VARIATION IN PERMEABILITY AND TREATABILITY IN SHORTLEAF PINE AND YELLOW POPLAR[1]

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ABSTRACT

Superficial gas permeability determinations were made for longitudinal, radial, and tangential flow on samples removed from different heights, radii, and distances along the radii in a young and a mature shortleaf pine (*Pinus echinata* Mill.) and in a yellow poplar (*Liriodendron tulipifera* L.). Permeability was measured at a mean pressure of 2.2 atmospheres and the wood was maintained at about 18% moisture content. Some of the samples were then pressure-treated with creosote under controlled conditions to estimate treatability. Specific gravity and latewood per cent were also determined. In the young pine, position in the tree showed no effect on permeability, whereas in the mature pine a slight increase with height and a sharp increase with distance from the pith were detected. In yellow poplar, an increase of permeability with distance outwards along the radius was detected, but no consistent height change. Treatability, particularly retention, was moderately correlated with permeability, particularly in shortleaf pine. In yellow poplar, inclusion of permeability values for all three structural directions was necessary to obtain correlation. All relationships were improved by transforming the permeability logarithmically. Specific gravity and latewood relationships with permeability were conflicting. Use of a mean pressure higher than atmospheric appeared to be advantageous in permeability determinations.

INTRODUCTION

Despite a large amount of work on permeability, very few quantitative data are available on the variability of permeability within a tree, particularly with respect to structural directions and wood types. This study was undertaken to obtain such information, on one softwood species and one hardwood species. A secondary objective of this study was to relate within-tree permeability variation to treatability, since past attempts (Arganbright and Wilcox 1969, Isaacs et al. 1971) were not successful in determining this relationship.

EXPERIMENTAL PROCEDURE

Sample preparation

Three straight and healthy trees growing at the Idlewild Plantation near Clinton, Louisiana, were selected, as follows:

Young shortleaf pine (*Pinus echinata* Mill.), 10 years old, 8-inch DBH

Mature shortleaf pine, 50 years old, 16-inch DBH

Mature yellow poplar (*Liriodendron tulipifera* L.), 40 years old, 15-inch DBH

From each tree, several bolts, each 1 ft in length, were removed at 2½-ft intervals up the bole starting from 1 ft above ground. A 2-inch-thick disk was cut from the bottom end of each bolt, and longitudinal dowel samples in the green condition were obtained with a ⅞-inch plug cutter, at intervals from pith to bark along several radii. In the mature shortleaf pine, eight radii separated by 45° were sampled, whereas in yellow poplar, because some defects were present, only four radii at 90° were sampled. A 4-inch-thick disk was also cut adjacent to each 2-inch disk, and from it a block extending from near the pith to bark, measuring 2 inches wide along the annual ring and 4 inches long along the grain, was obtained from each quadrant. From each block, tangential and radial dowels were prepared. From the dowel samples, permeability test samples measur-

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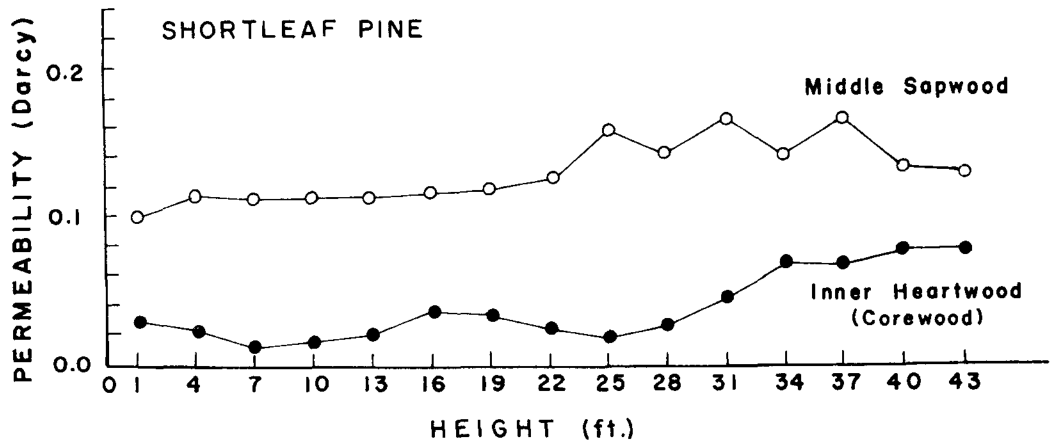

