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PERMEABILITY OF TWENTY-TWO SMALL DIAMETER HARDWOODS GROWING ON SOUTHERN PINE SITES[1]

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ABSTRACT

Gas permeability of hardwoods growing on southern pine sites is significantly affected by moisture content in the longitudinal direction. The ratio of permeability in the transverse to longitudinal directions is from 12,000:1 for post oak to over 1,000,000:1 for other oaks, but it is not affected by moisture. Although variation in longitudinal permeability varies greatly between and among species, for most species there was no height effect. A significant difference was detected between sapwood and corewood only in the longitudinal direction. Gas permeability tended to be somewhat less than liquid permeability.

Additional keywords: Gas permeability, liquid permeability, longitudinal permeability, transverse permeability, specific gravity.

INTRODUCTION

The permeability of wood has been the subject of numerous studies because of its importance to wood processing (Erickson 1970; Siau 1970; Choong et al. 1972; Tesoro 1973), and also because the methods of measuring permeability differ considerably (Resch and Ecklund 1964; Siau 1971). Despite large amounts of work on permeability, only a few limited studies have been made on the variation within trees (Comstock 1965; Fogg 1969; Isaacs et al. 1971; Choong and Fogg 1972), or on comparative permeability among various species (Smith and Lee 1958; Tesoro et al. 1966; Choong et al. 1972). The low-grade hardwoods occur in great abundance in the southern pine forests, but they are presently of no great economic importance. Little is known of their properties; consequently, as part of a series of studies to increase the utilization of these woods, this paper reports on their permeabilities.

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EXPERIMENTAL PROCEDURE

Sample preparation

Twenty-two species of hardwoods were selected for study. They comprise in excess of 95% of the hardwood volume growing on pine sites. These species, arranged by decreasing volume on pine sites, and their specific gravities are listed in Table 1.

For each species, ten 6-inch (dbh) trees were sampled from throughout that portion of the species range occurring in the eleven-state area extending from Virginia to eastern Texas. Samples for the permeability study were obtained from two heights in each tree: 6 ft and 14 ft above ground. Longitudinal, radial, and tangential permeability samples, each about ⅝-inch in diameter and ½-inch in length, were taken from each height at locations near the bark (sapwood) and near the pith (corewood). Dowel-shaped samples were cut from the air-dried wood using a Greenlee plug cutter. The ends of the dowels were either perpendicular to the grain (cross-section), or to the radial or tangential planes, so that the movement of fluid in each of these dowels would

TABLE 1. *The 22 species studied and their specific gravities*

Species		Specific Gravity Range[a]
Sweetgum	*Liquidambar styraciflua* L.	0.46 - 0.57
True hickory	*Carya spp.*	0.68 - 0.90
Black tupelo	*Nyssa sylvatica* Marsh.	0.45 - 0.67
Post oak	*Quercus stellata* Wangenh.	0.71 - 0.98
Water oak	*Q. nigra* L.	0.59 - 0.78
Southern red oak	*Q. falcata* Michx.	0.62 - 0.88
White oak	*Q. alba* L.	0.71 - 0.91
Yellow poplar	*Liriodendron tulipifera* L.	0.36 - 0.56
Sweetbay	*Magnolia virginiana* L.	0.38 - 0.55
Cherrybark oak	*Q. falcata* var. *pagodaefolia* Ell.	0.63 - 0.82
Black oak	*Q. velutina* Lam.	0.65 - 0.85
White ash	*Fraxinus americana* L.	0.64 - 0.76
Green ash	*F. pennsylvanica* Marsh.	0.51 - 0.71
Red maple	*Acer rubrum* L.	0.49 - 0.60
American elm	*Ulmus americana* L.	0.52 - 0.64
Winged elm	*U. alata* Michx.	0.62 - 0.77
Hackberry	*Celtis occidentalis* L.	0.51 - 0.70
Northern red oak	*Q. rubra* L.	0.65 - 0.80
Scarlet oak	*Q. coccinea* Muenchh.	0.64 - 0.86
Shumard oak	*Q. shumardii* Buckl.	0.66 - 0.83
Laurel oak	*Q. laurifolia* Michx.	0.60 - 0.74
Blackjack oak	*Q. marilandica* Muenchh.	0.70 - 0.86

[a]Specific gravity determined from longitudinal permeability samples, based on oven-dry weight and dimensions.

always be in one of the three primary structural directions. Permeability is greatly affected by surface smoothness (Choong et al. 1975); therefore, the ends of each test sample were individually and carefully cut clean and smoothed with sharp scalpel blades. Samples obtained from near the pith were classified as "corewood" since in some species the heartwood could not be distinguished from the sapwood on the basis of color.

Permeability measurements

The gas permeability of each sample was measured in a specially built apparatus (Fig. 1), which consisted of a sample holder made of a stainless steel barrel fitted inside with a neoprene rubber sleeve. The space between the barrel and the sleeve was filled with water and connected to a vacuum and pressure system. The wood sample, positioned between two stainless steel plugs with a ⅛-inch bore through the center of each, was sealed inside the rubber sleeve in the sample holder by hydrostatic pressure. Vacuum was used to expand the rubber sleeve in order to facilitate easy removal of the test samples.

