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MAXIMUM EFFECTIVE PIT PORE RADII OF THE HEARTWOOD AND SAPWOOD OF SIX SOFTWOODS AS AFFECTED BY DRYING AND RESOAKING[1]

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ABSTRACT

Air pressures were determined that will just displace water or water containing a wetting agent from the void structure of cross sections of green sapwood and heartwood of six different softwoods varying in thickness from 1/32 inch to 3 inches. Measurements were again made on the same specimens after air- and oven-drying and resaturating with water or water containing a wetting-agent solution. Maximum effective radii of the openings were calculated from these pressures and the surface tensions of the liquids. Maximum lumen radii and maximum fiber lengths were obtained from the linear plots of the pore radii against the thickness of the specimens in the thin-specimen range. Both were greater for sapwood than for heartwood. Maximum effective pit pore radii were obtained for passage through 50 pits in series from the linear plots of the logarithm of the effective pit pore radius against the logarithm of the number of pits traversed in series. These values were used to show relative differences in calculated permeabilities between sapwood and heartwood, which varied greatly between species, and to show the effect of drying with and without a wetting agent present. Wetting agents tend to prevent loss in permeability on drying, presumably by reducing the drying tension on the pit membranes, thus avoiding aspiration, at least in the pit membranes containing the larger pores.

INTRODUCTION

A previous report by Stamm (1966) has shown that maximum effective pore radii r of membranes can be determined from the pressure P required to just displace a contained liquid, with a surface tension σ, by a gas when the angle of wetting of the liquid with the solid is θ. Thus

$$r = \frac{2\sigma}{P}\cos\theta. \tag{1}$$

When the liquid completely wets the membranes, $\cos\theta$ is unity. The equation has been shown to hold even when the pores have radii as much as 20 times the thickness of the membrane. The measurements are, thus, not confined to passage through true capillaries as are the conventional equations for flow (Comstock 1965, 1967; Stamm 1963, 1967). Equation (1) holds for irregular as well as circular pores and even for triangular openings and slits (Stamm 1966). In the former case, the calculated radius is the mean radius of the largest inscribed circle and in the latter case, the largest inscribed ellipse.

The relationship reduced to

$$r = \frac{1.5\sigma}{P_1} = \frac{0.29\sigma}{P_2}, \tag{2}$$

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when r is in microns, P_1 in centimeters of mercury, and P_2 is in pounds per square inch for wetting liquids such as water in wood (Stamm, Clary, and Elliott 1968).

Equation (2) has been applied to the gas displacement of water from cross sections of softwoods with different thicknesses (Stamm, Clary, and Elliott 1968). It has also been applied to specimens saturated with water containing a wetting agent, and saturated with alcohol. Practically the same r values are obtained with water and water containing a wetting agent although the surface tensions vary about twofold. When the specimens were soaked in alcohol, higher r values were obtained for cross sections thicker than the maximum fiber length because of dissolving of extractives that tend to clog the pit membrane pores.

The r values decrease rapidly with an increase in thickness of the cross sections up to the maximum fiber length, and then decrease more slowly as displacement of liquid has to occur through pit membrane pores. The initial rapid decrease is due to a decrease in the number of fibers cut across twice and to the fact that such cuts have to occur nearer to the tapered ends. Extrapolation of the initially steep linear part of the r versus thickness plots to zero thickness gives the maximum lumen diameter (Stamm, Clary, and Elliott 1968). The measurements were made over a 0.25-inch-diameter circular area (area of 0.315 cm^2). As there are approximately 275 to 325 fibers per cm in the radial and tangential directions in softwoods (Stamm, Clary, and Elliott 1968), the measurements involved 24,000 to 31,000 fiber cross sections, and thus the maximum effective lumen radius is for this large number of lumen.

When the initially linear portion of the plot is extrapolated to zero radius, the maximum fiber length is obtained. These values are in quite good agreement with the values obtained from actual fiber length measurements and other flow measurements (Stamm 1964).