FIG. 1. Average permeability of mature shortleaf pine at various tree heights.

ing 0.8 inch in diameter and 1.0 inch in length were prepared. The surfaces of each sample were smoothly sanded, and any debris was blown off with a compressed air hose. These samples were dried at moderate humidity condition until their moisture contents were slightly below the fiber saturation point. Then they were conditioned to equilibrium over saturated salt solution of zinc sulfate (nominal 85% RH or about 18% EMC) in desiccators.

Permeability measurements

The permeability of each sample was determined, using Darcy's law for gas, from measurements in a specially built apparatus similar to the one described by Isaacs et al. (1971) using prepurified nitrogen gas. Two nullamatic regulators were used, one to control the sleeve pressure that held the sample inside a steel core holder and the other to regulate the upstream flow pressure to within 0.25 psig. A bank of five flowmeters, suitably calibrated for nitrogen, was used. These meters provided flow rates ranging from 1 cc/min to as high as 75,000 cc/min. The nitrogen gas was passed through a humidity chamber containing distilled water, so that the effect of moisture content on permeability was minimized.

All samples were measured at a mean pressure of 2.2 atmospheres. To obtain this pressure, the upstream pressure of low and moderately permeable samples was held at 25 psig, but the downstream pressure was regulated with a fine metering needle valve to 10 psig, giving a pressure drop of 15 psig. With the more permeable samples (> 1.0 Darcy) a higher upstream pressure was necessary to obtain a stable pressure drop. The permeability of a few samples was measured also at various mean pressures in order to obtain an extrapolated "true" permeability value at infinite pressure. For this purpose, flow was determined at different upstream pressures and pressure drops.

Treatment measurements

Following permeability measurements, about 200 samples from each species were coated on their sides with three coats of epoxy resin adhesive (Dow's D.E.R. 331, mixed with Dow's 14 hardener in equal proportion) in order to provide unidirectional (i.e. longitudinal, tangential, or radial) movement of fluid through the uncoated ends. After coating, care was taken to remove by sanding any resin that was found on the end surface of the dowel sample, and any debris was blown off with a compressed air hose.

Treatment was done in an enclosed impregnation chamber, which was small enough to be placed in a water bath. The

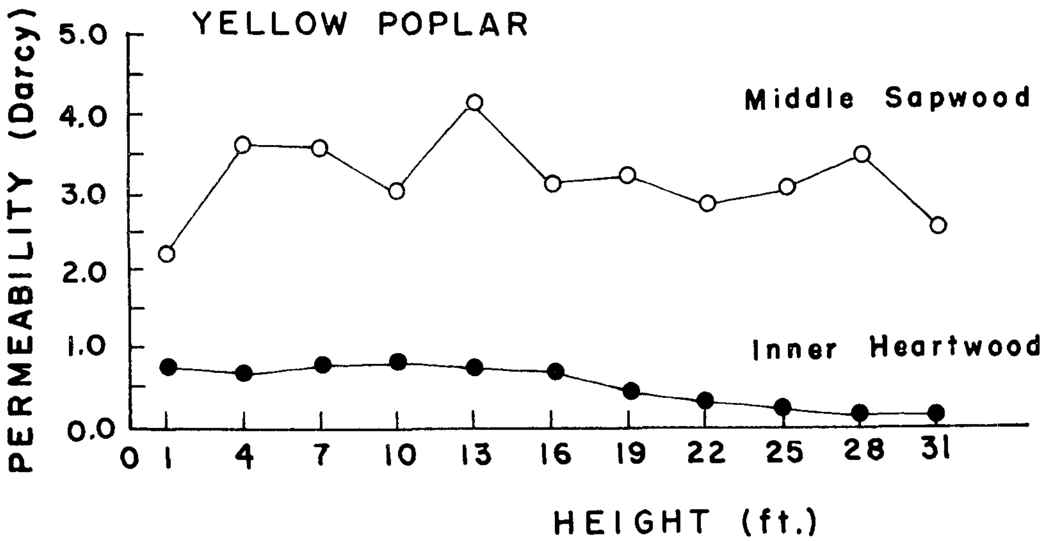

FIG. 2. Average permeability of yellow poplar at various tree heights.

