Longitudinal Permeability of Green Eastern Hemlock

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Permeability determines the ease with which a fluid flows through wood in response to a pressure gradient. It is important in any processing operation in which a fluid is introduced into or removed from wood. Pulping, preservative treatment, fire-retardant treatment, and drying are all influenced by the permeability of wood. The more permeable the wood, the more easily it can be dried or treated.

This investigation of the permeability of wood originated because of a need for fundamental information on how wood dries. It is recognized that the movement of moisture through wood is intimately related to permeability. However, the mechanisms that control permeability and how permeability relates to moisture movement have been largely a matter of conjecture.

The purpose of this research was to investigate the permeability of green wood. We sought to discover how permeability differs within and between trees of the same species, whether a significant relationship exists between permeability and other physical properties of the wood, and whether certain treatments will increase permeability. Understanding the factors which control permeability will aid in the development of more efficient drying and treating methods.

Darcy’s Law

The flow of fluids through porous media is generally governed by Darcy’s Law, which is treated mathematically by Muskat. The flow of an incompressible fluid is expressed by the following equation:

\[
\frac{Q}{A} = \frac{k}{\eta} \left( \frac{P_1 - P_2}{L} \right)
\]

where \( k \) = permeability (Darcy’s); \( Q \) = flow rate (cubic centimeters per second); \( A \) = area (square centimeters); \( L \) = specimen length (centimeter); \( P_1 - P_2 \) = pressure drop across the specimen (atmosphere); and \( \eta \) = viscosity of the fluid (centipoise).

Permeability is a function of the porous medium and should be independent of the fluid if the fluid does not affect its structure. Thus, gas and liquid permeability should be equivalent. Equation 1 can be used with gases if the compressibility of the gas is taken into account. This can be done by calculating the flow rate, \( Q \), at the mean pressure:

\[
Q = \left( \frac{P_1 + P_2}{2} \right)
\]

Liquid Flow

In determining the permeability of wood with liquids, three principle provisions of Darcy’s Law must be met: flow rate should be constant with constant pressure over extended periods of time; flow rate should be directly proportional to pressure; reversing the direction of flow should have no effect on flow rate.

The flow of liquids through wood has been studied for many years. However, attempts to measure the permeability of wood with liquids have encountered a decreasing rate of flow with time, suggesting that...
Darcy’s Law may not apply to the flow of liquids through wood. Various theories were advanced to account for this phenomenon (2, 24, 30), but no investigators had been successful in eliminating the decreasing rate of flow until very recently. Kelso et al. (25) determined that air blockage was largely responsible for the decreasing flow rate. Using a special technique to eliminate air blockage, they demonstrated that a constant rate of flow of water through wood can be maintained for extended periods of time and that direct proportionality of flow rate to pressure can be obtained.

When water flows through wood, its velocity in the small openings is considerably greater than that in the cell cavities. The pressure in the small openings is therefore reduced in accordance with Bernoulli’s theorem, and negative pressures may actually develop. Under these conditions hydrophobic surfaces present either in the wood or in the liquid may provide nuclei for the evolution of gas from the liquid; the ease with which this may occur is governed primarily by the gas content of the liquid and the available nuclei. Thus, Kelso et al. (25) concluded that the requirements for maintaining a constant rate of flow of water through wood are that the liquid be passed through an ultrafilter and that the dissolved gas content of the liquid be sufficiently low so that nuclei present in the wood will not grow. Filtration of the liquid also serves to remove particulate matter which might physically block the flow channels in the wood.

Kelso et al. also found that even where a constant rate of flow was maintained, the initial response of flow to pressure was not linear when pressure was increased. However, after the specimens had been exposed to a high pressure, flow rate varied directly with pressure and Darcy’s Law was obeyed through subsequent pressure changes. The nonlinear behavior is attributed to the presence of air bubbles in the wood remaining after the initial attempt to saturate the wood with water. Reversal of direction of flow also resulted in an increase in rate of flow, and this, too, is believed to be due to the presence of air bubbles in the wood. While impeding flow in one direction, the bubbles are probably flushed out when the flow is reversed. Chen and Hossfeld (10) demonstrated that when the direction of flow was repeatedly reversed, a constant value, the same in both directions, was approached. They have also shown that the flow of glycerine-water solutions through wood obey Darcy’s Law with respect to the viscosity of the solution.

