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THE TREATABILITY OF REFRACTORY SOFTWOODS[1]

John F. Siau

Wood Products Engineering Department, State University College of Forestry at Syracuse University, Syracuse, N. Y. 13210

and

Jeffry S. Shaw

Swedish Forest Products Research Laboratory, Stockholm, Sweden

ABSTRACT

The relationship between the permeability and treatability of seven eastern coniferous species and five western species was investigated. A linear relationship was found between fractional volumetric retention and logarithm of [permeability (pressure/viscosity)$^{0.32}$] for the eastern woods and logarithm of [permeability (pressure/viscosity)$^{0.18}$] for the western woods, indicating that permeability is the most significant factor affecting retention. The difference in the results for the two groups was attributed to variations in gross anatomical structure. The pressure impregnation of specimens with a light hydrocarbon oil and Cellon solvents followed by their subsequent removal resulted in a slight decrease in air permeability. This was interpreted as an indication that no significant change in the sizes of the pit openings occurred because of treatment with these solvents.

OBJECTIVES

The purpose of this investigation was to compare the treatability of specimens of refractory softwoods cut from boards supplied by Koppers Company, Inc. and to determine the influence of air permeability, treating pressure, and treating-solution viscosity upon the retention and penetration of oils. An additional objective was to determine if the solvents used in the Cellon process are able to dissolve materials from the wood that can occlude the pit openings and increase the difficulty of subsequent removal of these solvents.

LITERATURE REVIEW

Previous studies (Siau 1970a, b; Stamm 1970) have shown that the treatability of wood is strongly influenced by its permeability, which, in softwoods, is a function of the structure of the pit pairs between adjacent cell cavities. It has been generally accepted that heartwood is more resistant to flow than sapwood. Heartwood formation involves changes in the pit structures of coniferous woods such as pit aspiration, occlusion with extractives, and incrustation with ligninlike substances, according to Côté (1963).

It was observed by MacLean (1952) that the latewood of most softwoods is more easily penetrated than the earlywood, although one would expect higher permeability in earlywood, in the absence of aspiration, because of the larger number

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and diameters of the pits. Phillips (1933) investigated pit aspiration during drying and found that the number of aspirated earlywood pits increased gradually as the fiber saturation point was reached, at which time nearly all the pits were aspirated. This strongly suggests that aspiration is due to the displacement of the pit membrane by the capillary force exerted as the air-water interface recedes through the pit openings. The latewood pits resisted this effect and there was a correlation between the resistance to aspiration and the degree of wall thickening around the pit pair. Thus the reduced aspiration could be due to a more rigid structure and to the smaller size of the latewood pits.

Bramhall (1967) found the permeability of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] latewood to be essentially independent of drying method while air-dried earlywood had permeabilities that were from 1/100 to 5 times that of latewood with the permeability of earlywood usually less than that of latewood. Earlywood that was dried by low-surface-tension methods was enhanced in permeability by 8 to 30 times that of air-dried specimens. In agreement with this, Petty and Puritch (1970) found that only the latewood tracheids (32% of the total) of air-dried grand fir (*Abies grandis* Dougl.) wood were open to air flow, while in solvent-dried wood 83% of all the tracheids were conductive, including both earlywood and latewood.

Capillary forces, resulting from the surface tension at liquid-gas interfaces, play a significant role in the introduction of liquids into wood. Surface tension may be defined as surface energy per unit area. Because of surface tension, a quantity of liquid will seek the smallest possible surface area representing the lowest energy state. Thus a drop or a bubble is spherical in the absence of other forces. Work is therefore required to increase the area of air-liquid interfaces. During the impregnation of wood with a liquid, such an increase in area results when a liquid-air interface is forced through a pit opening to fill an adjacent lumen. The work is supplied by a pressure difference across the interface, which may be calculated as follows:

$$P_o - P_1 = 2\,\gamma \cos\theta/R \qquad (1)$$

where P_o = pressure in air, dynes/cm^2
P_1 = pressure in liquid phase adjacent to meniscus, dynes/cm^2
γ = surface tension of liquid relative to air, dynes/cm
R = radius of circular opening, cm
θ = contact angle, less than 90° for wetting liquids, 90° to 180° for nonwetting liquids.

It is clear from equation (1) that a certain minimum pressure is required to force a nonwetting liquid into wood. In theory no pressure should be required to inject a wetting liquid such as water into wood with no bubbles within the liquid. When bubbles are present, however, a pressure must be exerted on the water to force bubbles through pit openings. Thus if equation (1) were applied to the impregnation of wood with water, assuming a surface tension of 73 dynes/cm and a contact angle of 0°, it may be rewritten as

$$\Delta P = 21.4/(R) \qquad (2)$$

where ΔP = pressure difference required for impregnation, psi
R = radius of opening, micrometer (μm)

From equation (2) it is evident that a pressure of 430 psi would be required to force water into wood having pit-opening radii of 0.05 μm, assuming that bubbles must be forced through these openings. When oil, with a surface tension of 34 dynes/cm and an assumed contact angle of 180°, is used, equation (2) may be modified to read $\Delta P = 10/R$ and a pressure of 200 psi would be required with the same pit-opening radius.