bath was equipped with electrical heating coils so that the temperature of the treating fluid (and therefore its viscosity) could be controlled. Pressure was provided from a nitrogen cylinder and was controlled by a nullamatic regulator.

The Lowry process was used in the impregnation of test samples, at a pressure of 25 psig, a pressure period of 10 min, and a temperature of 160 F. These conditions were found from preliminary tests to be the most suitable for the particular sample size.

The retention of creosote (lb/cu ft) was evaluated in terms of the difference between the weights of the sample before and after treatment on a Mettler top-loading balance accurate to 0.001 g, for a given volume of wood. The excess surface accumulation of preservative was first blotted with tissue paper before the weight after treatment was obtained. The penetration (inch) was measured by splitting the treated sample immediately after weighing. The depth to which the liquid penetrated the sample was measured to a thousandth of an inch with a caliper. The minimum and maximum depths of penetration were measured, and the average was taken as the depth of penetration. In the case of two-component penetrations in summerwood and springwood, the average was calculated by weighting the penetration according to the area of the two components. The treatability results were discarded for any sample that showed signs of penetration from directions other than the sample ends.

DISCUSSION OF RESULTS

The pattern of variations in permeability within a tree was established by analysis of variance. In the young shortleaf pine tree, there was no difference in permeability with height or with distance from the pith. This phenomenon may be expected, since all wood at this age is in the "juvenile" stage. In the mature trees of shortleaf pine and yellow poplar, there were highly significant differences in permeability, for longitudinal flow only, with respect to distance from the pith. No attempt was made here to determine the variability of tangential permeability and radial permeability separately, because their ranges of values were too small for a meaningful evaluation.

There were differences among samples from different quadrants in the mature shortleaf pine tree, but not in the yellow

TABLE 1. *Permeability range of values for various trees, flow directions, and wood types at mean pressure of 2.2 atmospheres*

Flow direction and wood type	Permeability range			Obs.
	Min.	Max.	Mean	
	. . . . . . (Darcy)			
SHORTLEAF PINE, TREE No. 1 (10-year-old)				
Longitudinal				
All samples	0.154	0.853	0.569	50
Corewood	0.154	0.832	0.291	18
Sapwood	0.203	0.853	0.503	32
Radial				
All samples	0.036	0.348	0.178	13
Tangential				
All samples	0.005	0.026	0.009	14
SHORTLEAF PINE, TREE No. 2 (50-year-old)				
Longitudinal				
All samples	0.001	0.329	0.093	403
Corewood	0.001	0.094	0.063	102
Maturewood[1]	0.001	0.144	0.026	100
Sapwood	0.006	0.329	0.114	201
Radial				
All samples	0.006	0.057	0.028	80
Tangential				
All samples	0.003	0.027	0.009	65
YELLOW POPLAR (40-year-old)				
Longitudinal				
All samples	0.030	6.990	2.341	190
Corewood	0.030	1.048	0.426	39
Maturewood[1]	0.044	1.338	0.319	38
Sapwood	0.583	6.990	3.683	113
Radial				
All samples	0.003	0.030	0.010	40
Tangential				
All samples	0.002	0.015	0.006	33

[1] Maturewood indicates the heartwood portion next to the corewood in this case.

poplar tree. This effect, however, was small and there was no consistent trend, in contrast to the effect of distance from the pith. There was also a small but highly significant effect of height on permeability for both trees, for both longitudinal and transverse flow. In the shortleaf pine, permeability tended to increase slightly with an increase in height (Fig. 1); but in the yellow poplar there appeared to be no definite trend with height in the tree (Fig. 2).