For cross sections thicker than the maximum fiber length, the logarithm of the maximum effective pit pore radius decreases linearly with an increase in the logarithm of number of pit pores traversed in series (Stamm, Clary, and Elliott 1968). The slope of the plot is some function of the distribution of pit pore sizes. If all pits contained the same maximum pore size, *log r* should be independent of the number of pits traversed in series. If, however, there is a broad distribution of pore sizes in the pit membranes that vary considerably from pit to pit, then as the number of pits traversed in series increases, the probability of having the largest sizes of openings in the same series path decreases.

Measurements to date have been confined chiefly to predried and resoaked heartwood of 20 different Douglas-fir specimens (Stamm, Clary, and Elliott 1968). The maximum effective pit pore radii for passage through 100 pits in series varied about fiftyfold among the specimens. A few measurements were made on never-dried wood. The sapwood of loblolly pine gave maximum effective pit pore radii for passage through 100 pits in series 45 times the values for heartwood.

No measurements have as yet been made by this method to determine the difference in values between never-dried and dried and resoaked specimens. Normal drying is known to aspirate pits (Griffin 1919; Hart and Thomas 1967). Thomas and Nicholas (1966) have shown by electron microscopy that practically all of the pits of normally dried softwoods are aspirated, whereas those dried after successive replacements of water with alcohol and alcohol with pentane followed by flash evaporation caused no aspiration. Liese and Bauch (1967) claim to have accomplished the same thing by soaking the specimens in water containing enough wetting agent to reduce the surface tension below 26 dynes/cm. Comstock (1968) was not able to confirm Liese's findings, but he confirmed Thomas's findings. He feels that when evaporation is from a nonswelling low surface tension liquid such as pentane or hexane, the membranes are sufficiently stiff to resist aspiration under the surface tension force. Wetting agents in water,

TABLE 1. *Structural and permeability properties of the sapwood and heartwood of six different second-growth softwoods before and after drying and resoaking, determined from the pressure required to displace water and water containing a wetting agent by air*

Species	Part of wood[1]	Liquid displaced[2]	Surface tension of liquid	Max. lumen radius[3]	Max. fiber length[4]	Max. r for passage through 50 pits in series[5]		Permeability ratio[6]	
						Never-dried ND	Dried & resoaked DR	ND (S/H)[4]	(DR/ND)[4]
			dynes/cm	microns	mm	microns	microns		
Douglas-fir	S	W	55.3	18	4.7	0.20	0.17	1,065	0.52
(second growth)	H	W	53.8	14	4.1	0.035	0.025		0.26
Pseudotsuga	S	T	26.6	18	4.7	0.20	0.20	1,065	1.00
menziesii	H	T	25.0	14	4.1	0.035	0.033		0.79
Incense cedar	S	W	50.0	25	5.7	0.10	0.085	2,600	0.52
Libocedrus	H	W	50.0	22.5	5.0	0.014	0.012		0.54
decurrens	S	T	26.8	25	5.7	0.10	0.10	2,600	1.00
	H	T	26.8	22.5	5.0	0.014	0.013		0.75
Northern	S	W	52.8	16	5.0	0.24	0.17	8,500	0.25
white cedar	H	W	45.0	13	4.5	0.025	0.017		0.21
Thuja	S	T	25.1	16	5.0	0.23	0.23	3,450	1.00
occidentalis	H	T	25.3	13	4.5	0.030	0.027		0.66
Eastern	S	W	54.8	10	3.7	0.13	0.12	5,640	0.73
red cedar	H	W	42.5	7	3.0	0.015	0.013		0.56
Juniperus	S	T	25.2	10	3.7	0.13	0.13	5,640	1.00
virginiana	H	T	27.3	7	3.0	0.015	0.014		0.76
Eastern	S	W	39.2	16	5.0	0.55	0.50	124,000	0.68
larch	H	W	40.2	14	4.5	0.0165	0.008		0.55
Larix	S	T	24.6	16	5.0	0.55	0.56	124,000	0.94
laricina	H	T	25.2	14	4.5	0.0165	0.0155		0.78
Redwood	S	W	41.7	34	7.5	0.12	0.10	33	0.45
Sequoia	H	W	44.5	20	7.0	0.050	0.047		0.79
sempervirens	S	T	26.5	34	7.5	0.12	0.12	33	1.00
	H	T	26.4	20	7.0	0.050	0.048		0.87