Prepurified nitrogen gas was passed through a filter and two nullamatic regulators. One regulator was maintained at 75 psig to control the sleeve pressure that held the sample inside the steel barrel; the other regulator was used to regulate the upstream flow to the sample. Burets of different sizes were used as "flowmeters" since they are more accurate and more reliable for measuring gas flow than the commercial ball-type flowmeters that require frequent calibration. One leg of a Y-shape plastic tube was connected to each buret. The other leg was connected by a line to the outflow end of the sample chamber. To the vertical end of the "Y" was connected a rubber bulb, which was filled dropwise with a dilute soap solution. By carefully compressing the rubber bulb, a single film could be formed and the gas flow rate easily measured by recording the time (with a stopwatch) for the film to traverse between two marks representing a precalibrated volume.

All samples were measured at a mean pressure ($\bar{P}$) of 1.2 atm. Depending on the permeability of the sample, the upstream (P_1) and downstream (P_2) pressures were adjusted accordingly to give the same mean pressure. The superficial permeability K was calculated using Darcy's law for gas, as follows:

$$K = \frac{\bar{Q}\mu L}{A(\Delta P)} = \frac{Q_a \mu L P_a}{A\bar{P}(\Delta P)}$$

(Darcy, or cm^2- cp/sec-atm) (1

where $\bar{Q}$ (cc/sec) is the flow rate at mean pressure $\bar{P}$ (atm) $= (\bar{P}_1 + P_2)/2$, Q_a (cc/sec) is the flow rate at atmospheric pressure $P_a =$ 1 atm and ambient temperature of 72 ± 3 F, ΔP (atm) is the pressure drop (P_1–P_2), μ is the viscosity of nitrogen (0.0178 cp), A (cm^2) is the surface area of the sample through which the flow took place, and L (cm) is the length of the sample.

All test samples were first dried in a vacuum oven. After gas permeability mea-

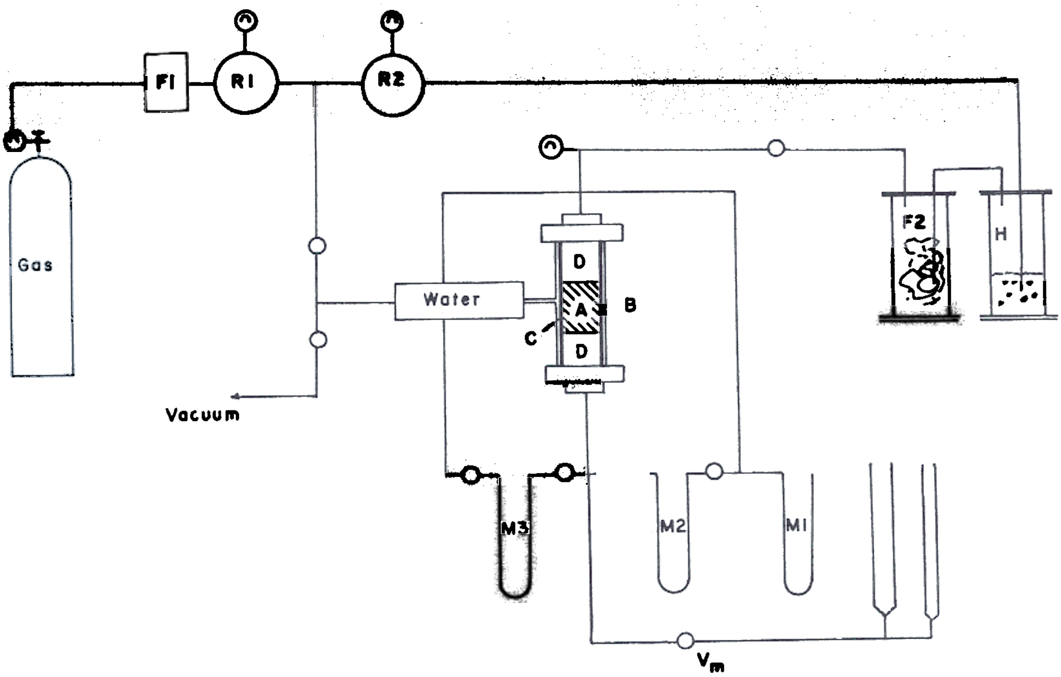

FIG. 1. Flow diagram of gas permeability apparatus. (A) wood sample, (B) permeability sample holder, (C) rubber sleeve, (D) steel plunger, (R1) 0–100 psig range pressure regulator, (R2) 0–30 psig range pressure regulator, (F1) gas filter, (F2) spun glass filter, (H) humidifier, (M1) mercury manometer for upstream pressure, (M2) mercury manometer for pressure drop, (M3) water manometer for pressure drop, (V_m) metering value, and (U) bubble meters for measuring flow rates.

surements were made at 0% moisture content, the samples were conditioned in an environment of nominal 92% RH (about 20% EMC) inside an Aminco Climate Lab chamber. Gas permeability was then measured at about 20% moisture content to determine the effect of wood moisture on permeability. Transverse permeability of wood is low and its measurement very time-consuming. The difference, if any, between radial and tangential directions was expected to be negligible; therefore, only limited numbers of transverse samples were measured at this higher moisture condition. To prevent severe drying effects during measurement, the dry nitrogen was first humidified by bubbling it through a chamber of water.

