LONGITUDINAL GAS PERMEABILITY MEASUREMENTS FROM EASTERN WHITE PINE, RED SPRUCE, AND BALSAM FIR

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ABSTRACT

The permeability of wood is an important factor in drying, in pulping, and in the preservative treatment of wood because it is indicative of the ease with which fluids can be transported into or out of wood.

The longitudinal superficial gas permeability of eastern white pine, red spruce, and balsam fir was measured in this study. Within each species the results were compared to determine if significant differences existed among trees, at differing heights within the trees, and between the heartwood and the sapwood of the trees.

Overall, the superficial gas permeability was far larger in eastern white pine than in red spruce or balsam fir, probably as a result of its basic structure or the level of resins and other extractives. Among-tree variation had a significant effect on the permeability of balsam fir and red spruce but not on eastern white pine. Heartwood/sapwood permeability differences were significant in eastern white pine and red spruce but not in balsam fir. Height was not a factor with any species tested.

Keywords: Permeability, longitudinal permeability, eastern white pine, red spruce, balsam fir.

INTRODUCTION

Permeability is a measure of the ease with which fluids flow through a porous medium. Its measurement is of importance to the wood industry because it relates to drying, to pulping, and to the preservative treatment of wood (Beall and Wang 1974).

The permeability of some commercially important species of the Northeast has been investigated. However, most of these studies fail to consider several important factors that may contribute to the variation of permeability within a single species. Specifically, the differences between heartwood and sapwood permeability and the variation of permeability with height have not been well addressed for some Northeastern species. In studies using other species, researchers have found significant differences in permeability among samples taken from different trees within a species (Wiedenbeck et al. 1990; Chen and Tang 1991).

The specific objective of this research was to measure the longitudinal superficial gas permeability of red spruce (*Picea rubens Sarg.*), eastern white pine (*Pinus strobus L.*), and balsam fir (*Abies balsamea (L.) Mill.*), The samples were taken from different trees, from varying heights within the trees, and from the heartwood and the sapwood.

BACKGROUND

Siau (1984) defines permeability as a measure of the ease with which fluids are transported through a porous solid under the influ-

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ence of a pressure gradient. Countless studies have been conducted over the past decades to determine the liquid and gas permeability of numerous wood species. Only a broad overview will be given in this paper.

Within wood, permeability is often estimated using a form of Darcy's law defined as shown in Eq. (1) (Siau 1984).

$$K_g = \frac{QLP}{A\ dP\ Pavg} \tag{1}$$

K_g = superficial gas permeability ($\mu m^3/\mu m$)
Q = flow rate (cm^3/sec)
L = length of sample (cm)
P = pressure at which Q is measured
dP = pressure drop across sample (mm Hg)
A = cross-sectional area of sample (cm^2)
Pavg = average pressure in sample (mm Hg)

The equation assumes that the flow is viscous and laminar, that the medium is homogenous, and that there is no interaction between the fluid and the substrate. Although some of these assumptions are violated when Darcy's law is applied to the flow of gases and aqueous liquids through wood, the basic equation remains a useful relationship between the flow rate and the pressure gradient.

According to Perng (1980), the gas flow rate through a porous material under steady-state conditions is generally expressed using Adzumi's equation, which consists of two components. The first originates from the Haagen-Poiseuille law and represents viscous flow occurring in large pores. The second originates from the Klinkenberg equation and represents slip flow dominant in small pores.

Slip flow, known also as Knudsen diffusion, occurs in capillary-porous bodies with lower permeabilities and when capillary dimensions are smaller than the mean free path of gas molecules (Siau 1984). Perng (1980) concluded that structural variation in the axial direction has a small or negligible effect on permeability and that the slip flow factor is nearly constant for different sample lengths of both hardwood and softwood. The superficial gas permeability, defined by Eq. (1), is used to estimate the combined effects of viscous and slip flow into one value, although the viscous flow component is often referred to as the true permeability of the substance. Further discussion is found in Wiedenbeck et al. (1990).