Yao and Stamm (1967) and Stamm, Clay, and Elliott (1968) have used equation (2) to measure the effective sizes of the pit openings in softwoods by determining the air pressure required to displace free water in wood specimens. Stamm et al. (1968) also observed a decrease in the maximum effective pit opening radius as the length of the specimen increased beyond the maximum fiber length. They found a linear negative relationship between the logarithm of the maximum effective pit opening radius and the logarithm of the number of pits traversed in a series path for Douglas-fir, baldcypress (*Taxodium distichum* L.), and loblolly pine (*Pinus taeda* L.). When there is a distribution of pit opening sizes, the number traversed in series increases the probability of passage through a small pit opening. The values of pit opening sizes ranged from 1 to 15 μm in specimens just exceeding the maximum fiber length to between 0.01 and 0.52 μm in sections of approximately 100 fiber lengths. The method measures the smallest radius of the most effective parallel path through the wood.

The unsteady-state flow of liquids into wood is an extremely complex process and therefore it would be very difficult to derive a complete theoretical relationship between the fractional volumetric retention and the variables such as specimen permeability, liquid viscosity, impregnation pressure, specimen length, and treatment time. Part of this difficulty is due to the wide range of permeability between latewood and earlywood and between sapwood and heartwood. A permeability measurement is an average value for a wood specimen that is usually composed of high- and low-permeability components. Also, the radii of the pit openings are associated with a minimum pressure required to force an air-liquid interface through the openings.

Siau (1970a), in agreement with Tesoro, Choong, and Skaar (1966), has found a highly significant linear relationship between the retention of a liquid and the logarithm of the superficial air permeability for several softwood and hardwood species. It was also established (Siau 1970a) that permeability was a more significant factor in determining retention than either pressure or reciprocal viscosity and that the effects of the two latter factors were approximately equal. A linear relationship between retention and the logarithm of [permeability (pressure/viscosity)$^{0.42}$] was found. In later work (Siau 1970b), where the effects of impregnation time and specimen length were also examined, the following proportionality was applicable within the limits of the variables investigated:

$$F_{vL} \propto \log [k_g P^{0.42} t^{1.3}/(\eta^{0.42} L^{2.1})] \quad (3)$$

where kg = superficial gas permeability

F_{vL} = fractional volumetric retention ($F_{vL} = 1.0$ for complete filling of voids)

P = impregnation pressure

t = impregnation time

η = viscosity

L = length of specimen in flow direction.

PROCEDURE

The investigation included a study of two groups of woods: seven eastern species designated as Group A, and five western species designated as Group B. Included in Group A were eastern hemlock [*Tsuga canadensis* (L.) Carr.], Norway spruce (*Picea excelsa* Link.), and jack pine (*Pinus banksiana* Lamb.) all from Pack Forest, Warrensburg, N. Y.; balsam fir [*Abies balsamea* (L.) Mill.], red spruce (*Picea rubens* Sarg.), and white spruce [*Picea glauca* (Moench.) Voss.], from Whitney Industries, Inc.; and loblolly pine (*Pinus taeda* L.) supplied by Dr. Peter Koch, Southern Forest Experiment Station, Pineville, La. One kiln-dried board was used for each of the eastern woods. Group B included Engelmann spruce (*Picea engelmannii* Parry), western larch (*Larix occidentalis* Nutt.), both from the area around Fraser, Colorado; and Sitka spruce [*Picea sitchensis* (Bong.) Carr.], noble fir (*Abies procera* Rehd.), and silver fir [*Abies amabilis* (Dougl.) Forbes] from the area around Tigard, Oregon. Two boards were used for each of the western woods (Group B), one of which was air dried and the other kiln dried. Specimens were obtained from every board except the air-dried silver fir, which was severely honeycombed.

Approximately 30 specimens measuring 2 cm by 2 cm by 10 cm in the fiber direction were cut from each board. Straight-grained specimens without defects were conditioned

TABLE 1. *Permeability subgroups of Group-A specimens*

Permeability subgroup no.	Permeability range cm^3 (air)/(cm atm sec)
1	30 to 70
2	7 to 11
3	4 to 7
4	2 to 4
5	1 to 2
6	0.3 to 1.0

to an equilibrium moisture content of about 9%. Both the permeability measurements and pressure treatments were performed at this moisture content.

The longitudinal air permeabilities were measured by applying a vacuum of one-half atmosphere at one end of the specimens and an appropriate Gilmont flowmeter at the other end to determine the rate of flow of air at atmospheric pressure through the specimens. The lower permeability specimens were measured, using a ⅛-inch bore capillary tube to measure water displacement according to the method described by Siau (1969). No attempt was made to evaluate the molecular slip flow through the specimens.

The specimens of Group A were divided into six permeability subgroups, irrespective of species, as shown in Table 1. The loblolly pine, which was always in subgroup 1, was included in the investigation for comparison with the other species because of its uniformly high permeability and easy treatability. Two specimens of the same species were chosen from each permeability subgroup to be used in each of the ten fluid treatments. In Group B two air-dried and two kiln-dried specimens of each species were selected for each of nine fluid treatments.