In an effort to verify the reliability of gas permeability measurement as an indication of fluid flow in wood, flow rates with liquid water were determined for selected longitudinal samples. Only the longitudinal samples were studied because it is virtually impossible, under known techniques, to completely saturate woods of low permeability. Also, the rate of flow in the transverse direction is extremely slow and difficult to measure.

The technique of determining water permeability is similar to the one already described by Choong and Kimbler (1971). Samples were first saturated in a stainless steel impregnation chamber by filling them with carbon dioxide gas in order to dissolve as much air in the wood as possible, next a vacuum was pulled and deaerated water was introduced; then the samples were subjected to mechanical shock (with a steel hammer) to induce cavitation. Flow measurements were made with a specially built apparatus that includes a precise constant-rate, positive displacement pump equipped with several gears to provide a choice of

TABLE 2. *Average gas permeability values for 22 hardwood species in the longitudinal direction at 0% moisture content, and ratios of permeability at 0% to 20% MC*

Species	Overall Mean (Darcy)	CV[b]	Sapwood N[a]	Sapwood Mean (Darcy)	Corewood N[a]	Corewood Mean (Darcy)	Permeability Ratio (0%/20% MC)
Sweetgum			35	13.879	30	15.327	1.46
True Hickory			39	7.891	33	1.307	1.68
Black Tupelo			25	8.105	17	8.405	1.12
Post Oak			37	0.161	35	0.067	1.43
Water Oak			39	32.375	36	16.554	1.02
Southern Red Oak			41	64.779	36	9.652	1.92
White Oak			35	1.359	34	0.045	1.75
Yellow Poplar			38	28.950	35	1.873	1.31
Sweetbay			39	14.992	35	11.438	1.41
Cherrybark Oak			32	69.162	28	12.916	1.81
Black Oak			29	66.804	36	28.404	1.53
White Ash			39	1.973	40	0.755	1.71
Green Ash			38	3.759	36	1.720	1.09
Red Maple			39	10.291	27	7.387	1.19
American Elm			42	5.815	37	1.274	1.30
Winged Elm			41	3.979	37	1.074	0.90
Hackberry			35	19.340	36	14.139	1.29
Northern Red Oak			28	61.920	34	56.733	1.37
Scarlet Oak			34	55.363	37	35.059	1.46
Shumard Oak			39	72.527	41	25.178	1.54
Laurel Oak			38	36.340	39	21.083	1.47
Blackjack Oak			40	2.492	28	0.539	2.40

a/ Number of observations

b/ Coefficient of variation (%)

some 30 flow rates. The apparatus also has two filtering systems, a transducer cell attached to a meter read-out for pressure measurement (0–5 psig range), and a permeability cell similar to the one illustrated in Fig. 1.

RESULTS AND DISCUSSION

Among and within-tree variability

Species averages and means by wood types (sapwood and corewood) for longitudinal and transverse (radial and tangential) permeability are presented in Tables 2 and 3 for 0% moisture content. The ranges of values for each species are shown in Fig 2 for longitudinal permeability and in Fig. 3 for transverse permeability. These permeability values are extremely variable, ranging from 124.7 to 0.0001 Darcys; and, as shown in tables, the coefficients of variation are very large. As expected, highly significant differences ($P < 0.01$) were found by analysis of variance (Table 4) among species, structural direction, and wood-type; but the effect of height was negligible.

Differences in permeability between longitudinal and transverse samples varied greatly from species to species; therefore, a separate analysis of variance for each direction was made with each species. In each case, the data were analyzed as a factorial with completely randomized block design with the trees as blocks.

Analyses for the longitudinal samples show that differences among trees are generally highly significant. A few species, however, show significance only at the 5% level of probability (i.e. black tupelo, yellow poplar, black oak, winged elm, and blackjack oak). The effect of height is generally nonsignificant, except for sweetgum, white ash, and red maple. This general lack of height effect is understandable, since the

TABLE 3. *Average gas permeability values for 22 hardwood species in the transverse directions at 0% moisture content, and ratios of permeability at 0% to 20% MC*