Choong et al. (1989) concluded that the gas permeability of wood is affected by pressure differences at higher pressures and permeabilities, presumably due to nonlinear flow. Generally, nonlinear flow would be expected at Reynolds numbers in excess of two thousand, which is much higher than can be achieved in most species of wood (Kuroda and Siau 1988). However, the situation is complicated because the pathways through wood are not continuous. Carman (1956) suggests that flow in porous media, has a "tortuous" or indirect flow path. As a result, the Reynolds numbers at which nonlinear flow occurs can be low. Siau and Petty (1979) state that nonlinear air flow can occur in porous media with Reynolds numbers in the region of 0.1 to 10.

There have been several studies challenging the validity of Darcy's law. Deviations from the law have been cited by Bramhall (1971) and Bolton (1988). Similarly, Kuroda and Siau (1988) found strong evidence to suggest that nonlinear flow occurs due to kinetic energy losses in low permeability softwoods. Although a number of sources of possible error exist, Darcy's law is still commonly used in the evaluation of permeability.

Even with a well-designed laboratory apparatus, variation in permeability results from several factors inherent in wood. Two of the more obvious factors are the anatomical structure and the chemical constituents of the wood.

After pore size and void volume, the most prominent effect related to the internal structure results from the cell-wall pits. Fluid flow pathways are highly dependent on the pit structure of the wood. During drying the structure changes, particularly in softwoods, due to pit aspiration. The result is a reduction in permeability (Choong et al. 1989).

The effects of chemical constituents are seen when comparing the permeability of heartwood versus sapwood. Wiedenbeck et al.

(1990), Chen and Tang (1991), Tesoro et al. (1974), Sebastian et al. (1965), Comstock (1965), and Choong et al. (1989) have found sapwood significantly more permeable than heartwood. Although the magnitude of the difference can change among trees of the same species, the differences are generally attributed to the presence of extractives, such as resin, in heartwood.

Two other sources of variation found in permeability measurements are among-tree and within-tree variation. The effect of among-tree variability within a single species was found to be an important source of variation in permeability by Wiedenbeck et al. (1990), by Perng (1980), and by several others. Conversely, Beall and Wang (1974) found among-tree variation in eastern hemlock insignificant.

Variation in permeability with tree height has been investigated with mixed results. Variation with height was found by Comstock (1965) and Isaacs et al. (1971). However, Chen and Tang (1991) found there was no systematic variation with respect to height in three species of hardwood.

Permeability measurements in wood are directional due to the anisotropic nature of wood. Comstock (1970) indicates that permeability probably varies with structural direction more than with any other commonly measured property. Resch and Ecklund (1964) found that permeability measured in the longitudinal direction was greater than either tangential or radial measurements. Due to the basic structure of wood, Weidenback et al. (1990) concluded that the measurement of axial (longitudinal) permeability is more reliable than the measurement of transverse permeability.

Sample diameter, length, and surface condition are important considerations in longitudinal permeability measurements. Larger levels of variation are common to samples of smaller diameter (Ameniya 1962; Bramhall 1971). Perng (1980) tested samples with diameters twice the size of those in Ameniya (1962) and Bramhall (1971) and found decreased levels of variation in permeability data.

There have been many investigations concerning the effect of sample length on permeability measurements. Perng (1980) found that at constant pressure gradient and average pressure in the sample, permeability was almost constant at any length except in certain hardwood species. Fogg and Choong (1989) also found that permeability remained constant as length was reduced for most species except for lengths below 0.75 inches. However, for species having low permeabilities, both Sebastian et al. (1965) and Siau (1972) found a significant decrease in permeability with length.

Finally, Choong et al. (1975) found that band-sawn surfaces are typically covered with loose fibers that inhibit gas and liquid flow in the axial direction. Sanded surfaces typically reduce the permeability by one percent from that of sawn surfaces. Surfaces must be free of obstructions when determining the natural permeability of wood. A sharp, thin knife is an effective way to prepare permeability samples.

METHODS AND MATERIALS

Sample preparation

Three trees each of eastern white pine, red spruce, and balsam fir were selected for the experiments. The trees were chosen randomly from naturally growing stands in Orono, Maine. An increment borer was used to determine the tree age, extent of heartwood and sapwood, and to check for evidence of decay.

