GAS PERMEABILITY OF PLANTATION LOBLOLLY PINE

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ABSTRACT

Gas permeability of loblolly pine sapwood was determined for samples from six plantation-grown trees. Longitudinal permeability measurements were made on wood from five heights in the trees, juvenile and mature wood, and earlywood and latewood. Samples were either solvent-dried to obtain a green-equivalent state or air-dried. Permeability was also measured in the tangential and radial directions. Longitudinal permeability was significantly less in the lower part of the tree than in the upper part. Mature wood was more permeable than juvenile wood for both green-equivalent and air-dried wood as well as earlywood and latewood. Permeability did not appear to be solely a function of specific gravity.

Keywords: Permeability, loblolly pine, solvent-dry, air-dry, juvenile wood, mature wood.

INTRODUCTION

Permeability is the property of a material that indicates how freely fluids flow in response to a pressure gradient. It is commonly reported in darcys, a mixed unit. Throughout this paper, the SI unit μm^2 is used, which is equivalent to 1.013 darcys. The permeability of a wood species is one factor that determines how easily it can be dried and treated. Wood exhibiting high permeability, such as southern pine sapwood, is easy to dry and treat; that with low permeability, such as Douglas-fir heartwood, is not easy to dry and treat.

The objective of this work was to compare the gas permeability of loblolly pine juvenile and mature sapwood as a function of position in the tree. Samples were selected so that differences in permeability could be compared for earlywood and latewood and permeability in

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the longitudinal, radial, and tangential directions.

BACKGROUND

The factors affecting permeability were discussed in general by Côté (1963), and for southern pine, by Erickson (1970). Comstock (1965, 1967, 1968, and 1970) and Comstock and Côté (1968) extensively investigated both gas and liquid permeability. Gas permeability of a softwood is affected by the anatomical characteristics of the species, pit aspiration during drying, and encrustation and aspiration during heartwood formation. The character and quantity of extractives can also affect heartwood permeability (Comstock 1970). Reported gas permeability values for southern pine sapwood at 14% moisture content in the longitudinal, tangential, and radial directions are 2.12, 0.0003, and 0.0112 μm^2, respectively (Comstock 1970).

Comstock (1967) demonstrated that wood permeability measurements are independent of the fluid type (liquid or gas) if the liquid is nonswelling or a correction is made for slip flow of the gas through the small pore spaces. Gas permeability is simpler to measure than is liquid permeability, because gas permeability has no problems with air blockages or suspended particles. A gas can be used to measure the permeability of green wood after removing the water by a method that does not aspirate the pits, such as solvent- or critical-point drying (Liese 1951).

METHODS

Six, 28-year-old, plantation-grown, loblolly pine (*Pinus taeda* L.) trees ranging from 34.5- to 42.4-cm- (13.6- to 16.7-in.-) diameter breast height were selected for study. This material was also used in a concurrent drying study (Milota and Tschernitz 1990). The initial planting density was 1,850 trees/ha (750 trees/acre) until thinnings at ages 14 and 22 when the stand density was reduced to 703 and 345 trees ha (285 and 140 trees/acre), respectively. At age 22, the stand was fertilized.

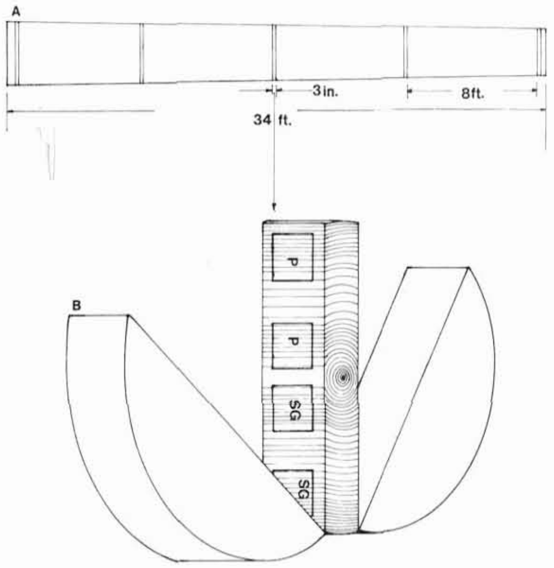

FIG. 1. Cutting diagram for (A) 7.62-cm (3-in.) disks from 10.1-m (33-ft) logs (not to scale) and (B) blocks from disks; P indicates block was used for permeability cores; SG indicates specific gravity.