Impregnations were accomplished using a full-cell process in which the specimens were evacuated for 30 min followed by the application of the treating pressure for 30 min. The specimens were impregnated at absolute pressures of 15, 75, and 255 psi, with the rate of pressure rise limited to 100 psi per minute. The pressure was applied from a nitrogen cylinder. The specimens of Group A were treated with oils having viscosities of 0.009, 0.045, and 0.22 poise at all three pressures and with a 0.44-poise liquid at 15 psi only. The specimens of Group B were treated with oils having viscosities of 0.045, 0.22, and 0.44 poise at all three pressures. The 0.009-poise oil was not used for Group B because of difficulties resulting from large quantities of nitrogen evolution when the pressure was released at the end of the impregnation period. Dupont Oil Blue A dye was added to all of the oils.

All specimens were weighed immediately before and after impregnation to determine the fractional volumetric retention or the fraction of the voids in the wood filled with liquid. The calculations were made by means of the following equation:

$$F_{vL} = m_L/(\rho_L \, V \, V_a), \qquad (4)$$

where F_{vL} = fractional volumetric retention
m_L = weight of liquid, g
ρ_L = density of liquid, g/cm^3
V = volume of specimen, cm^3
V_a = porosity of specimen.

The porosities were calculated on the basis of the initial weights and volumes of the specimens, using 1.46 as the specific gravity of dry cell-wall substance and 1.205 as the specific gravity of sorbed water at 9% moisture content, according to MacLean (1952).

Fractional volumetric retention may be converted to the more practical units of lb/ft^3 as follows:

$$\text{lb/ft}^3 = 62.4 \, F_{vL} \, \rho_L \, V_a, \qquad (5)$$

where 62.4 lb/ft^3 = 1 g/cm^3.

One-half of the specimens in Group B were split and photographed immediately after treatment and reweighing to indicate the penetration. The photographs appear in Figs. 6, 7, and 8.

A gravimetric indication of penetration was obtained by cutting the remaining one-half of the Group-B specimens into three lengths. Two 2.5-cm pieces were removed from the ends, leaving a 5-cm piece from the middle. The combined weight of the

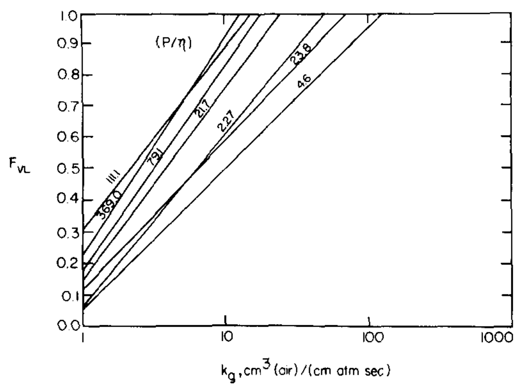

FIG. 1. Regression lines for fractional volumetric retention vs. logarithm of superficial air permeability for individual treatments using various pressure/viscosity ratios for wood specimens of Group A (eastern species).

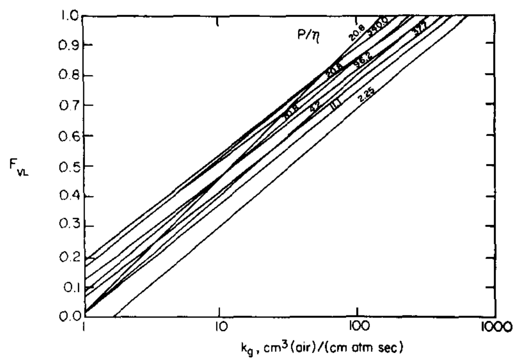

FIG. 2. Regression lines for fractional volumetric retention vs. logarithm of superficial air permeability for individual treatments using various pressure/viscosity ratios for wood specimens of Group B (western species).

two end pieces was used to calculate the fractional volumetric retention of the ends, which was compared with that of the center portion. The results of this study are summarized in Fig. 9.

A preliminary test was performed in which the permeabilities of 10 specimens from Group A were measured in the ovendry condition and then they were treated with light hydrocarbon oil (Sovasol No. 5, Socony Mobil Oil Company) at 255 psi, using a full-cell process. The oil was subsequently removed in a vacuum oven at 60 C and the permeabilities were remeasured with an average decrease of 26% from the original values.

A second similar test was conducted in which specimens from Group B were subjected to the Cellon treatment including the cosolvent but without the pentachlorophenol. Ten specimens of each species of Group B (5 air-dried and 5 kiln-dried) were conditioned to 9% moisture content, their permeabilities measured, and then they were sent to Koppers Company, Inc. for impregnation. The permeabilities were then remeasured, with an 8.3% average decrease, which was not statistically significant.

