RELATIVE PERMEABILITY AND THE GROSS PORE STRUCTURE OF WOOD

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ABSTRACT

Water-saturated, longitudinal core samples of nine hardwoods and three softwoods were measured for specific permeability and also for relative permeability to water and nitrogen gas. Constant flow rates were achieved for specific permeability. Relative permeability curve shapes were influenced more by the pore structure of wood than by its specific permeability. It appears that softwoods could be drained much lower in degree of saturation than hardwoods. In imbibition-type measurements, the softwoods were higher in saturation but lower in relative permeability than the hardwoods.

Additional keywords: Softwoods, hardwoods, specific permeability, effective permeability, absolute permeability, water, nitrogen gas.

INTRODUCTION

Most studies in wood permeability have been confined to single-phase flow measurements with either gas or liquid as the flowing medium. Permeability is important because it is used to predict the behavior of wood when subjected to various industrial processes such as preservative treatment, pulping, or drying. When the permeating fluid is a liquid, the wood specimen must be in a fully saturated condition; but when gas is used, the moisture content of the wood must be in the hygroscopic range for effective flow to take place.

The first reported study on multiphase flow in wood was made by Tesoro et al. (1972). Two fluids, oil and water, were used in the study. The fluids were simultaneously made to flow through the specimen in varying amounts, thereby creating a varying fluid saturation in the specimen. The permeability of the specimen to each fluid was calculated at a given saturation. They reported that the relative permeability to water decreased sharply with a slight decrease in water saturation of the specimen; but a small increase in oil saturation caused a great increase in relative permeability to oil.

This paper reports on a study of the relative permeability to water and nitrogen gas of a number of wood species and describes its relation to the gross pore structure of wood.

THEORETICAL CONSIDERATIONS

The fundamental relationship used to describe the conductance of an incompressible fluid, termed *absolute* or *specific* permeability (K_s), is based on Darcy's law:

$$K_s = \frac{Q\mu L}{A(\Delta P)} \quad \text{(Darcy, or cm}^2\text{-cp/sec-atm)} \quad (1)$$

where Q (cc/sec) is flow rate, μ (cp) is fluid viscosity, L (cm) is specimen length, A (cm^2) is cross-sectional area of specimen, and ΔP (atm) is pressure drop.

The above equation is basically for single-phase flow at the fully saturated condition. When the material is not fully saturated or when more than one fluid saturates the material as in the case of a multiphase system, the conductance of the material varies from the absolute value. Permeability to the mobile phase becomes affected by the other fluid even when such fluid remains immobile. The flow capacity

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of the composite porous medium with its fluid becomes dependent upon the nature of the fluids, the amounts present, and their distribution in the pore structure of the material. In such a condition, the conductance is termed *effective* permeability (K_e), which can be calculated by applying Darcy's law individually to each mobile phase, as follows:

$$K_e = \frac{Q_x \mu_x L}{A(\Delta P)} \quad \text{(Darcy)} \quad (2)$$

where Q_x and μ_x are, respectively, the flow rate and viscosity of fluid x.

Since the efffective permeability of the material to a given fluid varies directly, though not linearly, with the saturation by that fluid, it is necessary to specify the degree of saturation (Craft and Hawkins 1959). Effective permeability can be measured at numerous levels of saturation by a given fluid, and therefore it is more convenient to express it as *relative* permeability (K_r):

$$K_r = \frac{K_e}{K_s} \quad (3)$$

The relative permeability of a material to a given fluid when the fluid saturates the material completely is equal to unity.

When a compressible fluid such as gas is used, Eq. (1) is modified to account for the compressibility of the fluid. Assuming an ideal gas behavior, the superficial permeability for gas (K_g) is:

$$K_g = \frac{\bar{Q}\mu L}{A(\Delta P)} = \frac{Q_a \mu L P_a}{A\bar{P}(\Delta P)} \quad \text{(Darcy)} \quad (4)$$

where $\bar{Q}$ (cc/sec) is the flow rate at mean pressure $\bar{P}$ (atm) $= (P_1 + P_2)/2$, Q_a(cc/sec) is the flow rate at atmospheric pressure $P_a = 1$ atm, ΔP (atm) is the pressure drop ($P_1 - P_2$), P_1 is the upstream pressure and P_2 is the downstream pressure.