Species	Overall Mean (Darcy)	CV[b]	Radial Movement N[a]	Radial Movement Sapwood Mean (Darcy)	Radial Movement Corewood Mean (Darcy)	Tangential Movement N[a]	Tangential Movement Sapwood Mean (Darcy	Tangential Movement Corewood Mean (Darcy)	Permeability Ratio (0%/20% MC)
Sweetgum	0.0096	(157.7)[b]	30	0.0125	0.0056	29	0.0104	0.0065	0.40
True Hickory	0.0013	(123.2)	35	0.0012	0.0009	42	0.0010	0.0019	0.44
Black Tupelo	0.0003	(32.1)	22	0.0004	0.0003	24	0.0003	0.0002	0.39
Post Oak	0.0015	(234.9)	31	0.0028	0.0006	35	0.0011	0.0015	0.43
Water Oak	0.0004	(219.5)	41	0.0008	0.0006	46	0.0003	0.0001	0.76
Southern Red Oak	0.0011	(75.8)	31	0.0020	0.0008	35	0.0010	0.0005	0.26
White Oak	0.0004	(122.5)	31	0.0010	0.0004	34	0.0002	0.0002	0.37
Yellow Poplar	0.0093	(251.3)	48	0.0143	0.0100	38	0.0031	0.0040	0.48
Sweetbay	0.0068	(123.2)	43	0.0059	0.0054	34	0.0100	0.0055	0.57
Cherrybark Oak	0.0004	(188.5)	57	0.0005	0.0004	50	0.0003	0.0004	0.30
Black Oak	0.0023	(212.9)	34	0.0044	0.0016	35	0.0021	0.0016	0.84
White Ash	0.0004	(125.6)	39	0.0004	0.0004	29	0.0005	0.0002	0.39
Green Ash	0.0023	(142.3)	39	0.0034	0.0017	41	0.0019	0.0024	0.44
Red Maple	0.0010	(134.8)	45	0.0013	0.0009	39	0.0008	0.0007	0.27
American Elm	0.0070	(125.3)	40	0.0067	0.0066	28	0.0075	---	0.67
Winged Elm	0.0102	(82.8)	41	0.0082	0.0090	30	0.0124	---	0.57
Hackberry	0.0025	(162.0)	38	0.0044	0.0024	38	0.0013	0.0014	0.50
Northern Red Oak	0.0041	(103.8)	44	0.0035	0.0051	32	0.0013	0.0045	0.40
Scarlet Oak	0.0070	(106.7)	61	0.0106	0.0074	62	0.0056	0.0044	0.54
Shumard Oak	0.0018	(111.1)	40	0.0022	0.0021	31	0.0014	0.0012	0.19
Laurel Oak	0.0023	(223.9)	46	0.0045	0.0022	34	0.0006	0.0005	0.55
Blackjack Oak	0.0055	(100.2)	22	0.0093	0.0033	19	0.0020	0.0022	0.63

a/Number of observations
b/Coefficient of variation (%)

breast-height diameter was 5.5 to 6.5 inches, and at both heights their growth rates were quite similar.

The difference between sapwood and corewood is very pronounced in most of the species studied, with the sapwood showing higher longitudinal permeability than the corewood. Some species that exhibited no distinguishable heartwood-sapwood color differences still displayed greater longitudinal permeability in the sapwood than in the corewood. However, in four species, namely sweetgum, black tupelo, hackberry, and northern red oak, there was no difference in permeability between wood types. In northern red oak, heartwood was well developed, but corewood permeability was not different from that of the sapwood. It was higher than corewood permeability of the other eight species of the red oak group. This may indicate that heartwood vessels of northern red oak contain fewer tyloses than do the other red oaks tested.

In the analyses of transverse permeability, only among-tree variations within a species were generally significant. Tree height, wood type, and structural direction in most cases had no significant effect on permeability.

The largest difference in permeability occurs between the longitudinal and transverse directions. Anisotropic permeability for the various species is shown in Table 5. There is a wide range of permeability ratios in a given structural direction as well as between structural directions. When the extreme range of values is taken, the ratio for longitudinal to tangential permeability varies from 12,000 to 1 for post oak to as high as over a million to 1 for other oaks (i.e. scarlet, shumard, and laurel). These ratios are considerably higher than for softwoods (Comstock 1970; Choong and Fogg 1968, 1972). Longitudinal flow is obviously much greater than transverse flow in hardwoods, mainly because of the very high