DISCUSSION OF RESULTS

Regression analysis was applied to all the data from the individual impregnations at the various pressures and viscosities. The regressions of logarithm of permeability on retention were all significant at a level higher than that corresponding to the 1% level. The regression lines for treatments of Group A are given in Fig. 1. Those for Group B are given in Fig. 2. The lines within each group have similar slopes, but it is apparent that the lines for Group A are steeper and are displaced to the left of those for Group B.

Since a previous study (Siau 1970a) indicated that the effects of pressure and reciprocal viscosity upon retention were approximately equal, regression analysis was then used to find a relationship between permeability and the ratio of pressure to viscosity for a given retention. Values of k_g and (P/η) corresponding to F_{vL} of 0.2, 0.5, and 0.8 were read from the lines in Figs. 1 and 2 for Groups A and B. Significant linear relationships were found between the logarithm of the permeability and the logarithm of the pressure to viscosity ratio. In the case of Group A, the average slope was −0.32 such that

$$\log (P/\eta) \propto -0.32 \log k_g$$

or

$$k_g\,(P/\eta)^{0.32} = \text{constant} \qquad (6)$$

In the case of Group B, a lower slope was found such that

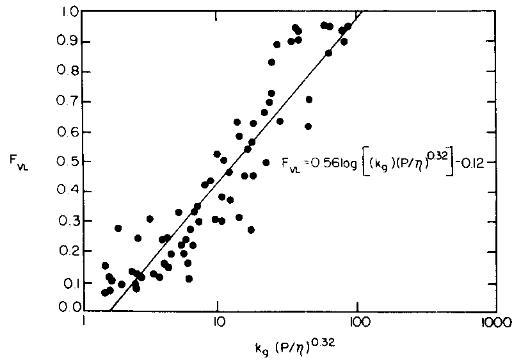

FIG. 3. Fractional volumetric retention vs. logarithm of $[k_g \, (P/\eta)^{0.32}]$ for wood specimens of Group A.

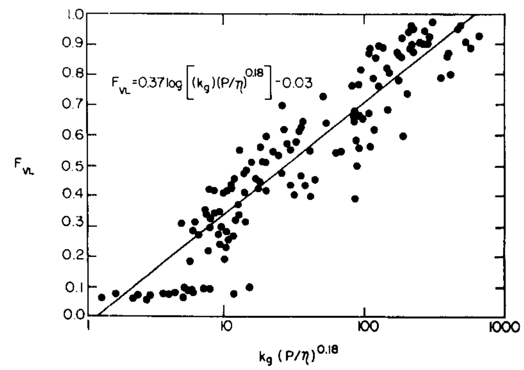

FIG. 4. Fractional volumetric retention vs. logarithm of $[k_g \, (P/\eta)^{0.18}]$ for wood specimens of Group B.

$$\log (P/\eta) \propto -0.18 \log k_g$$

or (7)

$$k_g \, (P/\eta)^{0.18} = \text{constant}.$$

All the data for Group A could then be normalized by multiplying the permeabilities by $(P/\eta)^{0.32}$ and those in Group B by $(P/\eta)^{0.18}$. The normalized data for Group A are presented in Fig. 3 and those of Group B in Fig. 4. Both regression equations representing these normalized data were highly significant and are given below:

$$\text{Group A } F_{vL} = 0.56 \log [k_g \, (P/\eta)^{0.32}] - 0.12 \quad (8)$$

$$\text{Group B } F_{vL} = 0.37 \log [k_g \, (P/\eta)^{0.18}] - 0.03 \quad (9)$$

A similar relationship obtained by Siau (1970a) is as follows:

$$F_{vL} = 0.47 \log [k_g \, (P/\eta)^{0.42}] - 0.09 \quad (10)$$

Equations (8) and (10) were recalculated from the data using the factor $(P/\eta)^{0.37}$, which uses an average value for the exponent. This recalculation made it possible to compare the equations by analysis of covariance, which indicated that there was no significant difference between the regressions or the slopes of equations (8) and (10).

A similar comparison was made of equations (8) and (9) by recalculating the regressions using an average exponent of 0.24 for the pressure to viscosity ratio. This produced two lines and equations as shown in Fig. 5.

$$\text{Group A } F_{vL} = 0.56 \log [k_g \, (P/\eta)^{0.24}] - 0.06 \quad (11)$$

$$\text{Group B } F_{vL} = 0.37 \log [k_g \, (P/\eta)^{0.24}] - 0.05 \quad (12)$$

An analysis of covariance indicated a significant difference between the slopes of the regressions expressed by equations (11) and (12). Thus the two groups of wood have behaved differently in their responses to the same impregnation process. An attempt will be made to explain these differences on a basis of anatomical differences in the woods.