MATERIALS AND METHODS

Materials

Preparation. Samples representing twelve species were selected for this study. These include:

Ring-porous
- Black locust (*Robinia pseudocacia* L.)
- American elm (*Ulmus americana* L.)
- White oak (*Quercus* spp.)
- Hackberry (*Celtis occidentalis* L.)

Semi-ring-porous
- Black willow (*Salix nigra* Marsh.)
- Cottonwood (*Populus deltoides* Bartr.)

Diffuse-porous
- Sycamore (*Platanus occidentalis* L.)
- Sweetgum (*Liquidambar styraciflua* L.)
- Soft maple (*Acer* spp.)

Nonporous (softwoods)
- Baldcypress (*Taxodium distichum* (L.) Rich.)
- Southern pine (*Pinus* spp.)
- Redwood (*Sequoia sempervirens* (D. Don.) Endl.)

For each species, eight dowel specimens (i.e., four sapwood and four heartwood) were obtained with a ⅞-inch plug cutter from a 2-inch-thick disc that was cut from a green log (except for the redwood samples, which came from a piece of green board). Each dowel was cut into three sections, with the central portion about 1.2 inches long and the other two about 0.4 inch. The longest section served as the permeability specimen. One of the shorter sections served as a premixer piece, to mix the fluids before they entered the test specimen. The other was used as an end- or boundary-effect piece, to maintain capillary continuity and to eliminate any saturation gradient at the outflow end of the specimen. The ends of the specimens and end-effect pieces were trimmed with a scalpel blade to remove loose fibers and to expose the pore structure.

Conditioning of materials. The specimens were fully saturated in a manner described by Choong and Kimbler (1971). This was done by first evacuating the specimens, followed by impregnation with carbon dioxide for one hour to replace the air in the wood. A subsequent vacuum was pulled on the specimens for another hour; then deaerated water was introduced into the small retort containing the specimens. The purpose of injecting carbon dioxide was to re-

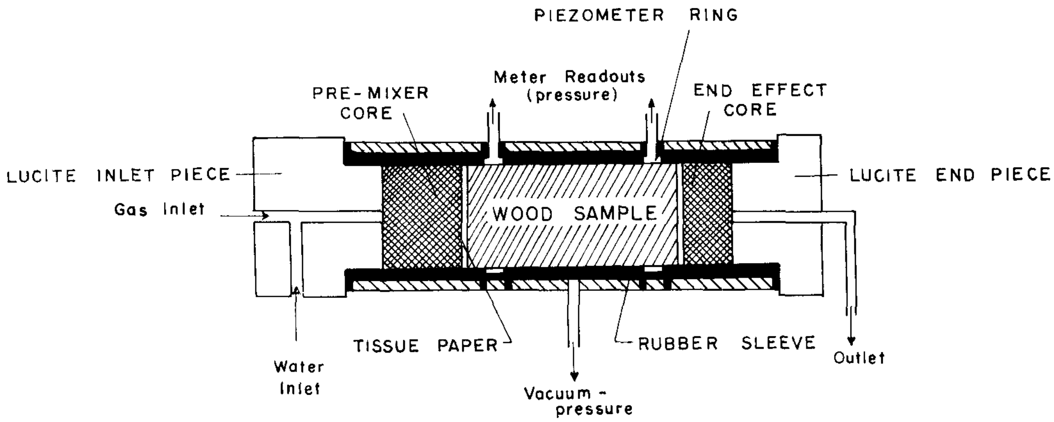

FIG. 1. Cross-sectional view of the relative permeability core shell.

place the air in the specimen. Carbon dioxide dissolves readily in water for easy flushing of the sample. To ensure that all the air was removed, the specimens were further immersed in deaerated water and subjected to oscillating vacuum-pressure treatment until no more gas bubbles were detected coming out of the specimens.

Deaeration of water was accomplished by subjecting a column of freshly distilled water under vacuum to cavitation, using applied mechanical shock with a metal hammer, until the amount of air nuclei was reduced to a minimum.