Five disks, 7.62 cm (3 in.) thick, were cut from each tree at 2.514-m (8-ft 3-in.) intervals, starting approximately 0.914 m (3 ft) above the ground (Fig. 1A). Two, 5.08- by 5.08- by 5.08-cm (2- by 2- by 2-in.) blocks were cut 1.27 cm (0.5 in.) from either transverse face of each disk (Fig. 1B). One block was taken close to the pith within the juvenile wood, and the other was taken on the same radius close to the bark within the mature wood. This set of blocks was frozen under water to eliminate deterioration. A matching set of 60 blocks was taken from the opposite radial side of each disk to obtain an estimate of specific gravity. The green specific gravity was determined by measuring the green block dimensions and weighing the oven-dried blocks.

Core preparation

Two cylindrical sample cores, 1.27 cm (0.5 in.) along the grain with a 1.27-cm (0.5-in.) diameter, were cut from each of the 60, 5.08-cm (2-in.) blocks so that the annual ring boundary crossed the sample (Fig. 2). The percentage of earlywood and latewood in the cores was selected to be representative of that in the

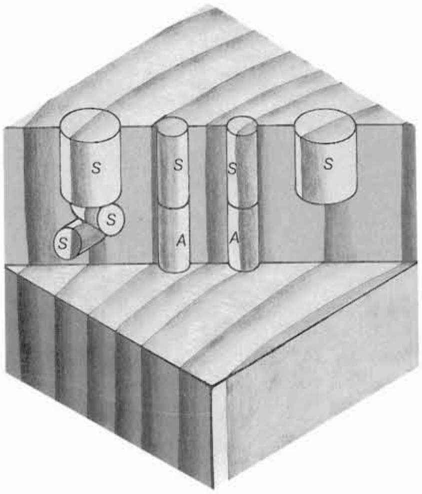

FIG. 2. Cut out view of block showing how 1.27- and 0.64-cm (0.5- and 0.25-in.) cores were cut. A indicates air-drying, S indicates solvent-drying.

block. After solvent-drying, these 120 cores were used to determine the longitudinal green-equivalent permeability as a function of position in the tree.

Additional cores, 1.27 cm (0.5 in.) long by 0.64 cm (0.25 in.) in diameter (half the diameter of the original 120 cores), were also cut from a 10-block subset of the 60 blocks (Fig. 2). The effects of grain direction, ring position, wood type (juvenile or mature), and drying method on permeability were compared. Two blocks were from each of the five disks, taken from a different height in five trees. This confounded the tree effect with the height effect, but still allowed a comparison of the effects in which we were interested.

Permeability as a function of grain orientation was determined using 10 pairs of cores cut so that the longitudinal axes of the cores corresponded to either the tangential or radial direction of the wood. Each pair of cores was matched along the grain (Fig. 2) to one of the 1.27-cm- (0.5-in.-) diameter longitudinal cores to allow a comparison of permeability measurements in the three directions. These cores were solvent-dried.

The effects of moisture state, ring position, and wood type on the permeability were determined using four sample cores from each of 10 blocks. The axes of the cores corresponded to the longitudinal direction of the wood. Each pair of earlywood and latewood cores was end-matched along the grain (Fig. 2). One core of each pair was solvent-dried, the other was air-dried.

Air- and solvent-drying

The green cores were solvent-dried in batches of approximately 20 cores by placing them in sealed jars with 150 cm^3 (5 oz) of absolute ethyl alcohol. The alcohol was replaced three times at 1-week intervals. Finally, the alcohol was drained, the mouths of the jars were loosely plugged with a paper towel to retard evaporation, and the alcohol was allowed to slowly evaporate in an oven at 49 C (120 F) for 1 week. The cores were heated to 107 C (225 F) for 24 h and then stored in sealed jars in a desiccator.

Air-drying was accomplished in an oven at 49 C (120 F), again in jars with the mouths plugged with a paper towel to retard drying and prevent checking. After 1 week in this condition, the cores were dried at 107 C (225 F) for 24 h and stored in sealed jars in a desiccator. In both air- and solvent-drying, few endchecks were observed.

The radial cleavage surfaces of eight cores 6.4 mm (0.25 in.) were examined using scanning electron microscopy (SEM). The cores came from earlywood and latewood and juvenile and mature wood that had been air- and solvent-dried. Observations confirmed that bordered pits in the longitudinal tracheids were completely aspirated after air-drying and unaspirated in the green-equivalent state. The size and number of bordered pits were greater in the earlywood; however, these values were not quantified.