There were generally more permeable specimens among Group B, with the most permeable of Group B being approximately ten times as permeable as those in Group A. It was also observed that the specimens in Group A were either all heartwood or all sapwood but that some of the samples of Group B contained both sapwood and heartwood. Generally, the permeability of sapwood is one or more orders of magnitude higher than that of heartwood. Therefore, specimens containing both kinds of wood constitute a two-component system of heartwood and sapwood where there are high- and low-resistance paths of flow in parallel. There are also earlywood and latewood in all the specimens and generally latewood is much more permeable than earlywood after

TABLE 2. *Values of fractional volumetric retention for parallel paths of various permeabilities and volumetric ratios for a pressure to viscosity ratio of 1.0 atmosphere per poise*

k_{g1}	k_{g2}	k_{g1}/k_{g2}	V_1	V_2	Mean k_g eq (13)	F_{vL} from components eq (14)	F_{vL} from mean k_g eq (11)
10	1	10	0.5	0.5	5.5	0.22	0.35
10	1	10	0.2	0.8	2.8	0.05	0.19
100	1	100	0.5	0.5	50.5	0.50	0.89
100	1	100	0.2	0.8	20.8	0.16	0.68

drying. Thus there are two or four volumetric components that would be expected to behave differently in response to an impregnation process. The most permeable component will fill first with a high retention followed by subsequent filling of the lower permeability component. When the permeability of a wood specimen is measured, an average value is obtained and it is this average value that has been used in the determination of the regression equations (8), (9), and (10). A uniformly permeable model is assumed and, if the various components of a specimen vary over a wide range of permeability or in volumetric fraction, this could cause a considerable deviation from the expected fractional volumetric retention.

Some numerical calculations can indicate the magnitude of possible differences in fractional volumetric retention because of permeability differences of components. The average permeability of a specimen in the fiber direction is a function of the permeabilities and volume fractions of the components.

$$k_g = k_{g1} V_1 + k_{g2} V_2, \qquad (13)$$

where k_g = average superficial gas permeability

k_{g1}, V_1 = permeability and volume fraction of component 1

k_{g2}, V_2 = permeability and volume fraction of component 2.

Group A consisted of either heartwood or sapwood specimens in contrast with Group B, many of whose specimens contained both heartwood and sapwood, thus constituting a two-component system in most cases. If it is assumed that equation (11) is valid for a one-component system, then, by the rule of mixtures, the retention for a two-component specimen with parallel flow paths may be calculated as:

$$F_{vL} = 0.56\, V_1 \log\, [k_{g1}\, (P/\eta)^{0.24}] + 0.56\, V_2 \log\, [k_{g2}\, (P/\eta)^{0.24}] - 0.06, \qquad (14)$$

where F_{vL} = fractional volumetric retention for a two-component specimen.

Table 2 gives the results of calculations of retentions of wood specimens having component permeabilities of 10 and 1 and 100 and 1. These are not extreme ratios of permeability between sapwood and heartwood. Volumetric fractions of 0.5 and 0.2 were used as values of V_1, the volume fraction of the high-permeability component. Theoretical retentions were then calculated from equation (11) using the average permeability as determined from equation (13). These values can be found close to the regression line for the Group A specimens in Fig. 5. Then the retention based upon the two components separately is calculated

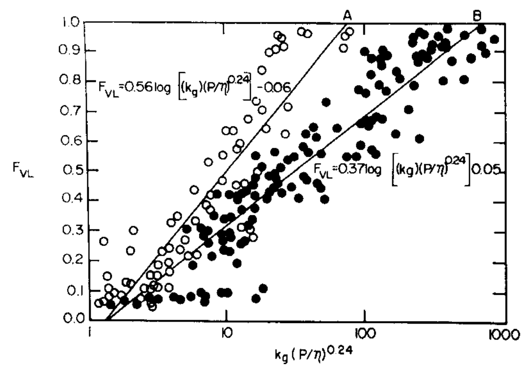

FIG. 5. Fractional volumetric retention vs. logarithm of $[k_g\, (P/\eta)^{0.24}]$ for wood specimens of Group A and Group B.

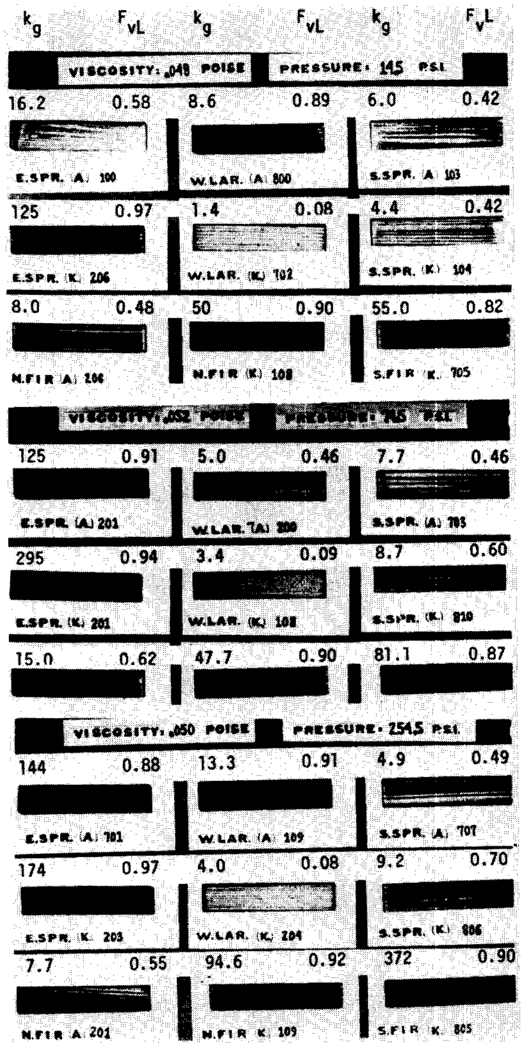

FIG. 6. Photographs of split specimens treated with 0.045-poise dyed oil at absolute pressures of 15, 75, and 255 psi.