Where decreasing rate of flow is encountered in investigations of liquid permeability, as has generally been the case in the past, the results of such investigations must be questioned. Permeability values obtained with decreasing flow rates are a function not only of the true permeability, but of pressure, time, and nuclei and gas content of the liquid used. The latter considerations may completely overshadow true permeability, in which case the results are meaningless.

Gas Flow

The flow of gases through wood is not accompanied by the same problems that confound the flow of liquids, but a different phenomenon, molecular flow, may occur in addition to the viscous flow. Molecular flow is discussed by Resch and Ecklund (37). They concluded from measurements of the flow of nitrogen and oxygen through redwood that molecular flow at normal atmospheric pressures can be neglected and that the flow of gases can, for practical purposes, be considered to obey Darcy’s Law.

Another factor confounds the relationship of gas and liquid flow in wood. Since wood shrinks when it loses adsorbed water, the capillary structure of wood changes and Stamm (42) has shown that wood becomes more permeable as it loses moisture below the fiber saturation point.

Resch and Ecklund attempted to correlate the flow of gases and liquids through wood using nitrogen gas and hexane, a nonswelling liquid. They encountered a decreasing rate of flow of hexane with time, however, and the results therefore did not obey Darcy’s Law for liquid flow. The values of permeability obtained from liquid flow were somewhat below those obtained from gas flow. The data indicated that the liquid was physically plugging the specimen with contaminants, since successive dryings after liquid flow showed a continual decrease in gas permeability.

Smith (40) concluded that liquid permeability measurements have no general validity and cannot be correlated to gas flow permeability measurements except in a few special cases. The relationship between gas and liquid flow in wood remains to be proved.

Table 1. -- DATA ON TREES USED IN THIS PERMEABILITY STUDY

<table>
<thead>
<tr>
<th>Tree</th>
<th>Age (Yrs.)</th>
<th>Height (Ft.)</th>
<th>Diameter (top of stump) (In.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>270</td>
<td>60</td>
<td>14</td>
</tr>
<tr>
<td>II</td>
<td>133</td>
<td>70</td>
<td>12</td>
</tr>
<tr>
<td>III</td>
<td>141</td>
<td>64</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Paths of Flow

The structure of wood is quite complex, and the question of which factor controls permeability is of considerable importance. Stamm
(44) demonstrated from physical measurements of the various wood structures involved in fluid flow that the resistance to flow is almost entirely in the pit-membrane pores. Coté and Krahmer (13) passed suspensions of carbon black particles through wood and, using electron microscopy, found that the path of flow is essentially through the pits. Balatinecz (4) studied the paths by which liquids flow into Douglas-fir by impregnating wood with monomeric styrene with an incorporated dye and catalyst and polymerizing the liquid in place. He found that flow in the longitudinal direction was primarily from tracheid to tracheid through the pits. The liquid was occasionally observed to spread laterally in ray tracheids, resin canals, and intercellular spaces. In the radial direction, ray tracheids were the main flow channels, which may account for the lack of correlation between longitudinal and transverse permeability found by some investigators.

Buro and Buro (7) investigated the paths by which liquid penetrated Pinus sylvestris and found that flow in the longitudinal direction was primarily through the bordered pits of tracheids and through resin ducts. Radially, the liquids passed through ray tracheids, and intercellular spaces were of local importance.

All of these studies point strongly to the pit structure of wood as the factor which controls permeability. Therefore, studies correlating pit structure and changes in permeability might be valuable in studying methods of increasing wood permeability.

Sources of Variation

The differences between the permeability of heartwood and sapwood have been recognized for many years; sapwood is much easier to treat and dry than heartwood. Several investigators have studied the gas permeability of various species after drying and found that the permeability of sapwood is considerably greater than that of heartwood (5, 13, 34, 39). Coté and Krahmer (13) report that the approximate ratio of the permeability of early sapwood to late heartwood was 34:1 for Douglas-fir, 10:1 for western hemlock, and 6.5:1 for western redcedar.