[1] S = Sapwood, H = Heartwood.
[2] W = Water, T = 1% Tergitol (nonionic T.M.N., trimethyl nonyl ether, Union Carbide Corp.).
[3] Extrapolation of maximum effective radius versus thickness plot to zero thickness.
[4] Extrapolation of maximum effective radius versus thickness plot to zero radius.
[5] Extrapolation of log of maximum effective radius versus log of number of pits traversed in series to the logarithm of 50.
[6] On basis of permeability varying as fourth power of the maximum effective pit pore radius.

which reduce the surface tension almost as much, because of their swelling power plasticize the membranes sufficiently to allow aspiration of the pits to occur even under a low surface tension force.

The object of this research was to determine the effect of drying softwoods from both water and water containing sufficient wetting agent to reduce appreciably the surface tension for both the sapwood and heartwood of several softwood species starting with never-dried wood.

EXPERIMENTAL METHODS

The equipment and technique used by Stamm (1966) and Stamm, Clary and Elliott (1968) were used for making the measurements. The species used in this study are listed in Table 1. They were originally collected by R. J. Thomas of North Carolina State University for electron microscope studies of the pits. His findings will be reported later.

The surface tension measurements were made at room temperature (22–24C), using

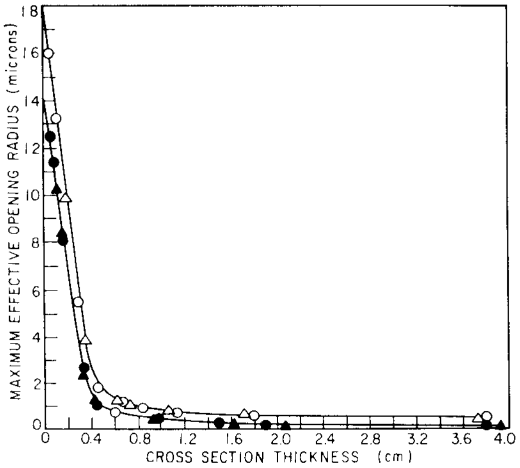

FIG. 1. Maximum effective opening radius versus the cross-section thickness for young never-dried second growth Douglas-fir. Open circles: sapwood, water displacement; shaded circles: heartwood, water displacement; open triangles; sapwood, wetting agent solution displacement; shaded triangles: heartwood, wetting agent solution displacement.

	Sapwood	Heartwood	
Maximum lumen radius	18.	14.	μ
Maximum fiber length	0.47	0.41	cm

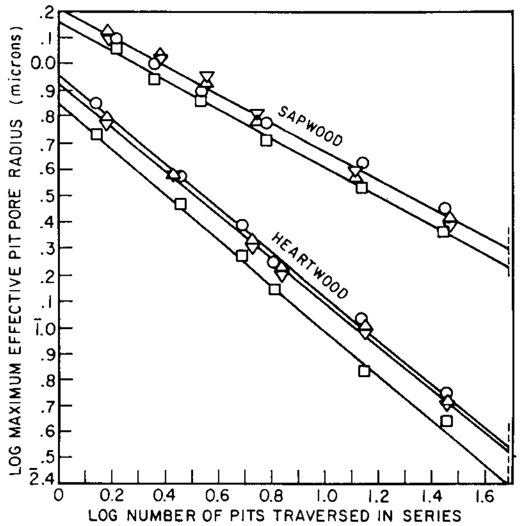

FIG. 2. Log maximum effective pit pore radius versus the log of the number of pits traversed in series for young second-growth Douglas-fir.* Circles: never-dried, water displacement; triangles: never-dried, wetting agent solution displacement; squares: dried from water and resoaked in water; inverted triangles: dried from wetting agent solution and resoaked in wetting agent solution.

the ring-tension method, correcting for the weight of liquid, lifted, according to the method of Zuidemn and Waters (1941).