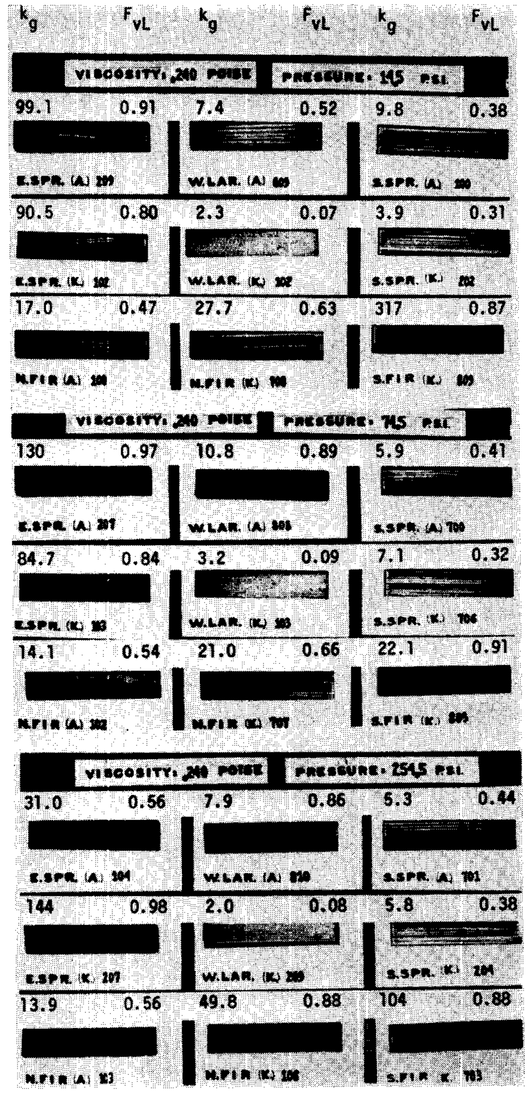

FIG. 7. Photographs of split specimens treated with 0.22-poise dyed oil at absolute pressures of 15, 75, and 255 psi.

from equation (14). These values are considerably lower than the former values and they correspond approximately to what was found for the Group B specimens. The difference in retentions is augmented by increasing the permeability ratio or the value of V_2. Reference to Fig. 5 shows that Group B, which contained specimens with both sapwood and heartwood, had retentions considerably lower than those of Group A, as would be expected for a two-component system. Thus the difference in behavior of the groups can be explained on a basis of the observed structural difference.

Bramhall (1967) has measured ratios of latewood to earlywood permeability between 0.2 and 100 in air-dried Douglas-fir. Siau (1970b) has observed sapwood to heartwood permeability ratios between 1 and 300 in Douglas-fir. Stamm (1970) estimated ratios between 33 and 124,000 from calculations based upon the pressure re-

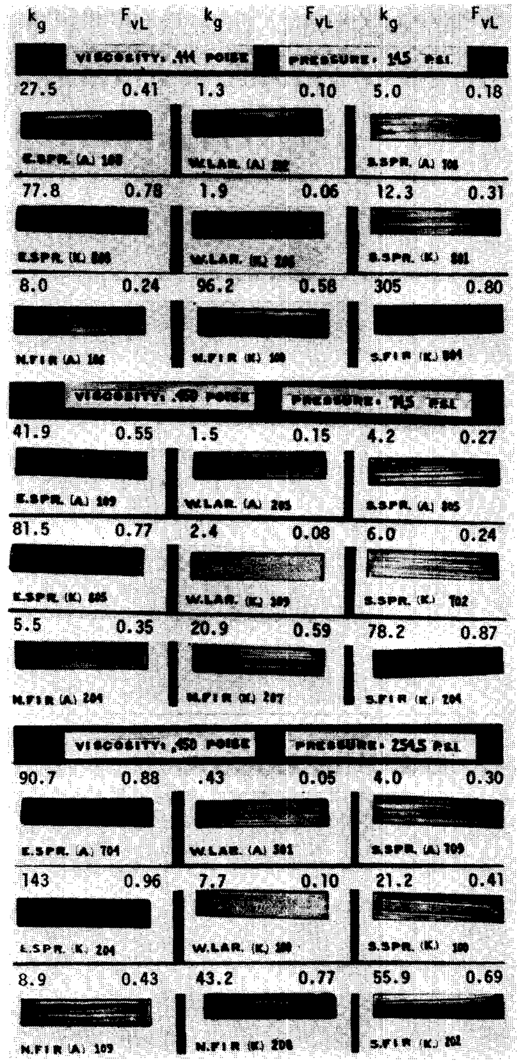

FIG. 8. Photographs of split specimens treated with 0.44-poise dyed oil at absolute pressures of 15, 75, and 255 psi.

quired to displace capillary water from specimens of six species of softwood. Thus large permeability differences between earlywood and latewood components are possible. This can account for widely varying retentions for a given measured permeability, which are evident in Figs. 3 and 4.