After felling, 3-inch-thick disks were cut from each tree at two different heights (Fig. 1). The disks were wrapped in plastic and then stored in a freezer until needed.

At least twenty plugs from each disk cross section were drilled using a 1-in. plug cutter. An equal number of heartwood and sapwood samples were machined from each height. The plugs were taken randomly within the heart and sapwood and at increasing distances from pith to bark.

The samples were conditioned at approximately 40°C to an equilibrium moisture content between 10 and 12%. The ends of the samples were shaved with a thin knife to re-

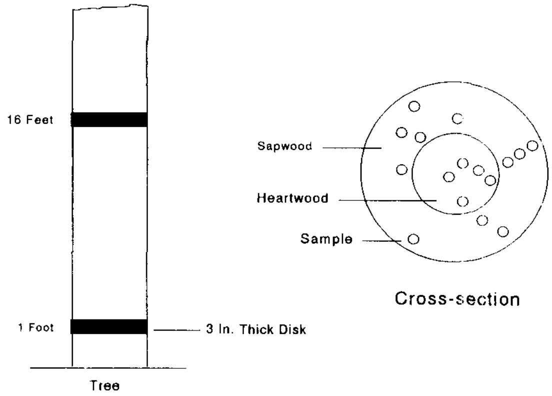

FIG. 1. Cutting diagram for the permeability samples. A minimum of 20 samples were cut from each tree.

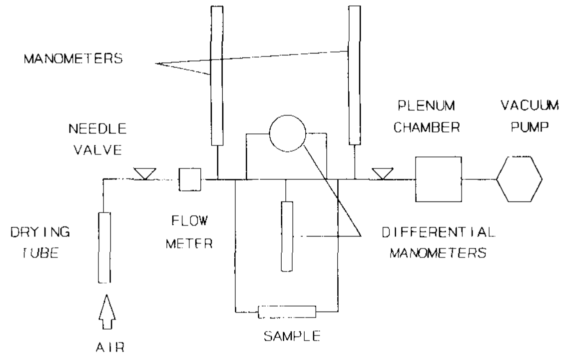

FIG. 2. Schematic of the apparatus used for the permeability measurements.

move any blockage of cells caused by sawing. The finished samples were cylindrical in shape, 1 in. in length, and 1 in. in diameter.

The experimental design for the solid wood superficial gas permeability measurements was a randomized complete block design with subsampling and a 2 × 2 factorial treatment combination. The design is shown in Table 1.

Permeability measurements

The apparatus used to measure the superficial gas permeability is illustrated schematically in Fig. 2 and was similar to that designed by Petty and Preston (1969). The apparatus is typical of those used in many permeability studies with few modifications.

A vacuum pump was used to maintain a constant pressure difference across the sample. Two precision needle valves were used to throttle the flow and to regulate the pressure at the plenum chamber and at the system inlets. Two vertical open-ended manometers (accurate to 0.6 in. of mercury) and two differential manometers were used in the system.

TABLE 1. *Experimental design for the experiments.*

Species	Trees	Wood-type	Heights	Replicates
3	3	2	2	5

One differential manometer (accurate to 0.6 in. of mercury) was used to measure large pressure differences. The other differential manometer (accurate to 1 in. of water) was a smaller, more sensitive instrument that could be used to measure minute pressure differences of 0 to 40 in. of water. To prevent air leakage around the sample during testing, a light coating of vacuum grease was applied to its circumference. The sample was then placed in a flexible tube and clamped around the outside.

Two flow meters were used. The first was a digital device (accurate to 0.05 l/min.) which was capable of measuring 0.1 to 5.0 l/min. The second was a glass-tube flowmeter (accurate to 5% of the reading) which was more sensitive and capable of measuring from 1 to 100 ml/min. A drying tube filled with a granular desiccant was used to remove moisture from the air entering into the system.

During testing, three levels of differential pressure were used on each sample. Readings were taken from the instruments when the system reached steady-state conditions. The differential pressures chosen were tested for unsteadiness with flow rate prior to recording data and adjusted manually to keep them constant during testing.