Methods

Absolute permeability measurements. Absolute permeability was determined in fully water-saturated specimens. Measurements were made with the apparatus described by Choong and Kimbler (1971). It consists of a stainless steel core holder whose diameter is slightly larger than the wood samples. This allows it to be fitted with a neoprene rubber sleeve to which gas pressure over water up to 15 times the flow pressure is supplied to hold the specimen tightly, thus preventing the passage of liquid between the sleeve and the side of the specimen. A Statham UC3 universal transducer cell attached to a pressure diaphragm is connected immediately before the core holder. Pressure is indicated on a Statham UR4 Meter Read-out. Three transducing cells equipped with pressure diaphragms of 2, 5, and 10 psi capacity were used, depending on the permeability of the specimen.

Liquid is supplied to the specimen at a constant rate by a precision positive displacement pump. Using appropriate gear ratios, the rate can be varied from 0.0034 to 8.046 cc/min, accurate to within less than 0.1% at 72 F. A Millipore (50 μm) filter was fitted between the pump and the core barrel.

Following absolute permeability measurements, those specimens that were to be used for the imbibition-type relative permeability measurements were slowly dried to near fiber saturation point. This was done by conditioning the specimens at nominal 98% RH to about 50% MC, then reducing the conditions to nominal 86% RH. At about 35% MC, the specimens were transferred to a desiccator containing a saturated solution of calcium sulfate (nominal 95% RH at room temperature) so that they could be dried slowly to slightly below the fiber saturation point. The desiccator was fitted with a variable speed fan to maintain uniform atmospheric conditions. When the specimens attained constant weight, the salt solution in the desiccator was replaced with distilled water to allow them to attain fiber saturation.

Relative permeability measurement. Flow measurements for relative perme-

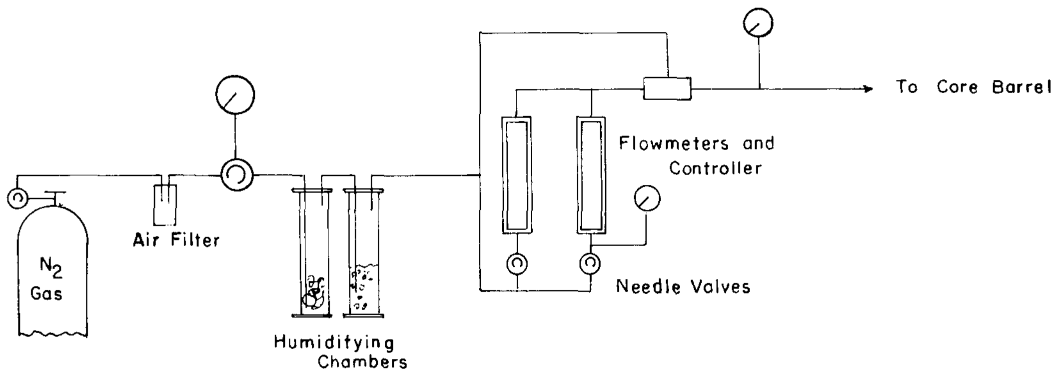

FIG. 2. Diagram of the apparatus for controlling the flow rate of gas at fluctuating pressures.

ability determinations were made on water-gas combinations of mobile phases with an apparatus similar to the one described by Tesoro et al. (1972). The permeability core cell (Fig. 1) is made from three segments of copper cylinder. Each cylinder is equipped with a rubber sleeve to which a liquid pressure is applied to produce a tight seal on the surfaces of the specimen. On each end of the middle cylinder is a piezometer ring connected to a Statham UC3 pressure transducer equipped with a pressure diaphragm. The permeability specimen, held between the premixer and the end-effect pieces and separated by tissue paper, is positioned in the core barrel with the premixer next to a Lucite[2] inlet piece.

Liquid is similarly supplied to the specimen by the constant rate positive displacement pump mentioned previously. Nitrogen gas from a supply tank is delivered at a constant rate, but at variable pressures, by an apparatus shown in Fig. 2. The gas passes through a humidifying chamber to preclude drying of the specimen. Volume flow is controlled by needle valves and a differential flow controller. The rate of the gas flow is measured by observing the time for a soap bubble film to travel a given distance through burets of varying sizes.