PENETRATION STUDIES

The penetration of Group B is depicted in Figs. 6, 7, and 8. It is observed, gen-

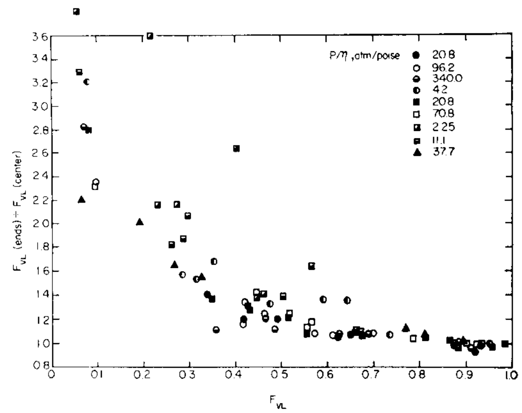

FIG. 9. Ratios of fractional volumetric retention of end pieces to that of center piece of treated specimens vs. fractional volumetric retention of the entire specimens.

erally, that there is more penetration of latewood than of earlywood. This is particularly true of the specimens of lower permeability. There was more uniform penetration throughout both the earlywood and latewood portions of the more permeable specimens. The western larch kiln-dried specimens exhibited very low penetration under all the conditions of treatment. Penetrations tend to increase with increasing pressure and with decreasing viscosity as expected.

The ratios of fractional volumetric retention of the end pieces to that of the center piece of the specimens that were sawed transversely for penetration determination are illustrated in Fig. 9. It is clear that this ratio increases as the fractional volumetric retention of the entire specimen decreases, in all of the treatments. The ratios are generally low, with most of them being less than 2.0. This is attributed to the two-component (earlywood-latewood) structure of the wood resulting frequently in a fairly complete penetration of the latewood with a much lower penetration of the earlywood. Both a high latewood-earlywood volumetric ratio and corresponding permeability ratio would tend to decrease the ratio of the retentions of the ends compared with the center pieces of the specimens. It is evident that the ratios tend to increase for the

TABLE 3. *Average air permeabilities and liquid retentions of all specimens of Group A and those specimens of Group B which were split and photographed*

Wood type	Average k_g cm^3(air)/(cm atm sec)	Average F_{vL}
Group A		
Loblolly pine	51.3	0.96
Red spruce (sapwood)	8.25	0.75
Eastern hemlock	6.10	0.60
Balsam fir	6.75	0.46
Norway spruce	2.32	0.32
White spruce	1.03	0.33
Red spruce (heartwood)	1.16	0.13
Jack pine	0.54	0.07
Group B		
Engelmann spruce (kiln-dried)	135	0.89
Silver fir (kiln-dried)	155	0.85
Noble fir (kiln-dried)	50	0.76
Engelmann spruce (air-dried)	79	0.74
Western larch (air-dried)	6.3	0.53
Noble fir (air-dried)	10.9	0.47
Sitka spruce (kiln-dried)	8.7	0.41
Sitka spruce (air-dried)	5.9	0.37
Western larch (kiln-dried)	3.2	0.08

treatments made at the lowest pressures and with the higher viscosity oils which have the lowest (P/η) ratios. This would be expected because a reduction in the (P/η) ratio reduces F_{vL}, while an increase in (P/η) would tend to produce a complete penetration of latewood resulting in a more uniform distribution along the length of the specimen.

The average permeabilities and corresponding volumetric retentions of all speci-

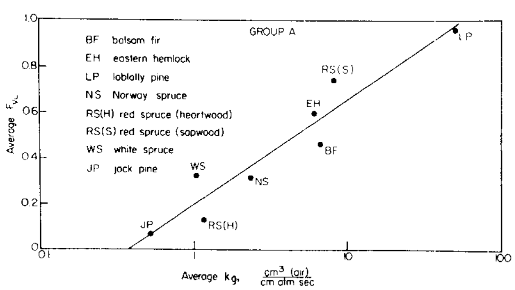

FIG. 10. Average volumetric retentions of all specimens of Group A vs. logarithm of corresponding average superficial air permeabilities.