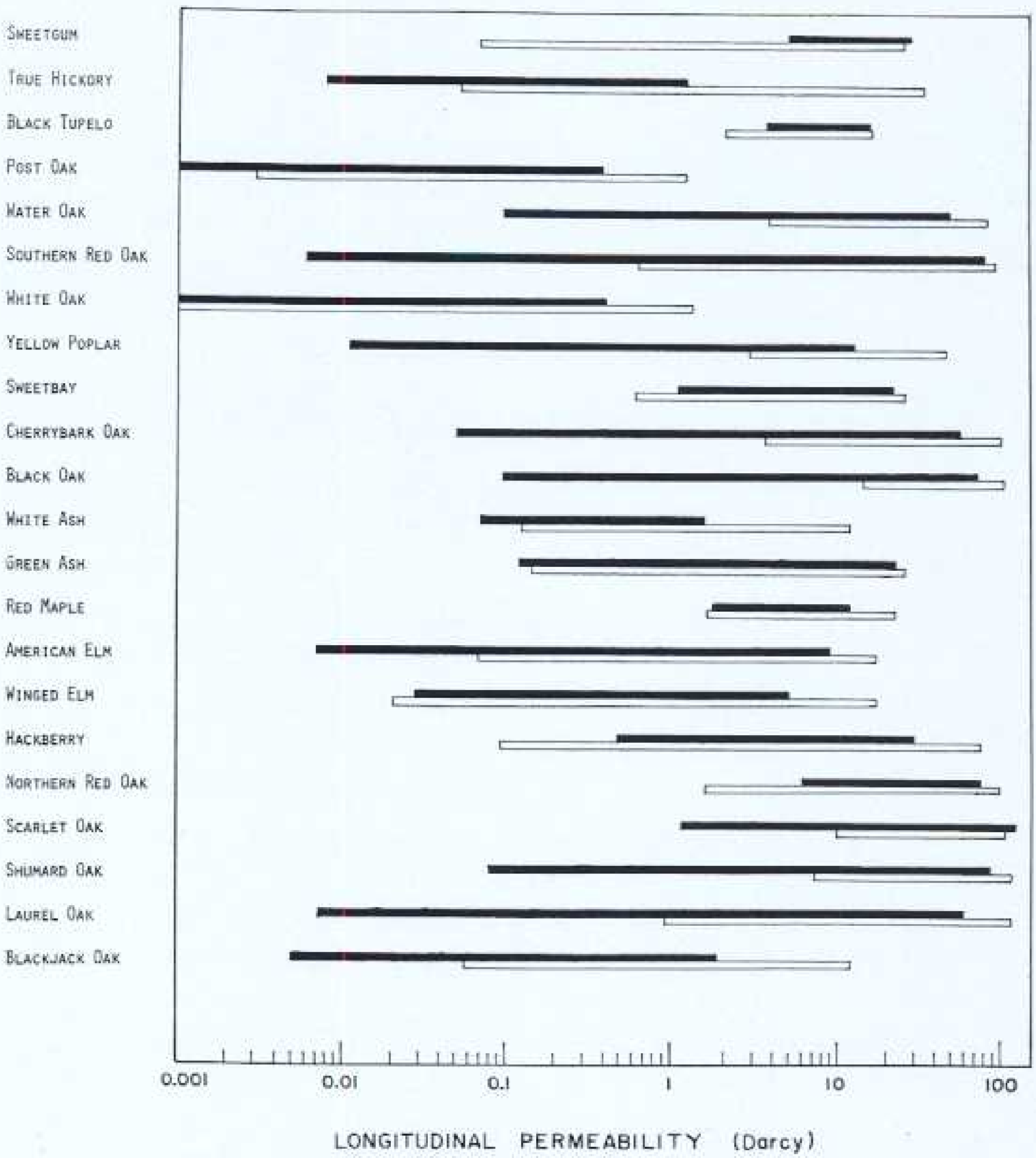

FIG. 2. Ranges of permeabiilty values in the longitudinal direction for various hardwood species at 0% moisture content. Shaded bars are corewood; unshaded bars are sapwood.

conductivity of the vessels present in these woods. However, in a few hardwood species the vessels are so occluded with tyloses and gums that flow of fluid through these cells would be inhibited and the longitudinal permeability can be expected to be very low. The data for post oak show that at 0% moisture content, the mean value in the longitudinal direction is only 0.110 Darcy, whereas in the transverse direction it is 0.0015 Darcy. The difference was significant only at the 5% level of probability.

Even though the permeability difference between radial and tangential directions is statistically not significant for most of the species studied, the mean values are gen-