Two kinds of relative permeability measurements were made in this study. In the *drainage* type, the specimens were initially fully saturated with the wetting phase, with the subsequent relative permeability measurement reducing its saturation. This was done by passing an increasing amount of gas with a corresponding decrease in the rate of water flow. The flow rates of water and gas were adjusted so that their combined rate was approximately equal to the rate of flow of water during the specific permeability measurements. In the *imbibition* type, the procedure was reversed. The moisture contents of the specimens were at or near fiber saturation, and any subsequent measurement results in an increase in the wetting phase saturation. Thus the flow of gas started at a high rate while that of the water was held low; subsequently, the water rate was increased with a corresponding reduction in gas flow rate, until only water was flowing.

After conditions had equilibrated at each flow rate, the pressure drop was recorded and the distance between the piezometer rings was measured each time. This distance could vary slightly from one data point to another because of variation in the degree of compactness of the rubber sleeves. Then the specimen was removed from the core barrel and weighed. The change in free water saturation of the specimen was determined from the increase or decrease in weight of the specimen. For the drainage measurement, saturation change was based on the saturated weight. For the imbibition measurement, it was based on the weight of the specimen at about fiber saturation point.

[2] Dupont trade mark of (poly)methylmethacrylate plastic.

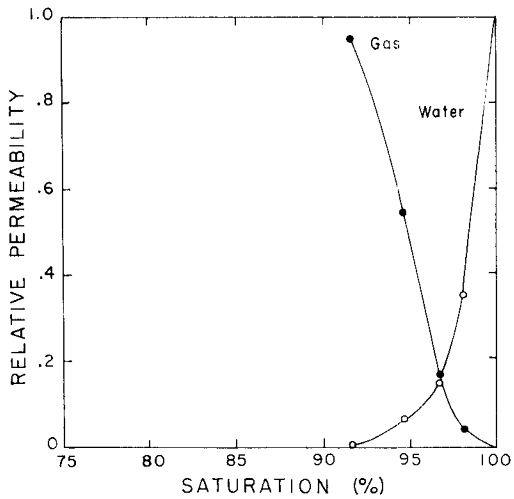

FIG. 3. Typical relative permeability curve of a ring-porous specimen (American elm) obtained from drainage-type measurements.

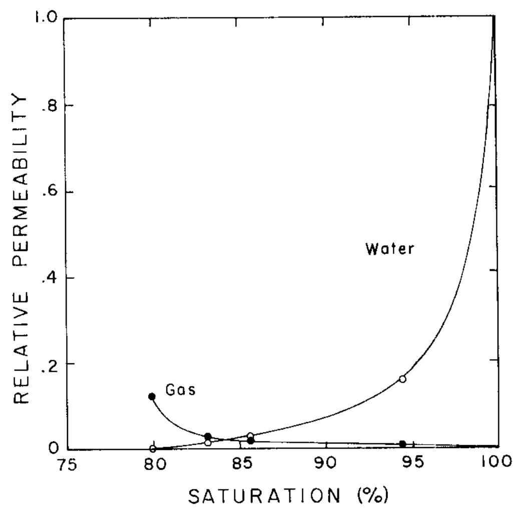

FIG. 4. Typical relative permeability curve of a softwood specimen (baldcypress) obtained from drainage-type measurements.

RESULTS AND DISCUSSION

Relative permeability

Drainage. Typical curves of the relative permeability by the drainage method are shown in Fig. 3 for American elm (a ring-porous wood) and in Fig. 4 for baldcypress (a softwood). Since the curves for the various replicated specimens within each species were similar, and there was very little difference between sapwood and heartwood, only one curve is shown for each species. As shown in these figures, the relative permeability of both types of wood decreased abruptly with the introduction of the second (gas) phase. When gas entered the American elm specimen, the water permeability was reduced from 100% to about 40%, indicating that the largest pore openings accounted for about 60% of the permeability; in baldcypress, about 5% of the pore openings accounted for about 80% of the permeability. The reason for the reduction in water flow is that the gas presented a barrier to the flow of the water in the largest capillaries of the system, which according to Brownscombe et al. (1949) are desaturated first. These openings account for most of the flow channels responsible for permeability. In the smaller capillaries, there is the possibility of entrapment of gas which would inhibit the flow of water.