All permeability data were analyzed using a computer statistics program (SAS). All effects were tested at the 5% and 1% levels of significance. Analyses of variance were conducted to determine the significance of among-tree, height, and heartwood/sapwood differences and interactions related to those variables.

RESULTS

Prior to analysis, outliers from each population were identified using a box plot graph (SAS), and the samples were removed from the data set.

Data were taken from each sample using three levels of differential pressure. An analysis of permeability versus differential pressure was done using dependent t-tests and revealed that there were no statistically significant differences (99% confidence level) associated with the level of differential pressure used. Hence, the average permeability from the three measurements was used for each sample.

The permeability data were graphed and appeared to be non-normally distributed. Analysis of the residual errors revealed that the random error was also non-normally distributed. Therefore, nonparametric analysis was used to analyze the data. The permeability values for each species were ranked in increasing value, and analyses of variance were conducted on these ranks.

Broad summary data from the tests are shown in Table 2 and discussed in more detail below. Among the species tested, eastern white pine had the highest mean permeability at 0.230 $\mu m^3/\mu m$ and red spruce the lowest at 0.017 $\mu m^3/\mu m$. The effect of height was most noticeable in pine, where the average at 16 feet was 1.8 times that at one foot. Heartwood/sapwood differences were clearly evident in both eastern white pine and red spruce and evident, although not pronounced, in balsam fir.

TABLE 2. *Summary data from the permeability test.*

	White pine		Red spruce		Balsam fir	
Source	N	Permeability ($\mu m^3/\mu m$)	N	Permeability ($\mu m^3/\mu m$)	N	Permeability ($\mu m^3/\mu m$)
Total	63	0.233	61	0.017	70	0.034
tree 1	20	0.181	20	0.025	22	0.044
tree 2	20	0.313	20	0.010	24	0.020
tree 3	23	0.208	21	0.015	24	0.037
Height						
1 ft	31	0.166	31	0.016	35	0.034
16 ft	32	0.297	30	0.017	35	0.033
Wood-type						
heartwood	31	0.052	30	0.004	35	0.030
sapwood	32	0.408	31	0.028	35	0.038

* N = number of samples.

Eastern white pine

Overall, the mean permeability of eastern white pine was nearly seven times larger than that of balsam fir and almost 14 times larger than that of red spruce. Heartwood and sapwood permeability differed widely as shown in Fig. 3a, mostly as a result of the sapwood of tree 2.

The average permeability for white pine at one foot was 0.164 $\mu m^3/\mu m$, about half the average at 16 feet (Table 2). The heartwood permeability at one foot (mean = 0.044 $\mu m^3/\mu m$) did not differ markedly from the permeability at 16 feet (mean = 0.058 $\mu m^3/\mu m$) as shown graphically in Fig. 3a. Most of the variation resulted from the sapwood, which differed substantially at each height. On average, the permeability of the sapwood at one foot was 0.274 $\mu m^3/\mu m$, while at 16 feet it was 0.539 $\mu m^3/\mu m$. Although the average permeability was clearly higher at 16 feet, the overall effect of height was not statistically significant when all data were grouped and analyzed.

The mean permeability from each tree differed widely (Table 2) but, when compared at both the 0.01 and 0.05 levels of significance, the among-tree differences were not statistically significant in white pine. The individual sample permeability measurements showed substantial variation. The mean coefficient of variation for the heartwood was about 38%, while for the sapwood it was over 23%, which may have led to lack of significance.