Permeability measurements

A core was placed in a rubber stopper that had been drilled along its longitudinal axis to the diameter of the core. The stopper and core were placed in a test jig so that flow could occur only parallel to the long axis of the core (Comstock 1967). The jig slightly compressed the rubber stopper to seal the cylindrical surfaces of the core. Nitrogen gas was reduced to a gauge pressure of approximately 0.138 MPa (20 lb/in.^{2}) and applied to the upstream side of the sample. The nitrogen cylinder was changed when the gauge pressure reached 3.45 MPa (500 lb/in.^{3}), to minimize the partial pressure of water vapor in the gas stream and maintain the dry state of the core. One of three rotameters was used to measure the flow on the downstream side of the sample at atmospheric pressure. The flow ranged from 400 to 1,100 cm^3/min (24 to 67 in.^{3}/min). The pressure drop across the sample ranged from 3.39 to 135 kPa (1 to 400 in. water) and was measured with either a mercury- or an oil-filled manometer. The diameter and length of each core were measured to the nearest 0.0254 mm (0.001 in.).

ANALYSIS

The permeability was calculated from the following (Comstock 1967):

$$K_g = \frac{Q}{A} \times \eta \times \frac{L}{\Delta P} \times \frac{p}{p'} \times 10^{-2}$$

where

K_g	is gas permeability, μm^2
A	specimen area, cm^2
L	specimen length, cm
Q	gas flow rate, cm^3/sec
η	gas viscosity, Pa·sec
ΔP	pressure drop, MPa
p	pressure at rotameter, MPa
p′	pressure in sample, MPa

The last term in the equation corrects for the gas pressure in the sample.

The following three comparisons were performed on solvent-dried cores:

(1.) The effect of position in the tree on longitudinal permeability was determined by averaging the values for juvenile and mature wood permeability from the 1.27-cm (0.5-in.) cores and using a two-way analysis of variance (ANOVA) on tree and height factors. Scheffe and Bonferroni's multiple comparison procedures were performed at a 0.05-significance level.

(2.) A paired *t*-test was then done on this same data set to compare the permeability of the juvenile and mature wood. Because of a lack of full independence, it was not appropriate to expand the ANOVA to include this factor.

(3.) The effect of grain orientation was investigated using a paired *t*-test on data from the radial and tangential cores. Linear regression analyses were performed to determine the relationship between the longitudinal and crossgrain permeability.

RESULTS AND DISCUSSION

Position in tree

As indicated by the Bonferroni groupings in Table 1, permeability was not statistically different from tree to tree, but it did depend upon height within the tree. The permeability increased significantly with height between the first and second disks, then slightly, if at all. This trend occurred in both juvenile and mature wood and in every tree (Table 1). This indicates that wood from the base of the tree may dry more slowly and be more difficult to treat than wood from farther up the stem. Similarly, Comstock (1965) observed increasing permeability with height for green eastern hemlock.

Juvenile wood had lower permeability than did mature wood, but juvenile wood also had a lower specific gravity (Table 1). In contrast, by tree, permeability was lowest in the tree with the highest specific gravity. The tree height ANOVAs were rerun with specific gravity as a covariate. The height effect did not vanish. From the ANOVA, it is clear that specific gravity explains part of the height effect, but not all of it (Table 2). Perhaps this is why the literature disagrees regarding the effect of specific gravity on gas permeability (Choong and Fogg 1968; Benvenuti 1968).

TABLE 1. *Effect of position in tree on longitudinal permeability.*[a]

	Moisture content[b] (%)	Ring count/cm[b]	Number of samples	Specific gravity[c]	Permeability[c] (μm^2)	Bonferroni grouping	Paired t grouping
Tree number							
5	149	1.42	20	0.41	10.5	A	
6	121	1.34	12	0.46	8.4	A	
13	116	1.42	12	0.42	9.0	A	
19	156	1.14	16	0.40	10.6	A	
24	141	1.46	20	0.41	9.8	A	
27	144	1.26	20	0.41	10.0	A	
Disk							
Top	156	1.22	20	0.39	11.4	B	
Fourth	146	1.34	20	0.40	10.3	B	
Third	145	1.42	24	0.40	10.9	B	
Second	134	1.54	16	0.43	10.2	B	
Bottom	105	1.14	20	0.48	5.7	A	
Wood type							
Juvenile	154	0.98	50	0.38	8.4		A
Mature	122	1.69	50	0.45	11.3		B
Combined	138	1.35	100	0.42	9.9		

[a] Six of the 120 1.27-cm (0.5-in.) solvent-dried cores were excluded from the analysis as outliers, four with visible checks.