Coté and Krahmer (12, 13) concluded from electron microscopic studies of the pit membranes of softwoods that three mechanisms may be responsible for the decreased permeability of heartwood. These are pit aspiration, pit occlusion with extractives, and pit incrustation. Pit incrustations are defined as ligno-complex substances differentiated from extractives by their lack of solubility in organic solvents.
Considerable variations exist between the permeability of various species of wood. The only comprehensive study of the permeability of various species to date is that of Smith and Lee (41). Reporting on the measurements of nearly 100 species of wood, they found a range in permeability of 5 million to 1 in hardwoods and a range of one-tenth that value for softwoods. Considerable variation was found within each species as well. Others (33, 34) also present information on the permeability of several hardwood and softwood species.

Springwood and summerwood are substantially different in many respects and yet there is conflicting evidence on which is more permeable. Rak (36) reports that beech springwood is on the average 15 times more permeable than summerwood. Erickson et al. (21) discovered that in heartwood, springwood is more permeable radially than summerwood, whereas in sapwood, the differences between the permeability of springwood and summerwood are not significant. Buro and Buro (8) report that springwood and summerwood permeability of pine were not consistently different. Osnach (34) found that in Canadian aspen the springwood was more permeable than the summerwood, whereas the converse was true in pine. Thomas and Scheld (46) have shown that in eastern hemlock, there are about three times as many pits on the springwood fibers as on the summerwood, and consequently springwood would be expected to be more permeable than summerwood.

Permeability also varies within trees (5, 8, 39), between trees (5, 19), and between geographic locations (14, 20, 28) in many instances. This brings about considerable difficulty in characterizing the permeability of a species, and accurate data for a given species would probably require extensive sampling.

**Effect of Drying**

One of the reasons for studying the permeability of green wood is our lack of understanding of what happens to the permeability of wood when it dries. Erickson and Crawford (19) found that the permeability of Douglas-fir and western hemlock sapwood was reduced after drying to 1 to 3 percent of the value of the green wood. They found that when the water was replaced with organic solvents of low surface tension before drying, the permeability after drying was the same as the green wood. The decreased permeability was attributed to aspiration of the pits, which did not occur when the organic solvents were evaporated from the wood. The permeability of heartwood was not measurably affected by drying.

Phillips (35) found that pit closure occurs gradually with loss of moisture down to the fiber saturation point, and at this point, nearly all of the springwood pits become aspirated, while a certain portion of the summerwood pits do not become aspirated. He found that aspiration was prevented when water was replaced by alcohol before drying.

Wardrop and Davies (47), while investigating the penetration of water into dried softwoods, found the presence of an alcohol-ether soluble fraction which appears to be a fatty substance. Drying of the wood made this fraction less soluble, indicating that the material underwent some type of fixation. If such a fatty material occurs in wood, this could greatly impede the flow of water, by presenting hydrophobic surfaces in the wood on which gas bubbles could form and block the flow channels.

### Table 2. - AVERAGE HEARTWOOD AND SAPWOOD PERMEABILITY FOR THREE EASTERN HEMLOCK TREES

<table>
<thead>
<tr>
<th>Tree No.</th>
<th>Sapwood (Darcys)</th>
<th>Heartwood (Darcys)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree I</td>
<td>3.52</td>
<td>0.0435</td>
</tr>
<tr>
<td>Tree II</td>
<td>5.98</td>
<td>.0378</td>
</tr>
<tr>
<td>Tree III</td>
<td>7.00</td>
<td>.1276</td>
</tr>
</tbody>
</table>

**Possibilities of Increasing Permeability**

A question of great practical importance is what can be done to increase the permeability of wood. There are three principal methods which have been used to date to increase permeability. These are steaming, extraction, and micro-organisms.

