal water flow rate through 3 sapwood, 4 wetwood, and 4 heartwood balsam fir samples over time.

were 40 to 50 years of age with trunk diameters (dbh) from 20 to 30 cm. After cutting, a reference line was drawn on the east side of the bark of each tree so that all specimens could be easily oriented. Sets of 0.5-m-long bolts and 0.15-m-thick discs were cut from each tree at about 0.7 m, 4.1 m, and 8.2 m. The discs were shipped in polyethylene bags to the laboratory and stored in a freezer until further processing.

Discs for measurement of moisture content were sawn in two along the diameter in the east-west direction. The north half and the south half were sawn along the annual rings into semicircular five-ring-thick strips using a band saw. The strips were further cut into small squares. Moisture content (oven-dry basis) of these squares was measured using the oven-drying method.

Toothpick-sized, oven-dried samples from sapwood, wetwood, and heartwood were ground in a Wiley mill to pass a 40-mesh screen. The ground wood was oven-dried again and placed in an extraction thimble, weighed, and extracted in a Soxhlet with alcohol-benzene solution for about 20 hours with a cycle time of about 12 min. After extraction, ground wood specimens in the extraction thimble were dried and weighed. Extractive content was expressed as the percentage of the original oven-dry ground-wood weight.

The pattern of flow specimen sampling is illustrated in Fig. 1. Blocks about 1.5 by 1.5 cm square were selected from sapwood, normal heartwood, and wetwood

TABLE 2. *Oven-dry basis extractive content of balsam fir.*

Wood types	Means (%)	Variations (%)	No. of samples
Sapwood	2.49	1.31–3.17	4
Wetwood	4.95	3.84–6.37	4
Normal heartwood	6.71	5.25–8.25	4