[b] Measured on sample blocks as received: 10 for tree, 12 for disk, and 30 each for juvenile and mature.

[c] Least squares means (Searle et al. 1980).

Directional permeability

The average permeability of the green-equivalent samples was 0.073 μm^2 in the tangential direction and 0.20 μm^2 in the radial direction (Table 3). The paired t-test showed this difference to be significant at the 95% confidence level ($P = 0.0053$). The difference between the radial and tangential permeability has been reported to be a factor of 20 for dry wood. However, the results presented here indicate that for green wood the difference may be less. This might be explained by a greater number of unaspirated pits in the radial walls while the wood is green (or solvent-dried), contributing to tangential flow while radial flow is predominately through the ray structure. Neither the radial nor tangential permeability was significantly different between the juvenile and mature wood.

TABLE 2. *Effect of adding specific gravity and height to the model.*

Wood type	Predictor[a]	R^2	Root mean square error
Juvenile	tree + SG	0.71	1.40
	tree + height	0.87	1.04
	tree + SG + height	0.88	1.02
Mature	tree + SG	0.49	2.25
	tree + height	0.79	1.57
	tree + SG + height	0.79	1.62
Combined	tree + SG	0.79	1.21
	tree + height	0.88	1.00
	tree + SG + height	0.88	1.03

[a] SG is specific gravity.

Linear regression analyses indicated no strong relationships between permeability in the longitudinal and radial directions ($r = -0.74$), longitudinal and tangential directions ($r = -0.01$), or the radial and tangential directions ($r = 0.60$). A strong relationship was not necessarily expected because of the anisotropic nature of the wood structure.

Moisture state, ring position, and wood type

The longitudinal permeability of green-equivalent cores was 8 to 29 times greater than that of air-dried cores, demonstrating the difference in moisture state on pit aspiration (Table 3). The difference was greatest in the earlywood, where the size and number of pits were

TABLE 3. *Effect of direction and wood type on permeability.*[a]

Direction	Permeability (μm^2) Juvenile	Mature	Combined
Longitudinal	7.8	11.3	9.5
Radial	0.21	0.19	0.20
Tangential	0.062	0.084	0.073

[a] Each value for juvenile and mature wood represents the average of 10 core measurements. Longitudinal and cross grain measurements were done on 1.27-cm (0.5-in.) and 0.63-cm (0.25-in.) cores, respectively.

greater. The average longitudinal permeability for the 0.064-cm (0.25-in.) green-equivalent cores was 10.1 μm^2. This agrees well with the value of 9.7 μm^2 obtained using the 1.27-cm (0.5-in.) cores, indicating that our measurements were independent of sample size.

Permeability was less for the air-dried earlywood samples than that for the latewood samples; however, the reverse was true for the green-equivalent samples. This is in agreement with Erickson (1970), who states that the earlywood of pine sapwood seems to have greater permeability in the green condition, whereas the results are more variable and permeability can often be greater in the latewood for the seasoned condition.

The mature wood consistently had 50% to 100% greater permeability than did the juvenile wood for both the 0.064-cm (0.25-in.) cores (Table 4) and the 1.27-cm (0.5-in.) cores (Table 1). This was true for both earlywood and latewood and the air-dried and green-equivalent samples. Mature wood also had a greater specific gravity than did juvenile wood; however, the permeability difference was probably attributable to wood type rather than specific gravity. Within our data, the effect of specific gravity could be interpreted differently, depending on which set of data was used. For example, based on the differences in permeability by tree or disk (Table 1), one could conclude an inverse relationship between specific gravity and permeability. It is experimentally difficult not to confound specific gravity and other wood effects.

TABLE 4. *Permeability as a function of wood type, ring position, and drying method.*

Wood type	Moisture state	Permeability (μm^2) Earlywood	Latewood	Average
Juvenile	Air-dried	0.34	0.81	0.58
	Green-equivalent	10.0	6.3	8.0
Mature	Air-dried	0.96	1.14	1.05
	Green-equivalent	14.4	9.5	11.9
Combined	Air-dried	0.65	0.98	0.81
	Green-equivalent	12.4	8.0	10.1

CONCLUSIONS

Loblolly pine sapwood from the lower part of the tree has a lower permeability and may not dry or treat as well as wood from higher in the tree. Also, permeability of juvenile wood is less than that of mature wood. Specific gravity is not a good indicator of permeability. It is also likely that factors such as presence of juvenile or mature wood and between-tree variability have a greater effect on permeability than does specific gravity.

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