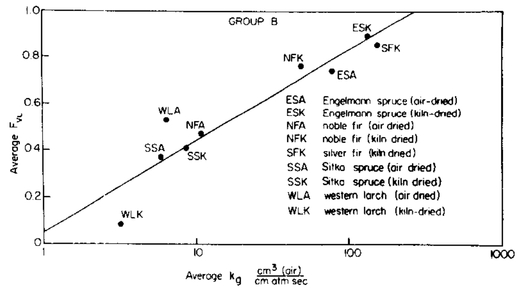

FIG. 11. Average volumetric retentions of all specimens of Group B vs. logarithm of corresponding average superficial air permeabilities.

mens impregnated by all the treatment schedules used are presented in Table 3. Figure 10 is a plot of the data for Group A including the highly significant least-squares regression line representing the relationship between the variables. The permeabilities and retentions of red spruce formed two populations and these were attributed to heartwood-sapwood difference. Figure 11 is a similar plot for Group B. A comparison of Figs. 10 and 11 indicates that the average permeabilities of specimens of Group B were approximately 2 to 5 times those of Group A for the same average retention, the difference being attributed to gross structure as previously described. Generally the kiln-dried specimens were easier to treat than air-dried, with the exception of the kiln-dried western larch. This anomalous behavior of western larch could have been due to heartwood-sapwood difference.

The data presented in Table 3 and Figs. 10 and 11 confirm the correlation of treatability to permeability but are not intended as a measure of the relative treatability of the various species tested. In most cases all the specimens of a given species were cut from the same board and therefore they are not representative of the species. The highest retention in Group B was observed with kiln-dried Engelmann spruce, which is regarded as a refractory species but, in this case, the specimens used had relatively high permeability to explain their high retentions.

It has been postulated that the difficulty in removing solvents from wood after treatment by the Cellon process is due to a plugging of the pit openings because of the removal of extractives by the solvents and their subsequent deposition in the openings. The preliminary test with 10 specimens of Group A showed that the treatment of wood specimens with a light hydrocarbon oil with its subsequent removal in a vacuum oven at 60 C caused an average decrease in the air permeability of the specimens of 26%. This was not considered sufficiently large to have any significant effect upon the rate of solvent removal from the wood. A chi-square statistical test indicated, however, that this was a significant change in permeability.

The second test was performed in which 45 specimens of the western species were subjected to the Cellon treatment with the cosolvent but without pentachlorophenol. The ratios of initial to final permeability for the specimens varied between 0.51 and 1.12, with an average decrease in permeability of 8.3%. A chi-square test indicated that there was no significant change in the permeability due to the treatment with Cellon solvents. If the pit openings were plugged because of solvent action, a very significant decrease in permeability would have resulted since nearly all the flow through coniferous woods is from tracheid to tracheid through the pit openings. Therefore the hypothesis that the difficulty of solvent removal is specifically due to clogging of the pit openings by solvent action is rejected. It is possible, however, for plugging of pit openings to occur because of the precipitation of pentachlorophenol during the normal Cellon treatment.

The effect of capillary forces upon the impregnation of the specimens may be estimated from their permeabilities. Comstock (1967) has calculated the size of the pit openings in eastern hemlock from nitrogen permeability measurements at different pressures by using the Klinkenberg equation, which may be written in the form

$$k_g = k\,[1 + 4\,\lambda/(R)], \qquad (15)$$

where k_g = superficial gas permeability with slip flow

k = gas permeability without slip flow

λ = mean free path of measuring gas at pressure at which k_g is measured

R = radius of pit openings.

Comstock then found that the gas permeabilities of many specimens of eastern hemlock were proportional to the 3.9-power of the calculated radii, which is close to the value of 4.0 predicted by the Poiseuille equation. Assuming an exponent of 4.0 and air as the measuring gas, Comstock's equation may be written as

$$k = 200\,R^4 \qquad (16)$$

where k = air permeability, cm^3(air)/(cm atm sec)

R = radius of pit openings, μm

Although Comstock's findings were limited to eastern hemlock, it is assumed that equation (16) is applicable to other softwoods because of the basic similarity in their structure. Then by combining equations (15) and (16), it is possible to estimate values of k and R corresponding to given values of superficial air permeability (k_g). The pressure required to overcome capillarity may be calculated from the relationship $\Delta P = 10/R$ which is applicable to oil with a surface tension of 34 dynes/cm. The results of these calculations are presented in Table 4.

TABLE 4. *Values of* k, R, *and* ΔP *calculated from* k_g *using equations (15) and (16)*

k_g, cm^3(air)/(cm atm sec)	k, cm^3(air)/(cm atm sec)	R, μm	ΔP, psi
0.2	0.034	0.115	87.0
4.00	1.4	0.29	34.5
25.00	11.4	0.49	20.4
200.00	120.0	0.88	11.4

It is apparent then that relatively high pressures are needed to force liquid into wood specimens having low permeabilities. In fact, if the permeability were sufficiently low resulting in a value of ΔP that exceeds the applied impregnating pressure, no retention would be expected.

SUMMARY OF RESULTS

This investigation confirms previous findings that the air permeability of wood, irrespective of species, is the predominant factor influencing treatability with liquids, and that the effects of pressure and reciprocal viscosity are approximately equal. Thus it should be possible to predict relative treatability from air permeability measurements and to estimate the effects of changes in impregnation pressure and solution viscosity. Kiln-dried specimens were generally easier to treat than air-dried specimens. The difficulty of removal of Cellon solvents from impregnated wood is apparently not due to the clogging of pit openings by material extracted from the wood by the solvents.

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