Steaming is of course the simplest of these methods and perhaps has the greatest potential for industrial use. Steaming has already found

### Table 3. - ANALYSIS OF VARIANCE FOR SAPWOOD PERMEABILITY WITHIN AND BETWEEN TREES

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Mean squares</th>
<th>Expected mean squares</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td>1022.286</td>
<td>2</td>
<td>51.7643</td>
<td>28.541</td>
<td></td>
</tr>
<tr>
<td>Heights</td>
<td>67.8776</td>
<td>1</td>
<td>67.8776</td>
<td>67.8776</td>
<td></td>
</tr>
<tr>
<td>Quadrants</td>
<td>1.6280</td>
<td>1</td>
<td>1.6280</td>
<td>1.6280</td>
<td></td>
</tr>
<tr>
<td>Radiants</td>
<td>120.3333</td>
<td>1</td>
<td>120.3333</td>
<td>66.951</td>
<td></td>
</tr>
<tr>
<td>R X Q</td>
<td>.2269</td>
<td>1</td>
<td>.2269</td>
<td>.2269</td>
<td></td>
</tr>
<tr>
<td>H X Q</td>
<td>16.6381</td>
<td>1</td>
<td>16.6381</td>
<td>16.6381</td>
<td></td>
</tr>
<tr>
<td>H X R</td>
<td>2.0000</td>
<td>1</td>
<td>2.0000</td>
<td>2.0000</td>
<td></td>
</tr>
<tr>
<td>H X Q X R</td>
<td>1.5408</td>
<td>1</td>
<td>1.5408</td>
<td>1.5408</td>
<td>.86</td>
</tr>
<tr>
<td>Error</td>
<td>25.1494</td>
<td>14</td>
<td>1.7964</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duplicates</td>
<td>11.1335</td>
<td>24</td>
<td>.4647</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. total</td>
<td>249.0853</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Significant at the 99.9 percent level.
2Significant at the 99 percent level.

### Table 4. - ANALYSIS OF VARIANCE FOR HEARTWOOD PERMEABILITY VARIATION WITHIN AND BETWEEN TREES

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of squares</th>
<th>Degrees of freedom</th>
<th>Mean squares</th>
<th>Expected mean squares</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td>0.080973</td>
<td>2</td>
<td>0.040486</td>
<td>2.792</td>
<td></td>
</tr>
<tr>
<td>C. total</td>
<td>249.325</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Significant at 90 percent level.
practical application in Australia as a means of reducing the drying time and improving wood quality (9) for certain eucalyptus species. Ellwood and Erickson (17) reported substantial reductions in both kiln drying and air drying times for redwood can be achieved by a four-hour steaming treatment. With regard to permeability, Erickson and Crawford (19) found that steaming had no effect on the permeability of green sapwood, but that steamed sapwood retained a much higher permeability after drying than sapwood which was not steamed. Benvenuti (5) discovered that the permeability of steamed loblolly pine is 30 times greater than unsteamed material. Whether there is, in fact, an increase in permeability or whether the steamed material merely retains its green permeability, as suggested previously, remains unanswered.

Extractions have been carried out with various solvents and the result is invariably an increase in permeability of the material (5, 16, 38, 39). The increases have ranged from only very slight changes to as high as 10,000-fold. The degree of increase obtained is probably dependent on the mechanism of permeability reduction associated with heartwood formation as discussed by Krahmer and Coté (29).

The influence of micro-organisms on permeability has been investigated to a very limited extent and most observations are qualitative rather than quantitative. Lindgren and Harvey (31) found that infection by the green mold, *Trichoderma*, results in a great increase in permeability of pine, due to breakdown of the ray parenchyma. Ellwood and Ecklund (15) and others (1, 23, 27) observed similar increases believed due to bacteria in mill storage ponds. Knuth (26) investigated the action of bacteria in wood and found that many bacteria attack the pit membrane preferentially, consequently increasing permeability.

**Material and Apparatus**

The material used in this study of permeability was all eastern hemlock *Tsuga canadensis* (L) Carr. Three trees were selected from M nominee County, Wisconsin and disks were taken from each of these trees at 2-, 11-, 20-, and 38-foot heights. Table 1 gives the age, height, and stump diameter for each of the three trees.

The material was cut in February while the wood was frozen, and it was stored in the frozen condition at 0° F. until used. There were no obvious changes in permeability during a storage period of several months.

The experimental apparatus which is shown in Figure 1 is very similar to that used by Kelso et al. (25). The water storage tanks are of double tough Pyrex glass pipe, which are suitable for pressures up to 100 pounds per square inch when protected. Tubing is 1/4-inch nylon with nylon fittings; valves are of stainless steel or polyvinyl chloride.