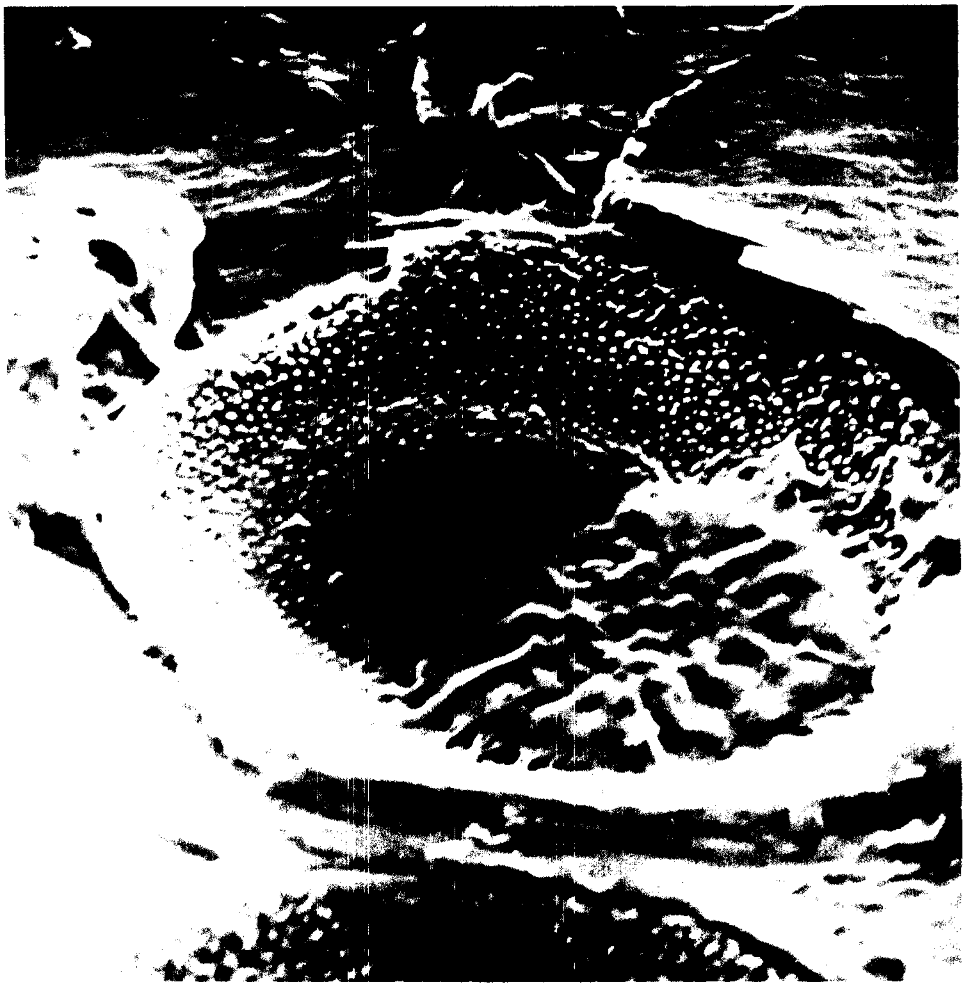

FIG. 4. Broken torus in latewood of sapwood dried by ethanol solvent-exchange. SEM, 7,900 ×.

(i.e., the zones designated by letters A, B, C and D [Fig. 1]), where zone D (heartwood) is in the same ring as zone B (wetwood). Test blocks were 3 cm along the grain, and each of these blocks was later cut into two 1.1-cm-long end-matched specimens, one for determining water flow and the other air permeability. Longitudinal water flow measurements were made through green specimens, and longitudinal air flow through solvent-exchange dried specimens.

TABLE 3. *Water flow rate through balsam fir under a constant pressure difference. Means of the first and last 10 min of a 150-min experiment.*

Time	Mean flow, g (cm^2 min)			
	Sapwood	Wetwood	Heartwood	Ratio s:w:h
0–10 min	0.360	0.104	0.016	45:6:2
140–150 min	0.176	0.036	0.008	11:4:1

FIG. 5. Torus collapsed through the pit aperture. SEM, 12,800×.

For determining the flow of water, blocks of sapwood, normal heartwood, and wetwood were cut into cylinders about 1.1 cm diameter and 1 cm in length using sharp razor blades immediately after they were sawn from the discs. The diameter and length of each cylinder were measured with a vernier caliper. The cylinders were pushed into a 0.9-cm-diameter, 5-cm-long section of rubber tubing and soaked in distilled water for more than 24 hours. The rubber tubing diameter was less than the wood cylinder diameter, providing a tight seal between specimen and tubing. Each specimen with rubber tubing was mounted in the apparatus as shown in Fig. 2.

The flow measuring apparatus (Fig. 2) consisted of three main parts: 1) a specimen in a section of rubber tubing; 2) a vacuum pump and reservoir to maintain a constant pressure drop across the specimen and 3) a unit to measure the inlet water weight. The ends of the rubber tubing were connected to two sections of steel tube. Freshly distilled water, filtered with an ultrafilter to remove air bubbles

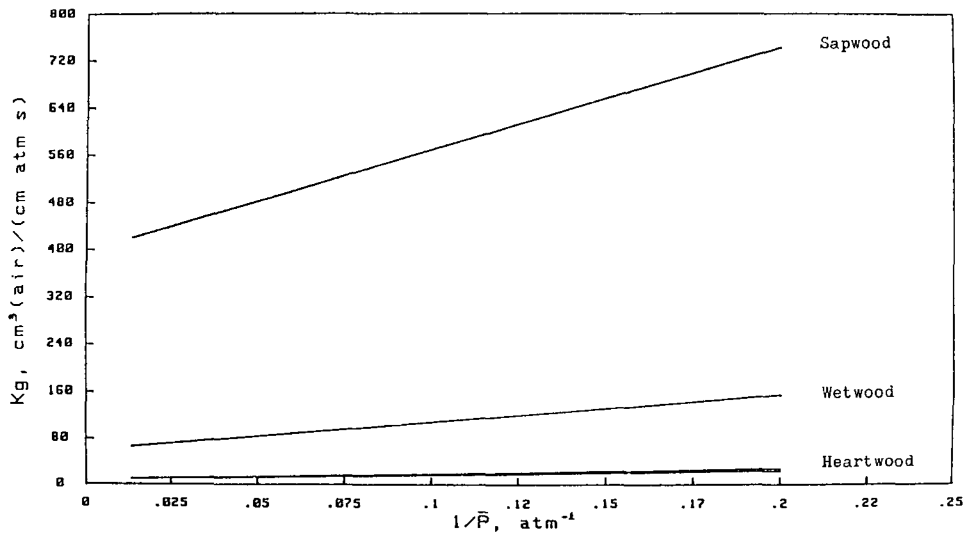

FIG. 6. Superficial air permeability regression against reciprocal mean pressure for balsam fir sapwood, wetwood, and heartwood.