The ranges and means of permeability are shown in Table 1. Within a given wood-type and flow direction, the average for the young shortleaf pine was higher than for the mature tree by a factor of six in both the longitudinal direction and radial direction. No difference was detected in the tangential direction since the permeability was exceedingly low. As expected, yellow poplar, which is a diffuse porous wood, had a much higher average permeability in the longitudinal direction than a coniferous wood such as shortleaf pine.

Effect of wood type

In both species, the permeability was lowest near the pith (corewood) and highest in the sapwood. The patterns of variation associated with distance from pith

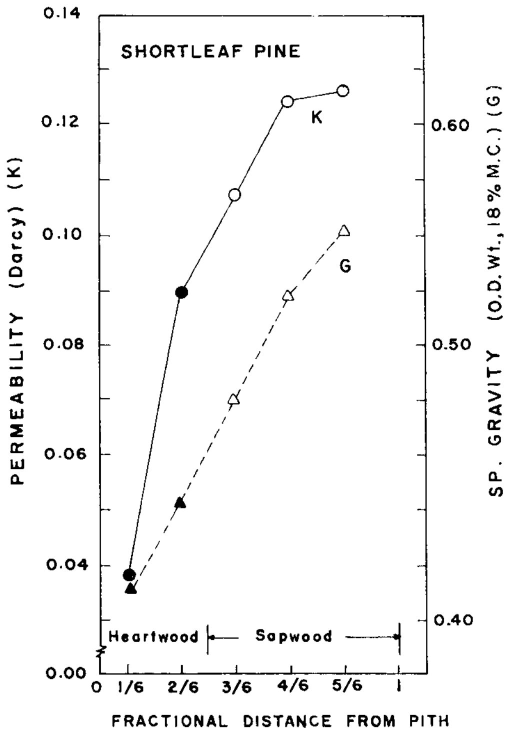

FIG. 3. Variation in average permeability and specific gravity with radial location in mature shortleaf pine.

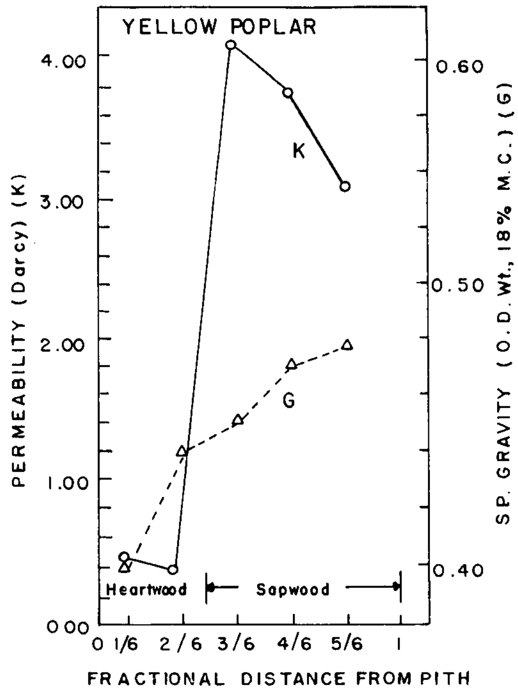

FIG. 4. Variation in average permeability and specific gravity with radial location in yellow poplar.

are shown in Fig. 3 for mature shortleaf pine and in Fig. 4 for yellow poplar. There was a substantial increase in permeability from the pith toward the bark. In shortleaf pine the maximum occurred in the outer sapwood. The same trend was observed by other investigators, i.e. Benvenuti (1963) for loblolly pine, Buro and Buro (1959) for Scots pine, and Comstock (1965) for eastern hemlock. The average ratio of longitudinal permeability between sapwood and heartwood was less than 10 times in each tree studied, but the maximum difference was 233 times in yellow poplar, 329 times in mature shortleaf pine, and only five times in young shortleaf pine. Other investigators have reported ratios of 380 times in longleaf pine (Erickson et al. 1937), 9 to 1178 times among individuals of the four major southern pines (Fogg 1968). Choong and Fogg (1968) reported a ratio of 105 times in yellow poplar, and 55 times in southern pine (*Pinus* sp.). In the transverse direction, the difference between sapwood and heartwood was very small; therefore any attempt to determine this effect is precluded by greater variations in permeability between the tangential and radial directions. The low permeability of heartwood, as compared with sapwood in southern pine, is believed to be the result of incrustation of membranes in the pits as well as pit aspiration (Thomas 1967).