The greatest difference in measured permeability was found when comparing heartwood and sapwood values. Within tree 1, the values ranged from 0.025 $\mu m^3/\mu m$ for the heartwood to 0.886 $\mu m^3/\mu m$ for the sapwood

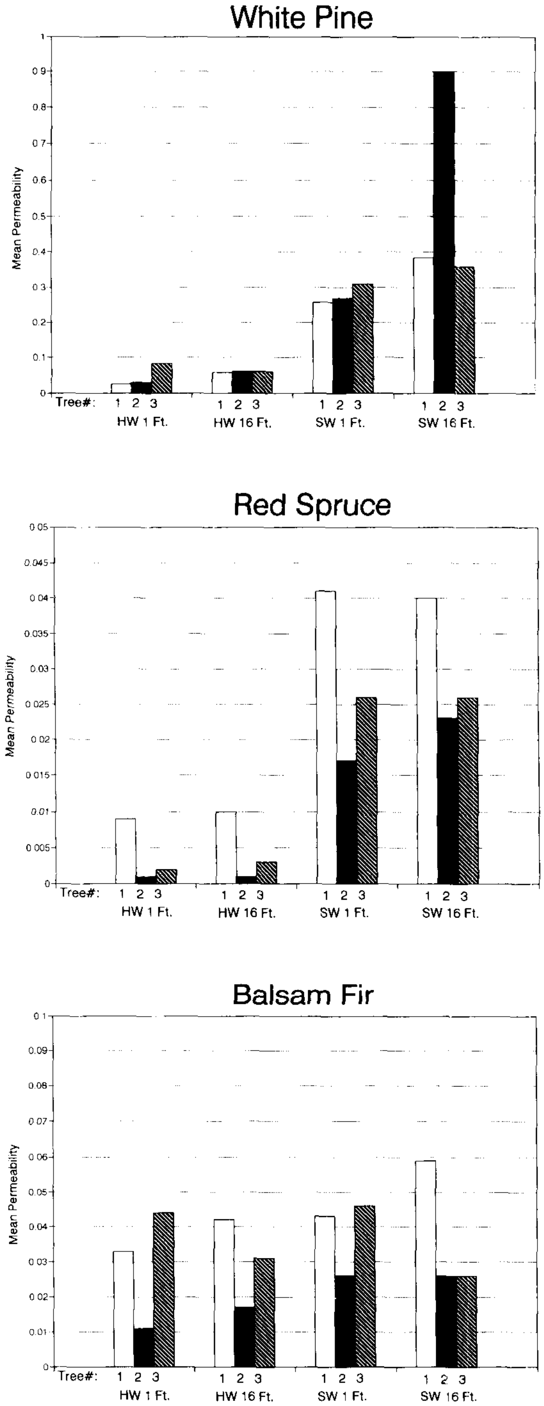

FIG. 3. Summary of the permeability measurements from eastern white pine, red spruce, and balsam fir. The units of permeability are $\mu m^3/\mu m$. HW = heartwood, SW = sapwood.

(Fig. 3a). The average sapwood permeability (0.403 $\mu m^3/\mu m$) was almost eight times greater than the average heartwood permeability (0.051 $\mu m^3/\mu m$). Overall, the permeability differences between heartwood and sapwood in white pine were statistically significant.

In summary, the analysis of variance showed that the only directly significant effect on permeability was from the heartwood/sapwood difference. Significant interactions included heartwood $\times$ tree (95% confidence level) and height $\times$ tree (99% confidence level).

Red spruce

The average permeability for red spruce was 0.017 $\mu m^3/\mu m$ and was the lowest of the species tested (Table 2). Heartwood and sapwood permeability differed substantially as shown in Fig. 3b, mostly as a result of tree 1.

The permeability showed little variation with height. The average permeability at a height of one foot was 0.016 $\mu m^3/\mu m$, while the average permeability at sixteen feet was 0.017 $\mu m^3/\mu m$. The heartwood permeability at one foot (mean = 0.004 $\mu m^3/\mu m$) was the same as at 16 feet. The sapwood permeability was much higher, averaging 0.028 $\mu m^3/\mu m$ at one foot and 0.03 $\mu m^3/\mu m$ at 16 feet. However, when the data were grouped and analyzed, the overall effect of height was not statistically significant.

Among trees, the average permeabilities for tree 2 and tree 3 differed by only 0.005 $\mu m^3/\mu m$, while the average permeability for tree 1 was over twice that of tree 2. Among-tree variation was statistically significant in red spruce, mostly as a result of the measurements from tree 1, as shown graphically in Fig. 3b. Overall, the data showed substantial scatter, and the mean coefficient of variation was over 28%.