and foreign particulate matter, was added to a storage tank attached by tubing to the specimen-holder. Flow through the specimens was measured by water loss in the storage tank using an electric balance (Mettler PC4400) with a recorder (Fisher Recordall, Series 5000). A manometer attached to the down-stream side of the specimen was employed to ensure constant pressure differences across the specimen. The up-stream side of the specimen was open to air.

The water flow from the tank occurred at a constant pressure difference of about 72 cm Hg and was recorded at 10-min intervals over a period of 150 min. Average flow rates (F) were calculated from the water loss (L, gm) per cross sectional area (A, cm^2) of the specimens and by time elapsed (T, min). Average flow rate of water is expressed by the following equation:

$$F = \frac{L}{AT} = \frac{g}{cm^2\ min}$$

Specimens used for the air flow measurements were solvent-exchange dried with ethanol in the same way as the SEM specimens. The dried blocks, about 1.1 cm long, were cut into 0.9- to 1.0-cm-diameter cylinders. The ends of each wood cylinder were examined with a hand-lens for checks or defects. The longitudinal surface of each cylindrical specimen was sealed with pourable silicone rubber (General Electric RTV-112).

The air flow measuring apparatus was designed and built by Dr. L. P. Sebastian in the Wood Science Laboratory at UNB and had been used in much of his work.

Air permeability (or the superficial gas permeability) was calculated using the following equation (Siau 1984):

$$K = \frac{76(\text{cm Hg/atm})QLPa}{A\ \Delta P(Pa - \Delta P1 + \Delta P/2)}$$

FIG. 7. Unaspirated pit membrane in sapwood, dried by ethanol solvent-exchange. SEM, 7,600×.

Where K is the air permeability of wood in cm^3 (air/cm atm sec, A is the effective sectional area of the test sample in cm^2, L is the sample length in cm, Q is the air flow through the sample per unit of time in cm^3/sec, Pa is atmospheric pressure in cm Hg, Pl is the open manometer reading on the vacuum side in cm Hg. In this study, a constant pressure difference of 8 cm Hg was used.

All measurements were made under room conditions (21 C). As with the water flow study, duplicate specimens were tested using end-matched replicates.

Preparation of Specimens for SEM examination

Sapwood, wetwood and heartwood specimens were solvent-exchange dried for more than two days each in ethanol-water concentrations of 30%, 70%, and 100%. The specimens were then dried in an oven at 60 C.

All specimens were cut with a sharp razor blade into cubes with dimensions of about 5 mm in the radial, and tangential direction and 3 mm along the grain.

FIG. 8. Aspirated pit membrane in air-dried sapwood. Torus loosely rests on pit border. SEM, 8,400×.

They were mounted on SEM specimen holders. In order to prevent electric charging of surfaces, a conducting silver paste was spread on the sides of the specimens to bring the top surface into electrical contact with the metal stub holder. The mounted specimens were placed in a high-vacuum chamber and their surfaces coated with gold for about 3 min. They were examined using a Cambridge S4-10 scanning electron microscope at 10 KV.

RESULTS AND DISCUSSION

Table 1 shows the average moisture contents of sapwood, wetwood, and heartwood of the four trees at three heights.

The moisture content differences of normal heartwood versus wetwood and normal heartwood versus sapwood were significant at the 1% level, but differences between wetwood and sapwood were not significant regardless of the height group.

FIG. 9. Pit membrane in wetwood, dried by ethanol solvent-exchange. Pit membrane is covered with oblong deposits. SEM, 7,700×.

These results suggest that the moisture content of balsam fir wetwood is not necessarily higher than that of the sapwood but is always higher than that of normal heartwood.

Overall average moisture contents of the mid-stem specimens were higher than those of the top and the top was higher than the butt.