Effect of structural directions

The anistropic permeability for the two wood species is shown as follows:

	L:R:T Ratios	
	Mean	*Extreme*
Shortleaf pine, young tree	63:19:1	170:70:1
Shortleaf pine, mature tree	10: 3:1	110:19:1
Yellow poplar, mature tree	396: 2:1	3850:15:1

There is a wide range of permeability ratios in a given structural direction as well as between structural directions. The L/T ratio is much less for shortleaf pine than that for yellow poplar. This is expected since the flow of a softwood is mostly through the tracheids which have only small interconnecting bordered pits; whereas in a diffuse porous wood the flow is mostly through the vessels whose lumen openings are not only larger than the pits, but which also serve as open capillaries through the entire wood. Since flow varies as the fourth power of the capillary radius (Hagen-Poiseuille law), permeability is expected to be greater in wood having large average flow channels, provided lumen resistance and/or turbulent flow is not a significant factor affecting flow.

The mean values for radial permeability are always larger than tangential permeability by several fold. Since ray cells are oriented in the direction of flow in radial permeability, they should serve as important paths even though the role of wood rays is still not clear (Erickson et al. 1938; Buro and Buro 1959).

Several investigators (Comstock 1970; Choong and Fogg 1968) have studied the directional flow of fluids in wood. Ratios of longitudinal permeability to tangential or radial permeability have been reported to be as high as several hundred thousand to one for gas permeability. In contrast, data obtained from this study using dowel samples of about the same size showed that the ratio for longitudinal to tangential permeability is less than 4,000 even when the extreme range values were taken (for yellow poplar). In another study, using somewhat the same experimental technique as that reported here, Isaacs et al. (1971) reported average L:R:T ratios for cottonwood of 317:1.4:1. Erickson and Estep (1962) also found rather low mean ratios of 63:14:1 in Douglas-fir heartwood. Buro and Buro (1959), working with Scots pine using rather high pressure, reported ratios of 179:6:1 and 252:4.4:1 for sapwood and heartwood, respectively. The apparent wide variations in directional permeability in published values are due, in part, to different techniques of measurement (i.e. gas vs. liquid, sample size, pressure difference, etc.), different histories of the samples (i.e. dry vs. green), and also to the inherent variability in the behavior of wood itself (i.e. lack of proper sampling). All these would undoubtedly contribute to discrepancies in the results. Furthermore, even though some progress has been made in theoretical evaluations of gas flow in wood, the effect of non-Darcy behavior is still largely unresolved.

It should be noted that although permeability values measured with gases and liquids are closely related (Comstock 1967, 1968), the relationship holds true only when the superficial gas permeability is extrapolated to infinite pressure or close to it. Most of the available permeability data, however, have been obtained with gas at mean pressures which were below atmospheric pressure (hereafter referred to as negative pressure range in contrast to the positive pressure range where mean pressure is above atmospheric). Comstock (1967) has noted an increase in permeability with a decrease in mean pressure and, although the effect of slippage (i.e. the product of the superficial gas permeability with the slope of the permeability vs. reciprocal mean pressure line, at a given mean pressure) is more pronounced at low permeability, the slope becomes steeper with increased permeability. Figure 5 shows this phenomenon for a few selected samples. In the negative pressure range, the permeability values are higher than at the positive pressure range; consequently, a greater spread of permeability values can be expected with the former. Thus, when negative pressures are used, the range of permeability may be as high as a million times between the high and the low values for a given direction as well as different directions of flow (Comstock 1970; Smith and Lee 1958). However, the permeability values reported here, which were obtained at a mean pressure of 2.2 atmospheres, show much less variation. At this pressure the superficial permeabilities are expected to differ little from the "true" permeabilities (at infinite pressure), and the cor-