Two filters are used in the apparatus. The water is filtered into the apparatus through a 0.45 micron Millipore filter. The other filter through which the water passes before reaching the sample is a 10 milli-micron Millipore filter. Water temperature is regulated at 25° ±1° C. by passing it through a water bath regulated at 25° ±1° C. before it enters the specimen.

The sample is held in a cell constructed of 1-inch-thick plexiglas. The specimen is sealed between two half-cells by applying pressure with four 1/4-inch brass bolts. A circular hole 3/8-inch in diameter in each half-cell provided a flow area of 0.95 square centimeter. Figure 2 shows the specimen holder.

Rate of flow through the samples was measured in one of four rotameters, which were calibrated to ± 1 percent of full-scale accuracy.

Pressure was applied to the water in the storage tanks using nitrogen gas. Pressure for the heartwood experiments was regulated with a standard pressure regulator on the nitrogen tank. Pressures used with sapwood were controlled by controlling the height of a water column with a float which acted as part of the regulating system. Pressure was measured with a differential water manometer for sapwood and a dial bourdon tube test gage for heartwood. The test gage was dead weight calibrated accurate to 1/10 pound per square inch. The water manometer was accurate ± 1 millimeter water.

Water used in the experiments was freshly distilled and partially deaerated by subjecting it to mechanical shock under vacuum for at least 15 minutes prior to making any permeability measurements.

The specimens used were roughly 25 millimeters square in cross section by 9 millimeters in the fiber direction. The transverse cuts were made using a hollow-ground saw. This gave a very smooth surface which permitted adequate sealing of the specimens in the specimen holder. This was quite important since any roughness of the surface would spread the liquid at the wood-cell interface and increase the effective area of flow.

Some of the experiments were run with specimens that were saturated with water. Others were run with specimens in which no attempt was made to saturate the specimens with water. The specimens to be saturated were evacuated in absence of water for 2 to 3 hours. Then water that had been distilled, filtered, and boiled was let onto them under vacuum. Although some water was evaporated...
from the specimens during the evacuation procedure, they retained their green condition. Specimens were essentially saturated within 1 hour after the vacuum was released. However, determining whether saturation is complete is difficult since small air bubbles remaining in some pit chambers could pass undetected.

Results

As discussed earlier, most research on the flow of liquids through wood have encountered a decreasing rate of flow. Darcy's Law requires not only that flow rate be constant, but that the rate of flow be directly proportional to pressure and the same when the direction of flow is reversed.

The results presented in this study have met the first requirement of a constant rate of flow for both heartwood and sapwood, and with sapwood, success has been obtained in meeting the other two requirements. Figure 3 is a plot of the permeability of a sapwood specimen as a function of time for several pressures and directions of flow. On the first reversal of direction, there is a slight increase in permeability. The initial increase is characteristic, but subsequent reversals have no influence on the permeability. The permeability does not change with time and it is independent of the pressure drop across the specimen. These results provide a basis for stating that the values measured for sapwood are the true permeability of the wood and not an artifact of the wood-water-air system.

Results with heartwood have not been as satisfactory as with sapwood. A constant rate of flow has been achieved almost invariably, but it is usually preceded by an increase in flow rate with time. The relationship between flow rate and pressure has not been linear, and there are some differences in flow in the two opposite directions. The effect of pressure on permeability for two specimens is shown in Figure 4. As pressure is increased, the permeability increases, and approaches a constant value. This is similar to the findings of Kelso et al. (25) for air-dried Sitka spruce. In their investigations, however, the specimens did reach a constant value of permeability and at a much lower pressure than that used here, probably because their material had much higher permeability, making it easier to flush out or dissolve air bubbles from the specimen. The values of permeability for heartwood reported here are not considered true values of permeability, but are a reflection of the wood-water-air system. It will be shown later that these values are reproducible.

At pressures below about 3 atmospheres, specimens which were saturated with water prior to measurement had a higher apparent permeability than those which were not saturated. At pressures in excess of 4 atmospheres, however, no significant differences were observed between saturated and unsaturated specimens.

The effect of reversal of direction of flow in heartwood is shown in Figure 5. Reversing the flow gradually increased the apparent permeability. This was not always the case, however, and in some instances the permeability rose to a maximum after several reversals and began to decrease slightly on successive reversals. The difference in the two directions was in some cases very slight.