Extractive content

The results of extracting twelve specimens of sapwood, normal heartwood, and wetwood with alcohol-benzene are given in Table 2. Sapwood had the lowest extractive content, while normal heartwood had the highest content. Extractive content of wetwood was not as high as that of normal heartwood but generally higher than that of sapwood. In a similar extractive study, Schroeder and Kozlik (1972) found that western hemlock wetwood had higher contentrations of ex-

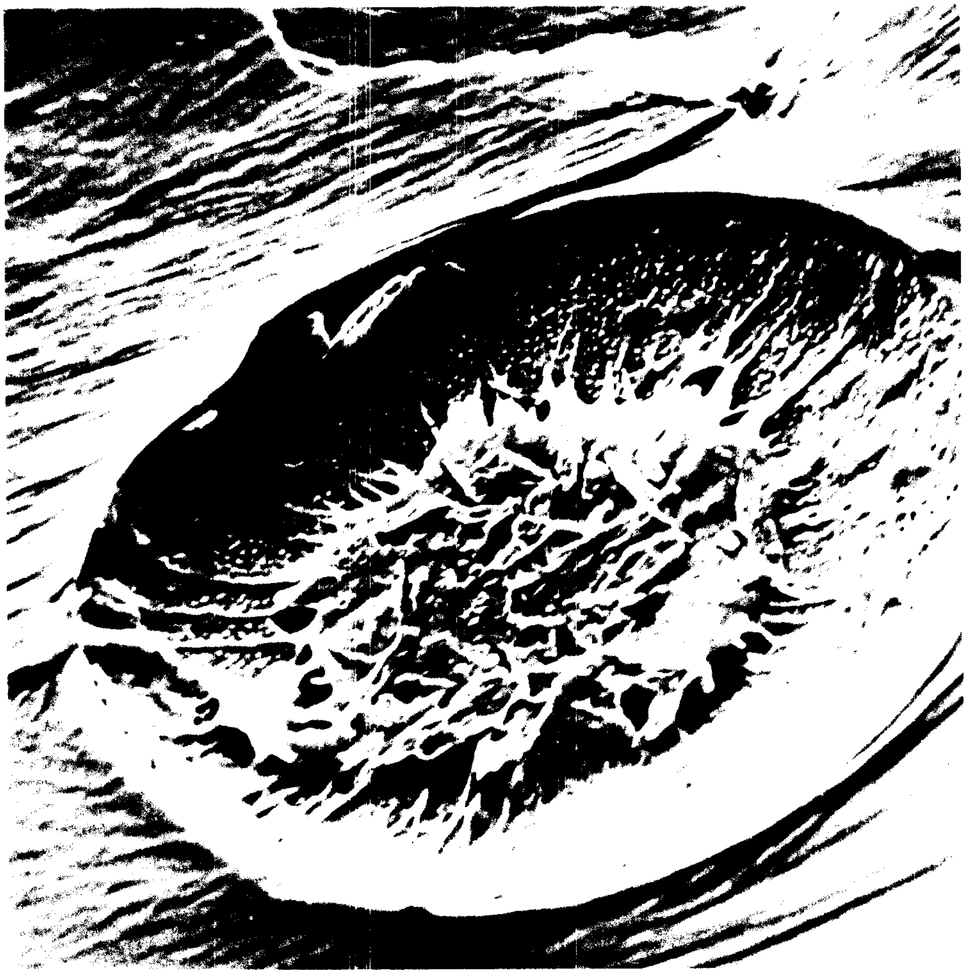

FIG. 10. Deposits on the pit membrane and oblong bodies on the torus in wetwood dried by ethanol solvent-exchange. SEM, 6,600×.

tractives than the normal wood. They found that the average extractive content of normal wood was 1.90% and ranged from 1.03% to 3.90%, and in wetwood it was 9.67% ranging from 4.07% to 14.93%.

Longitudinal permeability

Water flow of 43,248.6 g/(cm^2 min) was measured in the water flow apparatus without a specimen in place. Figure 3 and Table 3 show the mean flow rate of water through 3 sapwood, 4 wetwood and 4 heartwood samples. Sapwood flow rate was much greater than that of wetwood, and wetwood was greater than heartwood. Heartwood (including from areas labelled D in Fig. 1 that were within the same rings as wetwood) had much lower flow rate than wetwood.

The average sapwood water flow rate decreased by about 50% over the test, but wetwood and heartwood flow remained nearly constant.