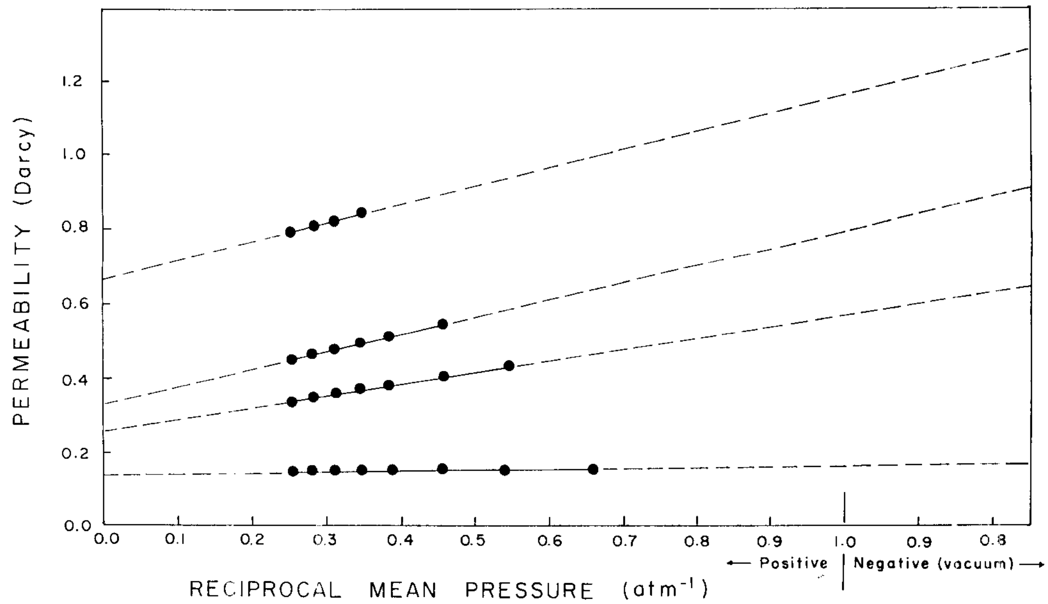

FIG. 5. Relationship of permeability with reciprocal mean pressure for several yellow poplar samples. Flow was measured at pressure difference of 15 psig.

relation between these two permeabilities, as shown in Table 2, is high ($r = 0.96$ for shortleaf pine, and 0.95 for yellow poplar), and their regression equations are almost identical.

On the basis of a theoretical model proposed by Comstock (1970), the predicted ratio of longitudinal to transverse permeability is between 22,500 and 10,000 for a fiber length/width ratio of 100. An extremely high ratio is conceivable considering that transverse permeability values as low as 1.0×10^{-7} Darcy have been measured recently (Choong and Kimbler 1971, Kininmonth 1971) with liquid as the permeant; in contrast, the longitudinal permeability of a softwood is generally less than 1.0 Darcy. With gas, the lowest permeability that could be measured so far is about 1.0×10^{-4} Darcy.

Effect of specific gravity and percentage latewood

A simple linear regression analysis of all permeability values and their corresponding specific gravities was found to be significant at the 1% level of probability for mature trees of both species for longitudinal flow, but not for transverse flow (Table 2). The correlation coefficients, however, are not very high, i.e. about 0.40 for both species, indicating that only a small portion (about 16%) of the permeability variations in the longitudinal direction can be accounted for by specific gravity variations. The average specific gravity, based on volume at 18% EMC, is 0.45 (0.31 – 0.71 range) for shortleaf pine and 0.44 (0.34 – 0.59 range) for yellow poplar.