Permeability differences between the heartwood and sapwood were statistically significant in red spruce. The average sapwood permeability was almost seven times greater than the average heartwood permeability (Table 2). Among-tree variations in heartwood and sapwood variability were also large. As seen in

Fig. 3b, tree 1 had much higher heartwood and sapwood permeability than the others.

In summary, statistical analysis showed that direct effects included among-tree and heartwood/sapwood differences which were statistically significant at the 1% level. There were no significant interactions for red spruce.

Balsam fir

The mean permeability of balsam fir was 0.034 $\mu m^3/\mu m$ and was far lower than that of eastern white pine but higher than that of red spruce. Moreover, the differences between heartwood and sapwood were less pronounced in balsam fir than with the other species tested as shown graphically in Fig. 3c.

The average permeability for balsam fir at a height of one foot was almost equivalent to the average permeability at 16 feet (Table 2). The heartwood permeability at one foot (mean = 0.029 $\mu m^3/\mu m$) was nearly equivalent to that at 16 feet (mean = 0.030 $\mu m^3/\mu m$). The mean sapwood values at each height were approximately 0.038 $\mu m^3/\mu m$ and did not differ markedly from the heartwood values. The overall effect of height on the permeability of balsam fir was not statistically significant and was similar to the results of both white pine and red spruce.

Details of the among-tree variation (Table 2) show that the average permeability of tree 2 was less than that of trees 1 and 3. However, the variation was substantial regardless of the source. The mean coefficient of variation for the sapwood was 29.9%, while for the heartwood it was 26.2%. Overall, among-tree variability was significant at the 1% level.

The heartwood and sapwood permeability differences were less pronounced in balsam fir than in either white pine or red spruce, as seen in Table 2. Comparative analysis of heartwood and sapwood permeability differences showed that they were not statistically significant at either the 1 or 5% levels. The difference between the average heartwood permeability (0.030 $\mu m^3/\mu m$) and average sapwood permeability (0.038 $\mu m^3/\mu m$) was small.

Overall the only direct effect that was statistically significant was the among-tree variation. Significant interactions included height × tree and heartwood/sapwood × tree, both significant at the 0.01 level

DISCUSSION

Most of the differences in average permeability among the three species can probably be attributed to basic anatomical structure differences or to resins whose deposition can vary substantially within the tree.

The largest tracheids from eastern white pine are much larger (50 μM) than those of red spruce (35 μM) but similar in size to those of balsam fir (50 μM). Based on the broad descriptions of anatomical structure provided by Panshin and DeZeeuw (1980), the pitting and the ray structure probably contribute to higher levels of gas transport in eastern white pine and to the differences among the species.

Extractives and the presence of tylosoids are also factors affecting the permeability of the three species.

Rowell (1984) reported that the extractive content for white pine averaged 15% and for balsam fir 11%. The species of spruce (*Picea sp.*) tested also had 11–12% extractives. High levels of extractives could impede the flow of gases and affect the permeability substantially. Moreover, since extractive deposition is not uniform and is generally confined to the heartwood, their presence may have contributed to the high coefficients of variation and to the significance of heartwood and sapwood permeability differences in white pine and red spruce. White pine and red spruce also have resin canals that contain tylosoids in the heartwood, which could affect both the magnitude and the variability of the measurements.

CONCLUSIONS

The longitudinal superficial gas permeability differed widely among the three species tested. Eastern white pine had, by far, the highest longitudinal permeability. Balsam fir was next, followed by red spruce. On average, white pine was over 14 times more permeable than red spruce. The coefficients of variation were high with all of the species tested, probably due to the presence of resins and other extractives.

Among tree variation had a significant effect on the permeability of both balsam fir and red spruce but, not on eastern white pine. Heartwood/sapwood variation was significant in eastern white pine and red spruce but not in balsam fir. Height was not a factor in any of the species tested.

The results suggest that moisture longitudinal moisture movement during drying, pulping, or treating would be far more rapid in white pine than in the other species.

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