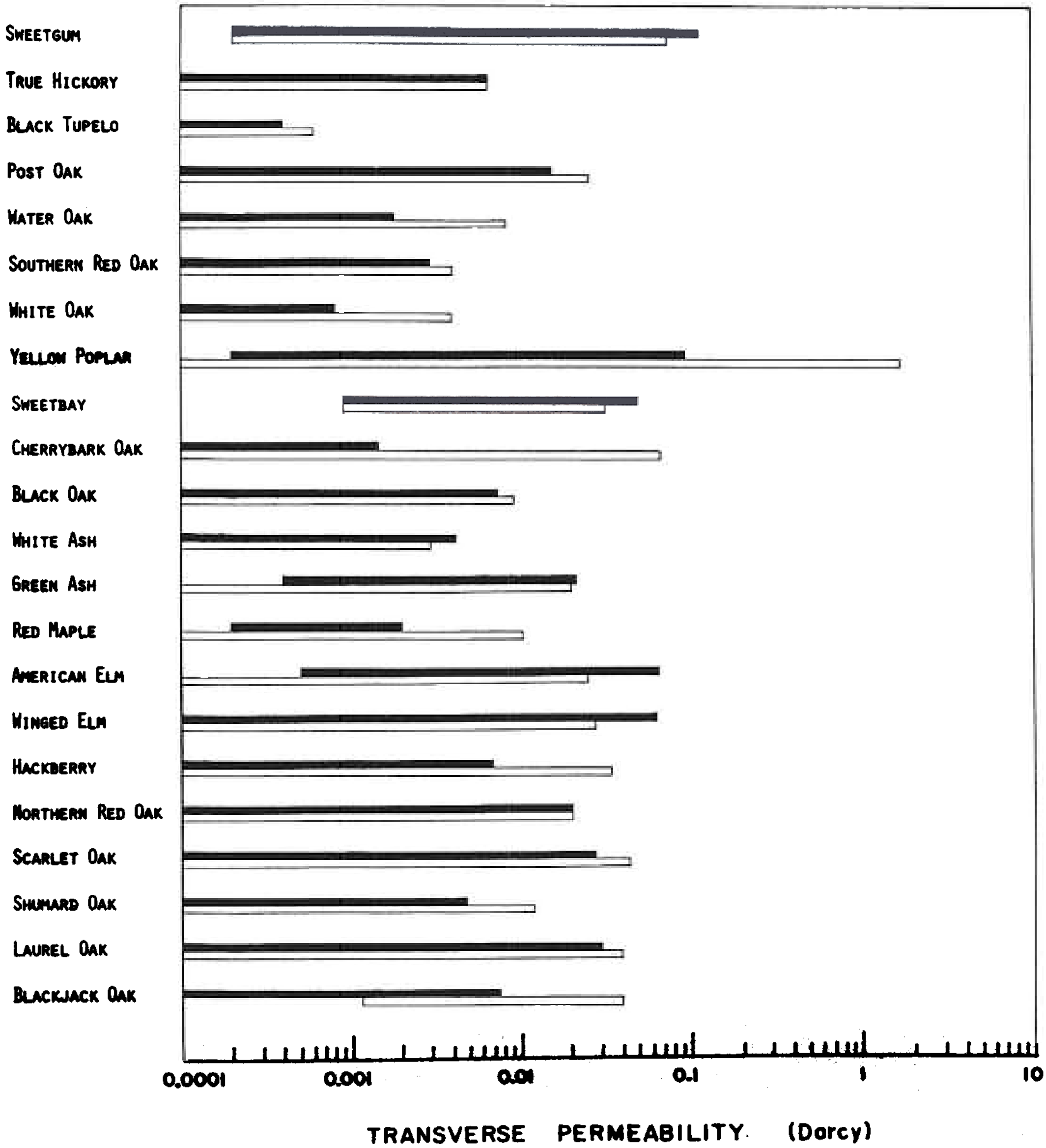

FIG. 3. Ranges of permeability values in the transverse directions for various hardwood species at 0% moisture content. Shaded bars are tangential movement; unshaded bars are radial movement.

erally higher for radial than for tangential permeability. The average ratio for all 22 species is 2.3 to 1. Most of the oaks show somewhat higher R/T ratios than the non-oak species. Higher radial permeability has been reported in the literature (Buro and Buro 1959; Comstock 1970; Isaacs et al. 1971; Choong and Fogg 1972) and is an indication that the ray cells serve as passageways for transverse conduction of fluid in wood.

Moisture content effects

The gas permeability of wood is affected by moisture content. When the flow is in the longitudinal direction, permeability is

TABLE 4. *Analysis of variance for gas permeability at two moisture content levels*

	0% MOISTURE CONTENT			20% MOISTURE CONTENT		
Variable	d.f.	Mean Square	F ratio	d.f.	Mean Square	F ratio
Species (S)	21	10,799.52	22.55**	21	7,649.74	24.15**
Tree/Species (Error A)	198	478.88		197	316.81	
Height (H)	1	513.20	4.37*	1	13.21	0.19 NS
Structural Direction (D)	2	148,102.31	1261.47**	2	30,159.20	430.94**
H X D	2	0.0	0.00 NS	2	0.0	0.00 NS
Wood Type (W) (Sapwood vs. Corewood)	1	15,181.60	129.31**	1	6,008.33	85.85**
H X W	1	140.58	1.20 NS	1	160.49	2.29 NS
D X W	2	24,401.19	207.84**	2	4,252.54	60.76**
H X D X W	2	225.21	1.92 NS	2	0.0	0.00 NS
S X H	21	196.98	1.68 NS	21	50.28	0.72 NS
S X D	42	6,953.37	59.23**	42	1,248.13	17.83**
S X H X D	42	0.66	0.01 NS	42	7.30	0.10 NS
S X W	21	2,926.55	24.93**	21	1,028.37	14.69**
S X H X W	21	87.92	0.75 NS	21	77.97	1.11 NS
Error B	2814	117.41		1545	69.98	
Total	3191			1921		

* Significant at 5% level of probability
** Significant at 1% level of probability
NS Not significant

about 1.5 times higher at 0% than at 20% moisture content (Table 2); but in the transverse direction (either radial or tangential), the permeability at 0% moisture content is about one-half lower (Table 3). The correlation of permeability between the two moisture conditions is very high ($r = 0.92$, $N = 1460$ in the longitudinal direction; $r = 0.81$, $N = 461$ in the transverse direction). The corresponding regression equations for 0% MC vs. 20% MC permeabilities are $K_{20} = 2.05 + 0.58(K_0)$ for longitudinal, and $K_{20} = 0.0027 + 1.47(K_0)$ for transverse movement.