When the permeability-specific gravity relationship was examined in individual trees and in different portions of the tree (i.e. corewood and sapwood), in the young shortleaf pine no correlation was found. On the other hand, in the older pine, within either corewood or sapwood, no significance was obtained, while for the whole tree a moderate relationship ($r = 0.40$) was found for all samples. This stronger relationship, when samples from all portions of the tree are put together, may be considered as due to an increase of specific gravity from pith to bark coincidental to a

TABLE 2. *Correlation of some physical properties with permeability*

Flow direction and physical property	Permeability (K) at $\bar{P}$ = 2.2 atm: Correlation coefficient (r) K	Ln K	Regression equation	Obs.
		SHORTLEAF PINE		
Longitudinal direction				
10-year-old				
Sp. gravity, corewood	0.22 NS			18
Sp. gravity, sapwood	–0.18 NS			32
Sp. gravity, all	0.14 NS			50
50-year-old				
Sp. gravity, corewood	0.16 NS			102
Sp. gravity, sapwood	0.12 NS			201
Sp. gravity, all	0.40†		K = –0.053 + 0.314 (G)[1]	403
Latewood, corewood	0.58†		K = –0.005 + 0.002 (L)[2]	102
Latewood, sapwood	0.24†		K = 0.003 + 0.003 (L)	201
Latewood, all	0.59†		K = 0.023 + 0.002 (L)	403
Retention (R)	0.49†	0.66†	R = 20.88 + 2.08 (Ln K)	111
Penetration (P)	0.21*	0.22*	P = 0.47 + 0.01 (Ln K)	111
Permeability at $\bar{P}$ = ∞ (K′)	0.96†		K′ = 0.008 + 0.870 (K)	50
Transverse direction				
Sp. gravity, all	0.17 NS			145
Retention	0.46†	0.59†	R = 21.97 + 2.98 (Ln K)	76
Penetration	0.42†	0.72†	P = 0.46 + 0.05 (Ln K)	76
All (L, T, R) directions				
Retention	0.52†	0.72†	R = 22.06 + 2.77 (Ln K)	187
Penetration	0.36†	0.66†	P = 0.46 + 0.05 (Ln K)	187
		YELLOW POPLAR (40-year-old)		
Longitudinal direction				
Sp. gravity, corewood	–0.51†		K = 2.53 – 5.07 (G)	38
Sp. gravity, sapwood	–0.15 NS			113
Sp. gravity, all	0.44†		K = –7.46 + 22.72 (G)	190
Retention	0.06 NS	0.13 NS		118
Penetration	0.05 NS	0.07 NS		118
Permeability at $\bar{P}$ = ∞	0.95†		K′ = –0.006 + 1.011 (K)	50
Transverse direction				
Sp. gravity, all	0.10 NS			73
Retention	0.06 NS	0.11 NS		59
Penetration	0.03 NS	0.00 NS		59
All (L, T, R) directions				
Retention	0.61†	0.89†	R = 13.00 + 1.82 (Ln K)	177
Penetration	0.62†	0.91†	P = 0.32 + 0.05 (Ln K)	177

* Significant at 5% level of probability.
† Significant at 1% level of probability.
NS = Not significant.
[1] G = Specific gravity.
[2] L = Percentage latewood.

general increase in permeability in the same direction; whereas within the separate portions of the stem, factors other than specific gravity strongly influence permeability. The effectiveness of flow may be increased with an increase in specific gravity, if there is a greater ease of flow in the dense latewood of softwoods in particular, as compared with the earlywood. Such has been found to be the case in some cases of Scots pine by Buro and Buro (1959).

In the yellow poplar corewood, a significant negative correlation of specific gravity and permeability was obtained. This would be anticipated because decreased specific gravity in a diffuse porous wood would normally be associated with an increase in proportion of the cross section occupied by pores which are the predominant conducting channels in the longitudinal direction. The lack of correlation in the sapwood is inconsistent with this explanation and is thought to be due to the influence of other factors not considered in this study. This latter reasoning is supported by the significant but not powerful correlation of the two variables for all the samples in the tree.