In American elm, the displaced phase (water) curve follows a sharp decrease during the initial part of drainage, indicating that at this stage the effective flow was through the large capillaries of about equal size. Such a phenomenon can be expected with any ring-porous wood. As more gas was admitted into the system, the next grade of capillaries was emptied. Since the contribution of these smaller capillaries to the total flow was not so great as the previously drained larger capillaries, there was less reduction in the relative permeability to water. The curve assumed a parabolic shape, and this indicates that after the largest pores were desaturated, the secondary pores that drained varied more in size. As shown in Fig. 3, the water curve approached a zero value at about 91% saturation, so that only about 9% of the pore space was composed of pores having radii with capillary pressures less than the applied pressure for drainage to occur, and this amount actually determined the permeability to gas.

The capillary system of the softwoods is wholly different from that of the hard-

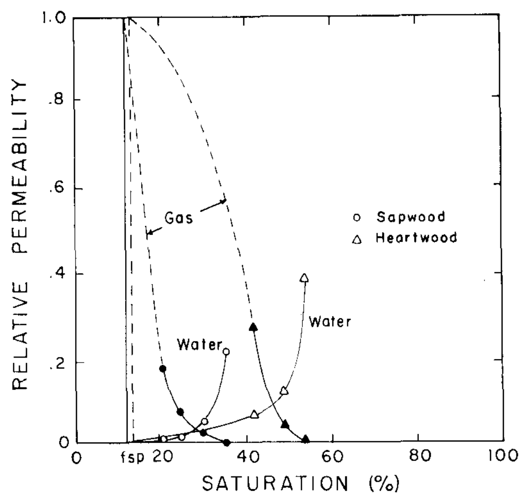

FIG. 5. Typical relative permeability curve of a ring-porous specimen (American elm) obtained from imbibition-type measurements starting from about the fiber saturation point.

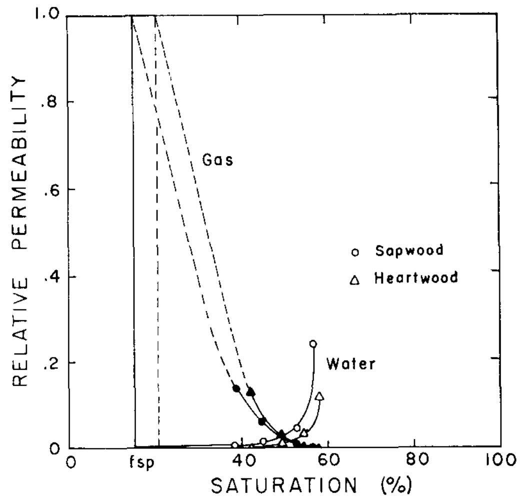

FIG. 6. Typical relative permeability curve of a diffuse-porous specimen (sycamore) obtained from imbibition-type measurements starting from about the fiber saturation point.

woods. Instead of a parallel arrangement, the capillaries in softwoods are in series separated by intercommunicating pit membranes. When gas is admitted, it seeks the openings that represent the path of least resistance. These would be in the series of pits in tracheids that possess the largest pit pore openings. If the gradation of pit pore openings is gradual, an additional volume of gas in the system results in a gradual reduction of the water permeability, and the water curve changes in slope, as shown in Fig. 4. In this case, the water in the specimen was drained to about 80% saturation. At this point, continuous gas channels are well established through the tracheids via the pit openings, which have been desaturated. The flow of gas through these channels effectively blocks the flow of water even though the water saturation remains very high.

The relative permeability to gas of baldcypress was very much lower than that of American elm. The former attained only 13% of the specific permeability of the material; whereas the latter reached 95%. This difference may be related to the smaller effective pore radii found in softwoods, and perhaps also to the formation of air-water menisci which impedes flow. These factors would cause a much lower ratio of flow rate to pressure gradient in the softwoods, so that the net result would be a large reduction in relative permeability.

The specific permeability of the specimens does not seem to affect the degree of drainage. The amount of desaturation appears to be more a function of pore structure than permeability. The presence of deposits and/or tyloses in wood, however, would affect the amount of drainage insofar as these factors affect the flow of fluids through wood.