FIG. 11. Dense flaky deposits on the torus and pit annulus in wetwood, dried by ethanol solvent-exchange. SEM, 8,300×.

In general, several factors, including air bubble blockages and pit aspiration from applied pressure, can reduce water flow over time. An attempt was made to minimize the influence of air bubble blockages in this study by using ultrafiltered, freshly-distilled water. Nonetheless the air bubble effect could not be excluded entirely. Bailey and Preston (1970) concluded that aspiration can take place by applying pressure to a pit membrane. When water passes through wood, the unaspirated membranes of bordered pits are subject to differences in hydrostatic pressure, which could cause tori to be displaced from central, unaspirated positions. The scanning electron micrographs show that pit membrane strands, mainly in earlywood tracheids, were partly or completely broken so that the torus fell on the inside surface of the pit border or collapsed through the pit aperture into the cell lumen (Figs. 4 and 5). This suggests that the supporting strands were weak. This weakness may have contributed to the observed flow decrease with time.

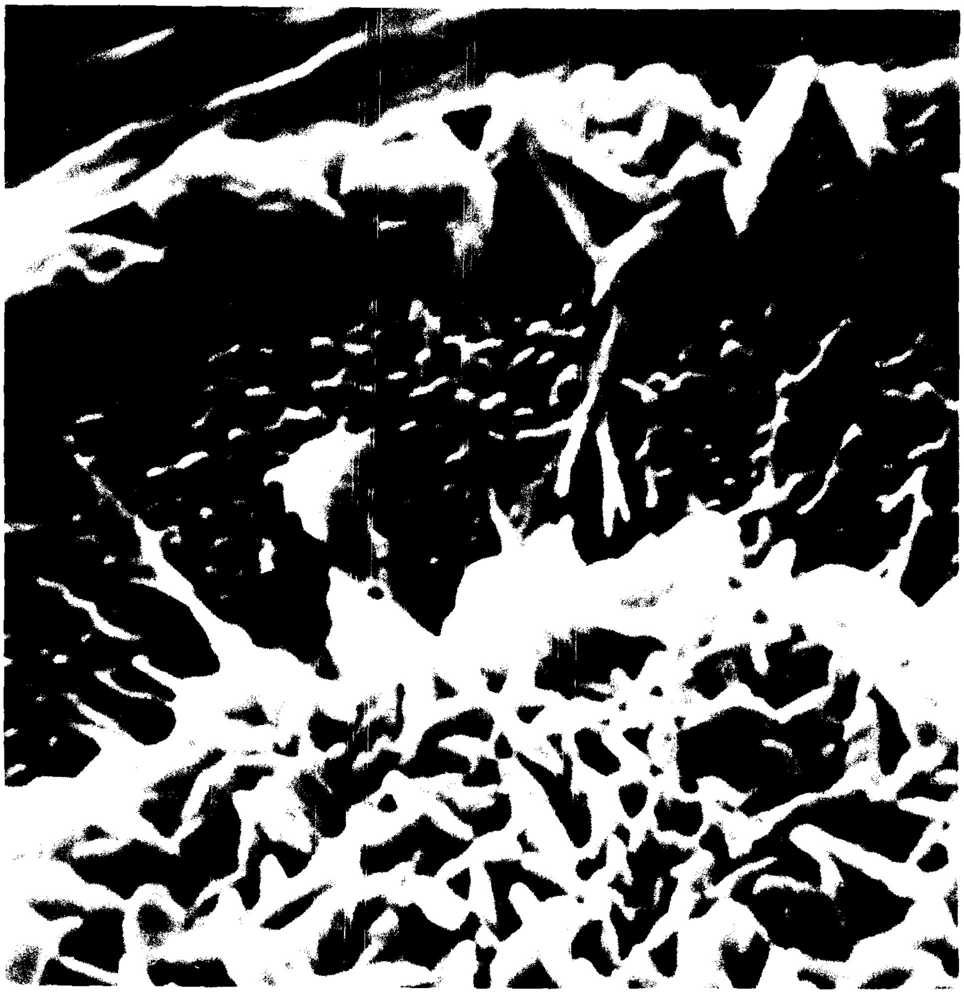

FIG. 12. Close view of a membrane with flaky deposits in wetwood, using dried ethanol solvent-exchange. SEM, 21,500×.