Two end-matched sets of cross sections ranging in thickness from 1/32 inch to 3 inches were cut from both the sapwood and the heartwood of clear green second-growth specimens of each of the six species 1.5 by 1.5 inch in cross section. One set of specimens of each species was immersed in distilled water and the other in a 1% aqueous solution of the wetting agent, Tergitol TMN (trimethyl nonyl ether) nonionic, Union Carbide Corp. in vacuum desiccators. Air was removed from the specimens by pulling a vacuum overnight and leaving the specimens submerged at atmospheric pressure for at least two days before making the measurements. All of the thinner specimens became completely saturated. A few of the highly resistant thick heartwood specimens did not completely saturate. This was not considered serious since it was felt that the most permeable part of the structure, through which subsequent displacement would occur, would become saturated to the extent that liquid minisci formed in each pit.

RESULTS

Figure 1 is a plot of the maximum effective pit pore radius, calculated from equation (2), versus the cross-section thickness for the second growth Douglas-fir. Extrapolation of the initially linear portion of the plot to zero thickness gave a maximum lumen radius of 18 μ for the sapwood and 14 μ for the heartwood. Extrapolation in the reverse direction to zero r gave the maximum fiber length, 4.9 mm for the sapwood and 4.1 mm for the heartwood.

Figure 2 is a plot of the logarithm of the maximum effective pit pore radius for speci-

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* The number of pits traversed in series was calculated using equation (3) assuming an average fiber length for the redwood of 6.0 mm, for the eastern red cedar of 2.5 mm, and for the other three species of 3.5 mm.

mens thicker than the maximum fiber length versus the logarithm of the number of pits traversed in series. The number of pits traversed in series

$$n = \frac{t - l}{\frac{3}{4} l}, \qquad (3)$$

where t is the thickness of the specimen in centimeters, and l is the average fiber length. Free passage occurs on the average through half a fiber length at each end without traversing a pit. The overlap of adjacent fibers is on the average about a quarter of a fiber length at each end. Flow from one lumen to another in the fiber direction should thus range from half a fiber length to a full fiber length, or average three-fourths of a fiber length. This equation, simpler than the one previously used (Stamm, Clary, and Elliott 1968), meets the conditions satisfactorily. Figure 2 is a linear plot similar to those previously obtained (Stamm, Clary, and Elliott 1968). It is, however, extrapolated to only 50 pits in series rather than 100 pits in series to avoid such a long extrapolation.

Table 1 gives the data for all six species. The surface tensions of the equilibrium liquids are well below the value for pure water, namely 70 to 72 dynes/cm. This is due to the fact that the water-soluble portion of the sap acts as a partial wetting agent (Stamm and Arganbright 1970). In general, the 1.0% Tergitol solution lowers the surface tension of water to a value about half of the value obtained with the natural extractives.

Table 1 gives the maximum lumen radius and the maximum fiber length for the six species determined by extrapolation of the linear plots of maximum opening radius against the thickness of the cross sections as in Fig. 1. Making the measurements by displacing the Tergitol solutions gave virtually identical values to those obtained by water displacement. In all cases, the sapwood gave higher values than the heartwood. As sapwood would eventually have turned to heartwood, if the trees had not been cut, without a change in fiber dimensions, this effect is probably a tree-age effect. This will be confirmed in a later paper. It is of interest that considerably greater maximum lumen radius and maximum fiber length were obtained for the redwood than for the other species. This same trend has been observed by Resch and Arganbright (1968) by actual fiber measurements on redwood.

Table 1 also gives the maximum effective pit pore radius for passage through 50 pits in series obtained from plots such as that of Fig. 2 for both the never-dried and dried and resoaked specimens. Water and Tergitol solution displacement gave practically identical values for never-dried wood. Sapwood values for redwood were only 2.4 times the heartwood values, but they were 33.3 times as great for the eastern larch. If the permeabilities varied as the fourth power of the maximum effective pit pore radius, as they do approximately for the average radius, the sapwood of the redwood would be only 33 times more permeable than the heartwood. In contrast, the sapwood of the larch would be 124,000 times as permeable as the heartwood. The ratios of the permeabilities of the sapwood to the heartwood for never-dried wood of the other species fall in the intermediate range of 1,065 to 8,500. Only in the case of the northern white cedar did the radii for never-dried wood vary sufficiently between water displacement and wetting agent solution displacement to warrant drawing separate lines through the two sets of points.