Imbibition. The relationship between relative permeability to water and nitrogen gas vs. moisture saturation was established for all samples representing various species and wood types. Within each wood type, the relationships for individual samples were essentially the same. Typical curves for ring-porous (e.g. American elm), diffuse-porous (e.g. sycamore), and semi-ring-porous (e.g. black willow) woods are presented in Figs. 5, 6, and 7, respectively. All these "porous" woods show the same characteristic, low sweeping curves at low water saturation. A small amount of water admitted into these woods caused con-

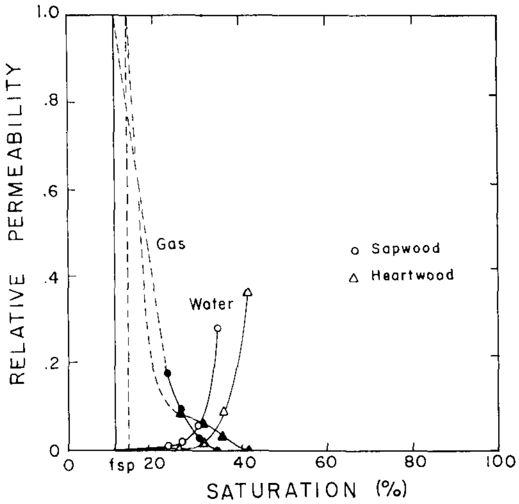

FIG. 7. Typical relative permeability curve of a semi-ring-porous specimen (black willow) obtained from imbibition-type measurements starting from about the fiber saturation point.

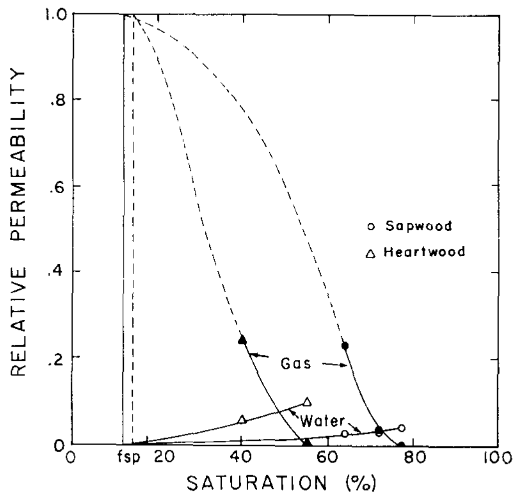

FIG. 8. Typical relative permeability curve of a softwood specimen (baldcypress) obtained from imbibition-type measurements starting from about the fiber saturation point.

siderable and abrupt reduction in the effective permeability of the gas. In both the ring-porous and semi-ring-porous specimens, about 20% of the effective pore space in the sapwood[3] was responsible for about 80% of the gas flow; while in the diffuse-porous specimens about 30% effective pore space accounted for an equal percent of the permeability of the gas. Also, there was a higher percentage of saturation obtained in the diffuse-porous specimens, indicating that a higher percentage of the pore space of the ring-porous and semi-ring-porous woods was occupied by trapped air that could not be displaced by the applied pressure.

The water curve for baldcypress, a "nonporous" wood, shown in Fig. 8, is rather flat, rising very slowly. Even at the stage where only water was flowing, the relative permeability was much lower than in the hardwoods. The reason is that when a fluid moves through the capillary system of the softwoods, it must travel from one tracheid to another through a tortuous route, instead of only a single straight capillary of equal radius. A single flow path would, therefore, involve a greater void space in the softwood. Under a steady-state condition of flow, there must be continuity of the liquid in the void spaces involved in the flow of that phase. To obtain this continuity, a greater volume of liquid must enter the specimen. For this reason, the softwood attained a higher percentage water saturation than the hardwoods.

One notable difference between the imbibition- and drainage-type relative permeability measurements was that the fluid increased in volume in the former was also the wetting phase. At very low water saturation, the water tends to occupy the least favorable portions of the pore space, i.e., as thin layers on the walls of the pore cavities and in minute capillaries. This explains the slow rise of the water curve in the imbibition-type measurements.

Permeability to water

Average values of specific permeability to water $(\bar{K}_s)_w$ and effective permeability to water $(\bar{K}_e)_w$ at the degree of saturation attained for sapwood and heartwood specimens of each species are shown in Table 1. For all species except cottonwood, the heartwood showed a much lower

[3] Based on % void space within the range of water saturation above the fiber saturation point.