A typical plot of gas permeability as a function of reciprocal mean pressure is shown in Fig. 6. Each of these regression lines was based upon 8 to 16 flow measurements at a constant pressure drop of 8 cm Hg. The regression coefficient for all groups ranged from 0.98 to 0.99. The ratio of the permeability of sapwood to wetwood to normal heartwood was 50:9:1, which was calculated at an average mean pressure of 0.5 atmosphere (38 cm Hg) and was similar to the ratios observed for average water flow rates. Comstock (1967) stated that if air blockage is eliminated and slip flow is considered, the permeability of wood is independent of fluid and is a function only of wood. This study appears to support that conclusion.

Most pit membranes in sapwood were unaspirated and were free of incrustation (Fig. 7), thus permitting fluid flow through the tracheids. Figure 8 shows that in air-dried wood the dished center portion of a torus is drawn tightly into the pit aperture. The torus is clear of incrustations.

FIG. 13. Torus surface as viewed through the aperture from the lumen side of a tracheid in wetwood, dried by ethanol solvent-exchange. SEM, 16,600×.

However, in heartwood, the bordered-pit membranes in the earlywood tracheids were aspirated, and the latewood pit membranes more commonly remained unaspirated. In both the earlywood and latewood tracheids of heartwood, pit membranes were incrusted. Such aspirated and heavily encrusted heartwood pit membranes would likely permit little fluid flow. Unaspirated pit pairs in the latewood would allow some flow, but, even so, flow was so small that a process of pit aspiration during testing would not be noticeable.

Most latewood pit membranes of wetwood were unaspirated but its earlywood pit membranes were mostly aspirated. There were differences among the pit membrane structures of wetwood. Micrographs of the pit membranes were selected to demonstrate typical structures such as oblong bodies visible on some membranes. The bodies appeared to be coated by thin amorphous deposits and to be closely attached to the membrane (Figs. 9 and 10). These membranes are not broken,

FIG. 14. Spherical body in wetwood tracheid lumen. SEM, 8,300×.

and a number of openings can be observed among the membrane strands. Similar bodies, which he called bacteria, were reported by Ward (1986). He concluded that presence of bacteria in wetwood could increase its capacity to absorb and hold moisture.

Another typical structure was dense, flaky deposits on the torus and pit annulus of an intact and incrusted membrane shown in Fig. 11. This appearance was unique to wetwood. Figure 12 is a close view of such a torus and pit annulus at a higher magnification. The flaky substance shown in these figures appears to produce voids which prevents a seal between an aspirated torus and aperture (Fig. 13). The final typical structure seen in wetwood was spherical bodies in tracheid lumens. An example is shown in Fig. 14.

No attempt was made in this study to explore the relationship of the structures observed in wetwood to wetwood formation, nor to identify these structures. This could be the subject of another study.

SUMMARY AND CONCLUSIONS

Typically, wetwood MC was comparable to that of sapwood. Heartwood was lower. The extractive content of wetwood lay between that of sapwood and heartwood.

Longitudinal water and air flow measurements showed that sapwood had the highest flow rate, heartwood had the lowest, and wetwood was in between. The ratios of the average water flow rate of sapwood to wetwood to heartwood at the first 10-min point and last 10-min point were 45:6:2 and 11:4:1, respectively. The ratio of the air permeability of sapwood to wetwood to heartwood was 50:9:1, which was calculated at an average mean pressure of 0.5 atm. The low flow rate and permeability of heartwood appear to be caused by pit aspiration and incrustation of the pit membranes. In wetwood, the same factors appear to reduce flow, but are modified by the incrustations found in the pits. The SEM observations indicated differences between the pit membranes of earlywood and latewood tracheids in sapwood and heartwood. The margo of the pit membranes of earlywood tracheids was thin and threadlike, while the margo of the membranes of latewood was coarser. The membranes observed in earlywood were mostly aspirated. There was little evidence of aspirated membranes in latewood of sapwood or heartwood. These descriptions are also applicable to wetwood.

The SEM examinations showed that wetwood had deposits and substances on its pit membranes not found in normal sapwood or heartwood. The membranes observed in wetwood had oblong bodies, warty and amorphous deposits, and flaky deposits. The scope of this study did not include identification of these substances.

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