The relationship between permeability and specific gravity is somewhat conflicting. Resch and Ecklund (1964) working with redwood, Fogg (1968) with southern pines, and Arganbright and Wilcox (1969) with white fir all reported no correlation betweeen permeability and specific gravity. On the other hand, an inverse relationship between longitudinal permeability and specific gravity has been reported by Comstock (1965) for eastern hemlock heartwood, by Isaacs et al. (1971) for cottonwood heartwood, by Choong and Fogg (1971) for sweetgum, and Benvenuti (1963) for loblolly pine. In addition, Comstock also showed a significant relationship between permeability and percentage latewood, but the correlation coefficient was quite low.

An analysis to determine the relationship between longitudinal permeability and percentage latewood in shortleaf pine indicates a correlation coefficient of 0.58, which is highly significant at the 1% level of probability. This relationship could again be thought as coincidental. However, in the pines there is a greater frequency of resin canals in the latewood than in the earlywood. Additionally, the latewood assessment would be unaffected by the presence of extractives, which may or may not affect permeability. Therefore, the correlating of specific gravity with latewood is compatible with a permeability-latewood relationship and no permeability-specific gravity relationship. Nevertheless, specific gravity in softwoods is closely related to percentage latewood, and in this study a high correlation was obtained ($r = 0.80$) which indicates that the visual estimate of latewood (varying from 5 to 80%) is a satisfactory method for estimating this variable.

Permeability vs. treatability

The relationships of permeability with treatability are shown in Table 2. In shortleaf pine, significant correlations were obtained with both retention and penetration of creosote, for longitudinal and transverse directions separately as well as together. However, there is no significant relationship in yellow poplar in either the longitudinal and transverse direction separately, but when these were combined, the correlation coefficients for retention and penetration are not only significant but also very high. The reasons are that yellow poplar exhibited very erratic permeability values in the longitudinal direction, and very low and less varied permeability values in the transverse direction, but their corresponding treatability values do not vary a great deal (Table 3). When the longitudinal and transverse data were pooled together, a significant relationship was obtained simply because of unusually high longitudinal to transverse ratio. It should be noted that even though there is a significant relationship between permeability and treatability, the regression equations differ considerably among the structural directions. Other workers (Tesoro et al. 1966; Siau 1970; Siau and Shaw 1971) have also found considerable scatter, to the extent that no significant relationships could be obtained unless the permeability values were logarithmically transformed. The relationships with treatability were better defined when the permeability was expressed in logarithmic form in this study also, as indicated by higher values of correlation coefficients and less varied regression equations.

TABLE 3. *Treatability range of values for shortleaf pine and yellow poplar*

Flow direction	Treatability range						Obs.
	Retention			Penetration			
	Min.	Max.	Mean	Min.	Max.	Mean	
	. . . (lb/ft^3) . . .			. . . (inch) . . .			
	SHORTLEAF PINE						
Longitudinal	0.97	24.18	15.97	0.20	0.58	0.36	111
Transverse	2.58	20.94	9.46	0.00	0.37	0.21	76
	YELLOW POPLAR						
Longitudinal	11.21	20.30	14.51	0.32	0.39	0.37	118
Transverse	1.24	4.99	2.59	0.00	0.07	0.02	59

There is a slightly better correlation of permeability with retention than with penetration. Penetration, as a general rule, tends to be more difficult to evaluate because of variations in anatomical structure, particularly when a two-component feature (e.g. latewood and earlywood) exists. This phenomenon partially explains the reason for the lower correlation coefficient ($r = 0.22$) for penetration, as compared with retention ($r = 0.66$), in the longitudinal direction of shortleaf pine.

CONCLUSIONS

1. Distance from pith and height were found to influence permeability of shortleaf pine in the mature tree, whereas little variation could be attributed to these sources in a young (10-year-old) tree. A slight increase of permeability with height and a considerable increase with distance from the pith were detected.

2. In yellow poplar, similar effects were noted, except that variations of permeability with height were inconsistent.

3. Treatability as measured by retention was moderately well correlated with the logarithm of the permeability, especially in shortleaf pine. In yellow poplar, however, only by including transverse and longitudinal results on analysis could the relationship between the two variables be detected.

4. Use of the so-called "positive pressure" range appears to offer hope of more consistent and meaningful results for permeability than use of the "negative pressure" range.

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