TABLE 1. *Average[a] values of the specific permeability to water $(\bar{K}_s)_w$ and the effective permeability to water $(\bar{K}_e)_w$ for various species and wood types*

Species and wood types	$(\bar{K}_s)_w$ [100% Saturation] (Darcy)	$(\bar{K}_e)_w$ (Darcy)	Measured Saturation (%)
BLACK LOCUST			
Sapwood	26.1315	4.4692	55.9
Heartwood	1.6691	0.1435	60.4
AMERICAN ELM			
Sapwood	14.4362	3.8554	35.1
Heartwood	0.8232	0.3341	52.8
WHITE OAK			
Sapwood	4.9280	1.7186	48.0
HACKBERRY			
Sapwood	13.2725	1.7162	40.9
Heartwood	9.2882	1.4536	48.6
SYCAMORE			
Sapwood	10.4677	4.5387	50.6
Heartwood	8.0155	3.2809	52.3
SWEETGUM			
Sapwood	2.7114	0.3597	56.1
Heartwood	2.3356	0.2088	56.0
SOFT MAPLE			
Sapwood	0.2973	0.0408	37.7
BLACK WILLOW			
Sapwood	8.4329	3.3186	41.2
Heartwood	4.9565	1.2859	40.2
COTTONWOOD			
Sapwood	4.6460	1.2634	45.3
Heartwood	8.3320	2.4530	50.9
REDWOOD			
Sapwood	0.1896	0.0290	46.6
Heartwood	0.0807	0.0015	44.1
SOUTHERN PINE			
Sapwood	1.2091	0.0048	54.0
BALDCYPRESS			
Sapwood	0.8251	0.0251	70.9
Heartwood	0.0070	0.0009	53.7

[a] Average of four samples per wood type in a given species.

specific permeability than the sapwood. This trend is also shown with effective permeability but to a lesser degree.

In measuring for specific permeability, a steady-state condition was taken to have been attained when the pressure drop remained unchanged for a definite period of time. In most measurements, a steady-state condition was attained. With very permeable specimens, the pressure drop was observed to be unchanged with time, while in the less permeable specimens the pressure drop increased for a short period and then remained steady. A typical plot of the

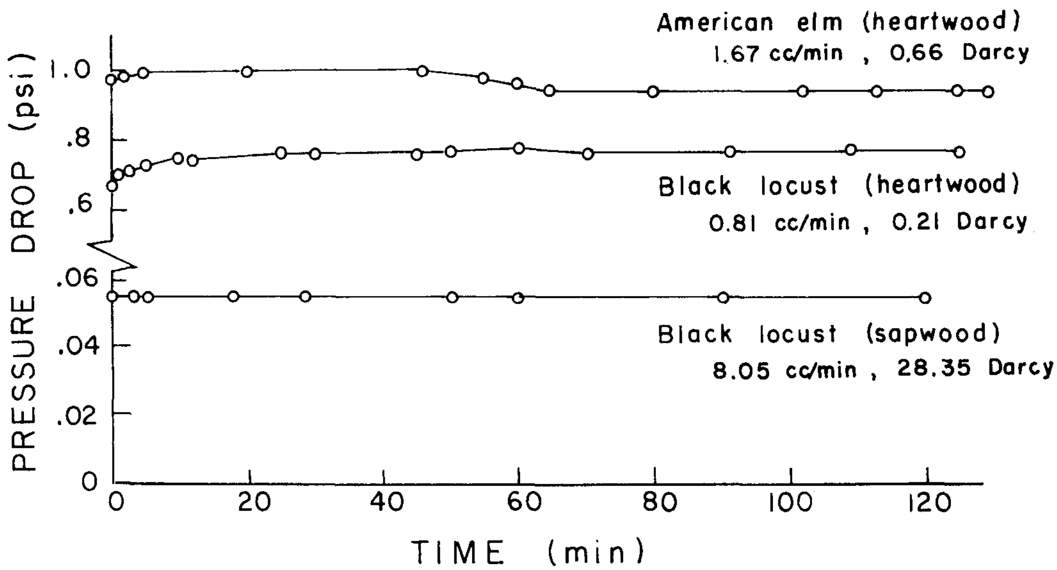

FIG. 9. Relationship between pressure drop and time during specific permeability measurements with water under constant flow rate.

changes in pressure drop with time for three hardwood specimens is shown in Fig. 9. The less permeable specimen (i.e., American elm heartwood) shows increased pressure with time during the initial stages of measurement; then it either remained steady or first decreased before becoming constant. Similar results were recorded in the softwood specimens. The reason for the change in flow rate before it leveled off may be due to air blockage (Kelso et al. 1963) in very minute flow channels of wood. Narayanamurti et al. (1951) recorded similar results with Indian hardwoods. The initial decrease in flow rate, which is equivalent to an increase in pressure in this study, was observed before flow became constant. With the more permeable specimen (i.e., black locust sapwood), the pressure at the start of the measurement did not vary with time. In some cases there was an initial decrease in pressure before it became constant, indicating that residual air inside the wood was pushed out until no more could be removed.