Drying from water reduced the calculated permeability ratio in all cases. The reduction was greater for the heartwood than for the sapwood in the Douglas-fir, eastern red cedar, and larch, about the same for incense cedar and northern white cedar, and less for the heartwood than for the sapwood in the redwood. There thus appears to be an appreciable species variation. A greater loss in permeability on drying was expected for sapwood than for heartwood because the pits are initially more aspirated in the latter so that less further aspiration can occur. This condition was found only for the redwood.

In no case was the effect of seasoning as great as was expected. This is possibly due to pits with the largest membrane pores being less subject to aspiration than pits with smaller maximum-sized pores because less tension can be exerted on them by the surface tension forces.

The loss in calculated permeability resulting from drying the sapwood of all of the species containing wetting agent was negligible. In this case, sufficiently large pores must be present in all of the pit membranes to resist significant aspiration. There was, however, a significant reduction in the calculated permeability of the heartwood dried from the wetting agent to cause further aspiration. This may be due to a greater effective tension on the pit membranes resulting from their smaller maximum effective pit pore radii.

SUMMARY AND CONCLUSIONS

Measurements were made of the air pressure required to just displace either water or water containing a wetting agent from the void structure of both the sapwood and the heartwood of 1/32-inch to 3-inch-thick cross sections of six originally green softwood species, and also from the previously air- and oven-dried specimens that were resoaked. Maximum lumen radii and maximum fiber lengths were graphically obtained from extrapolation of the initially linear portion of a plot of the calculated maximum effective opening radii against the thickness of the specimens, below the maximum fiber length, to zero thickness and zero radius respectively. Maximum effective pit pore radii for passage through fifty pits in series were obtained from the linear plots of the logarithm of maximum effective pit pore radii against the logarithm of the number of pits traversed in series. These data show that the maximum lumen radius in all cases is greater for the sapwood than for the heartwood. This is believed to be a tree-age effect. The same trend was found for the maximum fiber length.

The sapwood of never-dried specimens of all of the softwood species had larger effective pit pore radii for passage through 50 pits in series than the heartwood, ranging from 2.4-fold for redwood to 33.3 for eastern larch. If the permeability is assumed to vary as the fourth power of the maximum effective pit pore radius, which is approximately the case for the average radius, the sapwood of the redwood would be only 33 times as permeable as the heartwood. The sapwood of the larch, on the other hand, would be 124,000 times as permeable as the heartwood. Drying reduced the calculated permeability in all cases except the drying of the sapwoods from the wetting agent solutions. In this case no further aspiration appears to occur in the pits with the initially largest pit membrane pores, although it may occur in other pits where the tension, because of surface tension forces, may be great enough to cause aspiration. Permeability ratios for drying, as here calculated, thus need not correlate with the extent of aspiration of the pits. The presence of the wetting agent in the dried and resoaked heartwood of all of the species was found to have a smaller effect in preventing the reduction of the calculated drying permeability ratio below that obtained without a wetting agent present. This is not surprising, as the heartwood contains considerably smaller effective pit pores, resulting in a considerably greater drying tension on the pit pores, which in turn could result in more pit aspiration. In all cases the calculated permeability ratio for drying was higher for wood containing a wetting agent than for wood containing only water. It can hence be concluded that wetting agents that reduce the surface tension of water to 27 dynes/cm or lower reduce the loss in the calculated permeability of the larger pit membrane pores when the wood is dried. The effect is far less than anticipated and not sufficient to warrant commercial use as a means of retaining permeability of wood dried prior to impregnation treatments.

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MELICHAR, J., and ST. VEJMOLA. 1969. Utilization of the mechanical computing technique by the management of sawn timber production in the USSR. *Holztechnologie* 10(1): 57–62 (G.gre). The purpose is to produce any quantity of sawn wood from a minimum quantity of logs. A mechanical process for determining degree of utilization by simulating the conversion variable is explained. This process can be coupled with optimization. (A)