Increased longitudinal permeability at low moisture content was also reported by Fogg (1969) on southern pines, who lent support to the theory of Tiemann (1910) regarding the formation of minute checks in the cell-wall structure as the possible cause of increase in apparent permeability of wood during drying. This reasoning could explain the results of this research since the wood samples in this study had been previously air-dried, so that minute checks could have occurred in them; when the samples were conditioned to higher moisture content, the openings could have closed by swelling of the cell wall so that the flow path was mainly through the cell lumens of the coarse capillary structure.

In the transverse directions, flow must pass through some openings of the cross-walls. Despite the apparent absence of openings in the pit membranes, Behr et al. (1969) reported penetration of oily preservatives in the fibrous tissue of beech, red oak, and American elm, and thus showed evidence of passage of fluid through the interconnecting pit hairs in hardwoods. The slightly higher permeability values at 20% moisture content, as compared with those at 0% moisture content, are not consistent with the explanation of minute check formation. Such a phenomenon suggests the possibility of increased pit membrane permeability when vacuum-dried wood is resaturated. The possibility of specimen irregularity contributing to leakage is discounted because tests at both moisture contents show no evidence of gas passing between the rubber sleeves and the edges of the samples. When their ends were sealed off with layers of epoxy adhesive and Saran

TABLE 5. *Ratios of longitudinal, radial, and tangential (L/R/T) gas permeability values at 0% moisture content*

Species	L:R:T Ratio (Mean Values)	Extreme Range[a]
Sweetgum	1,598 : 1.10 : 1	147,807 : 1
Hickory	3,481 : 0.79 : 1	352,264 : 1
Black Tupelo	27,423 : 1.00 : 1	167,513 : 1
Post Oak	100 : 1.73 : 1	12,144 : 1
Water Oak	82,603 : 2.00 : 1	830,848 : 1
Southern Red Oak	43,339 : 1.56 : 1	958,710 : 1
White Oak	3,558 : 3.50 : 1	133,432 : 1
Yellow Poplar	2,753 : 2.09 : 1	230,572 : 1
Sweetbay	1,585 : 0.67 : 1	29,203 : 1
Cherrybark Oak	143,045 : 1.33 : 1	691,618 : 1
Black Oak	25,298 : 12.1 : 1	708,224 : 1
White Ash	2,712 : 0.80 : 1	119,890 : 1
Green Ash	1,318 : 1.24 : 1	64,708 : 1
Red Maple	11,379 : 1.38 : 1	113,117 : 1
American Elm	491 : 0.89 : 1	35,361 : 1
Winged Elm	210 : 0.69 : 1	180,477 : 1
Hackberry	12,871 : 2.77 : 1	758,454 : 1
Northern Red Oak	17,902 : 1.39 : 1	956,606 : 1
Scarlet Oak	8,956 : 1.82 : 1	1,247,256 : 1
Shumard Oak	37,124 : 1.69 : 1	1,141,323 : 1
Laurel Oak	47,687 : 5.83 : 1	1,136,673 : 1
Blackjack Oak	844 : 4.25 : 1	118,299 : 1

[a]Ratio of highest longitudinal permeability to lowest transverse (tangential) permeability observed.

coating, the flow of gas was completely inhibited.

Gas permeability vs. liquid permeability

A relationship between superficial gas permeability and liquid permeability had not been truly established, although Comstock (1968) reported that the specific permeability (i.e. superficial gas permeability at various mean pressures extrapolated to infinite pressure) and the nonswelling liquid permeability are the same for longitudinal flow in hemlock. Non-Darcy phenomena, however, can be expected to occur with gas, since the structural components of wood are changed with variations in moisture content in the hygroscopic range. However, if superficial gas permeability is a meaningful indication of fluid flow, it should be well correlated with liquid permeability. As shown in Fig. 4, such a relationship occurs for longitudinal flow in the hardwoods, but the liquid permeability shows slightly higher values than gas permeability when the range is over 1 Darcy. Below 1 Darcy, the liquid permeability is not significantly different from gas permeability. Such a correlation between gas and liquid permeability, however, is contrary to the generally accepted explanation that slip flow with gases and low moisture content should make the gas permeability higher than the liquid.