Based on the analysis of variance in Table 2, the relative permeability of the hard-

TABLE 2. *Analysis of variance of the means of the relative permeability to water $(\bar{K}_r)_w$ between species groups (softwoods vs. hardwoods)*[a]

Source of Variation	df	Sum of Squares	Mean Square	F-ratio
Species Group	1	0.3859	0.3859	15.62**
Error	62	1.5302	0.0247	
Total	63	1.9161		

[a]Means: Softwoods = 0.0858; Hardwoods = 0.2786

** Significant at 0.01

TABLE 3. *Analysis of variance of the means of the degree of saturation between species groups (softwoods vs. hardwoods)*[a]

Source of Variation	df	Sum of Squares	Mean Square	F-ratio
Species Group	1	0.0736	0.0736	9.44**
Error	62	0.4817	0.0078	
Total	63	0.5553		

[a]Means: Softwoods = 0.5518; Hardwoods = 0.4675

** Significant at 0.01

woods was significantly higher than that of the softwoods, but the softwoods showed a significantly higher percent saturation at the end of the relative permeability experimental run (Table 3). The reduction in gas permeability was less abrupt in the softwoods than in the hardwoods.

Between specific permeability and percentage saturation, there was a highly significant negative correlation. The lower permeability specimens reached a higher saturation at the end of the experimental run. In low permeability wood, the fluid moves slowly through the pore structure. Since fluid was supplied at a constant rate, a large volume accumulated in the pore spaces before a continuous liquid system was developed from one end of the specimen to the other. In highly permeable wood, the liquid moves rapidly across the specimen forming a continuous system, and begins to flow out of the opposite end much earlier than in low permeable wood. As a consequence, there is less buildup of liquid in the capillary system in permeable wood. Since the longitudinal permeability of the softwoods is lower than that of the hardwoods, the softwoods attained a higher degree of saturation. Within a given species, the lower permeability heartwood also reached higher saturation than the sapwood.

The lower relative permeability of the softwoods may be accounted for by the reduction in permeability of the specimens due to pit aspiration caused by drying. A microscopic examination of the pit membranes of undried baldcypress specimens showed about 26% pit aspiration in the sapwood springwood, while 47% aspiration was noted in the undried heartwood (Table 4). Drying increased the pit aspiration in the sapwood by 42–57%, and in the heartwood by 60–74%. With a reduction in

TABLE 4. *Percent aspiration of the springwood bordered pits in green and air-dried baldcypress*

Specimen	Number Observed		Percent Aspiration
	Aspirated	Unaspirated	
Green Sapwood	26	74	26.0
Green Heartwood	32	36	47.1
Dried Sapwood	33	32	50.8
	36	50	41.9
	32	57	35.9
Dried Heartwood	50	25	66.7
	50	32	61.0
	58	20	74.4

permeability, a higher pressure gradient was needed for water flow across the specimen. In southern pine, the relative permeability was found to be very low (i.e. 0.0005), which can be attributed to pit aspiration.

CONCLUSIONS

The specific permeability to water and the relative permeability to water and nitrogen gas for various wood species of different pore types were studied and compared. On the basis of the results obtained, the following conclusions are drawn:

1. In specific permeability, a constant flow rate was obtained in most permeability measurements with water. In a few instances the pressure drop increased before it became constant. The permeability of the sapwood in any given species was always higher than that of the heartwood.

2. The relative permeability of wood for both drainage and imbibition saturation histories could be conveniently measured. The shape of the relative permeability curve is more a function of wood structure than of its specific permeability. It appears that softwoods could be drained much lower in degree of saturation than hardwoods. In imbibition-type measurements, the softwoods were higher in saturation but lower in relative permeability than the hardwoods.

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