Recent work by Tesoro (1973) indicates that the gas permeability of both softwood and hardwood longitudinal specimens was indeed significantly higher than the water permeability. He measured the gas permeability at moisture contents near the fiber saturation point by drying the samples very slowly from the green condition; even so, the water permeability in never-dried samples was found to be consistently different from that obtained after resaturation. It appears, therefore, that drying brings changes in the inner structure of wood in such a manner that the permeability of

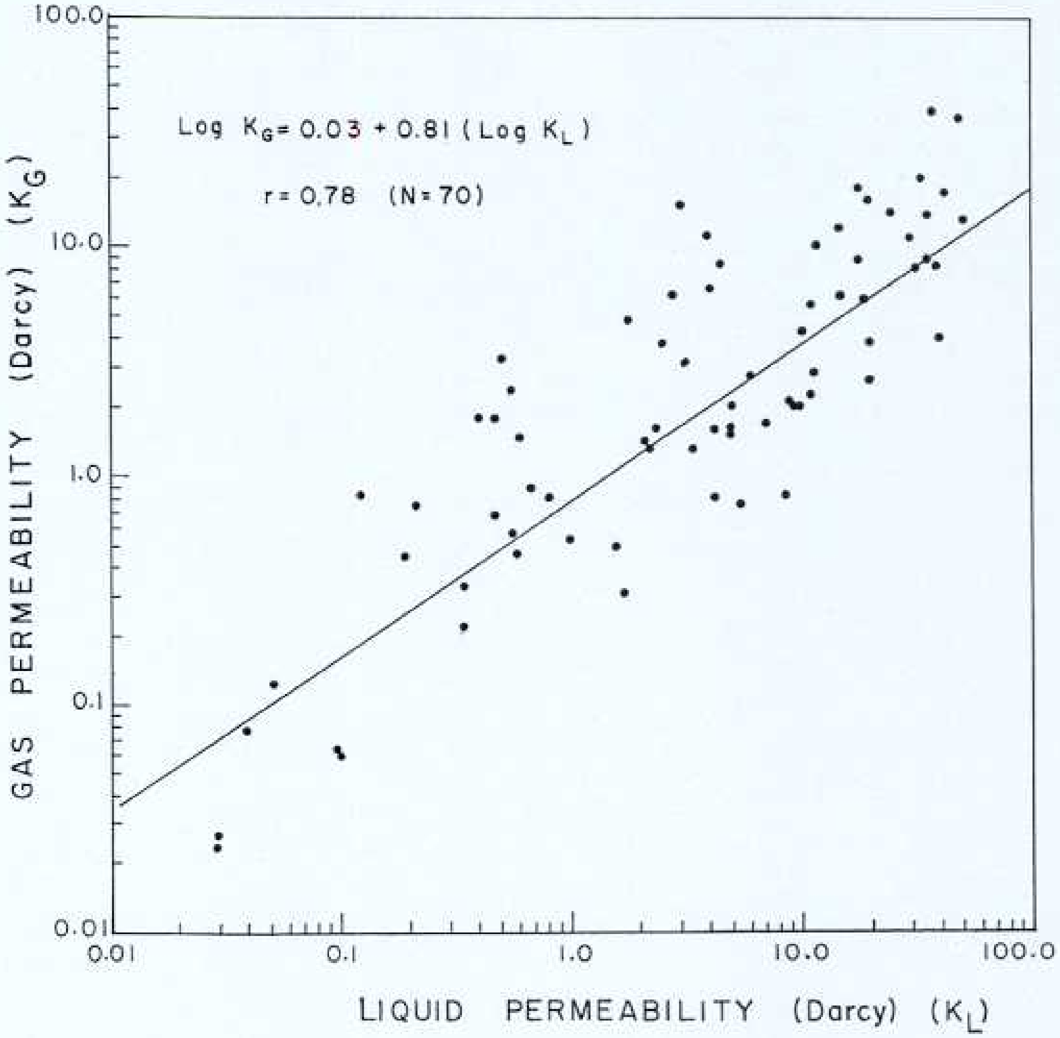

FIG. 4. Correlation between superficial gas permeability at 0% moisture content and liquid permeability.

wood cannot remain the same after treatment. The possibility of increased permeability when samples are resaturated after they have been dried to very low moisture contents cannot be discounted.

CONCLUSIONS

The variation in longitudinal permeability for the 22 hardwood species tested is very large. Both longitudinal and transverse gas permeability differed among trees of the same species. Generally the differences in permeability between sapwood and corewood are significant in the longitudinal direction, but not in the transverse direction. Tree height did not have a significant effect on the longitudinal permeability in most species or on the transverse permeability in any species. Also, in general, there was no significant difference between radial and tangential flow, even though the average radial permeability for any given species tends to be slightly higher than tangential permeability.

Moisture content of wood significantly affects longitudinal permeability. Gas permeability decreased with an increase in moisture content from 0 to 20%; also, the effect of moisture seems to increase with permeability. No such effect was observed with the transverse samples.

Gas permeability was found to be slightly lower than liquid permeability when the range is over 1 Darcy, probably because of the effect of resaturation. The relationship between liquid and gas permeability, however, is highly correlated.

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