The permeability data obtained for heartwood and sapwood are summarized in Table 2. Data presented are the average values for each of the three trees, each value being an average of 16 specimens. Sapwood permeability averaged about 100 times greater than heartwood.

Sapwood Variability

Four variables were considered in this experiment. These were trees, heights in trees, radial location, and quadrant. Three trees were used and two levels of each of the other variables were considered. Heights were 2 and 38 feet, the two radial locations were innermost and outermost, and the north and south quadrants were considered. Two observations with end-matched specimens were made for each set of conditions. Table 3 gives the analysis of variance for this experiment. Differences in permeability associated with trees, heights, and radial locations are all significant at the 99.9 percent level. Radial location appears to be the most important variable. The height by quadrant interaction is also highly significant. This means that the effect of height is different in the north and south quadrants.

Some indication of the degree of reproducibility is given by the duplicate mean square in Table 3. This is the variability in permeability between duplicates in the sapwood experiment and includes the experimental error as well as the variability between pieces end-matched along the grain. Of particular significance is the fact that the variation between duplicates is quite small compared to the normal variation in permeability. From this, it can be inferred that the technique is satisfactory, because random variation in permeability is much greater than that due to the technique of measuring and matching specimens. The standard deviation for end-matched samples is 0.68 Darcy. The mean value for sapwood is 5.5 Darcys, which gives a coefficient of variation of 12.4 percent.

Figures 6 and 7 demonstrate graphically the pattern of variations associated with heights, radial location, and trees. Figure 6 shows the difference between inner and outer sap-
Table 6. - EFFECT OF TREATMENTS ON THE PERMEABILITY OF HEARTWOOD

<table>
<thead>
<tr>
<th>Location of heartwood</th>
<th>Control</th>
<th>Steamed</th>
<th>Extracted Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K (Darcys)</td>
<td>K (Darcys)</td>
<td>K (Darcys)</td>
</tr>
<tr>
<td>11 feet</td>
<td>0.043</td>
<td>0.095</td>
<td>0.084</td>
</tr>
<tr>
<td>Tree I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 feet</td>
<td>.050</td>
<td>.081</td>
<td>.063</td>
</tr>
<tr>
<td>11 feet</td>
<td>.039</td>
<td>.066</td>
<td>.066</td>
</tr>
<tr>
<td>Tree II</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 feet</td>
<td>.038</td>
<td>.078</td>
<td>.033</td>
</tr>
<tr>
<td>11 feet</td>
<td>.109</td>
<td>.195</td>
<td>.156</td>
</tr>
<tr>
<td>Tree III</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 feet</td>
<td>.124</td>
<td>.232</td>
<td>.200</td>
</tr>
<tr>
<td>Average</td>
<td>.0672</td>
<td>.1237</td>
<td>.1003</td>
</tr>
</tbody>
</table>

Table 7. - CORRELATION COEFFICIENTS OF SOME PHYSICAL PROPERTIES WITH PERMEABILITY

<table>
<thead>
<tr>
<th>Physical property</th>
<th>Heartwood(^a)</th>
<th>Sapwood(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log K</td>
<td>0.292(^b)</td>
<td>0.319(^b)</td>
</tr>
<tr>
<td>K</td>
<td>0.312(^b)</td>
<td>0.273(^b)</td>
</tr>
<tr>
<td>Percent summerwood</td>
<td>0.382(^b)</td>
<td>0.436(^b)</td>
</tr>
<tr>
<td>Rings per centimeter</td>
<td>0.333(^b)</td>
<td>0.352(^b)</td>
</tr>
</tbody>
</table>

\(^a\)Based on 51 samples.
\(^b\)Based on 24 samples.
\(^c\)Significant at 95 percent level.
\(^d\)Significant at 97.5 percent level.
\(^e\)Significant at 99 percent level.
\(^f\)Not significant.

Heartwood for each tree and for each height. Without exception, the outer sapwood is considerably more permeable. This is in agreement with the findings of Benvenuti (5) for the permeability of loblolly pine determined with nitrogen gas. On the other hand, Krahmer and Coté (29) found that the sapwood permeability of western hemlock and western redcedar did not change perceptibly from the bark inward, while Douglas-fir showed a trend similar to that exhibited here for eastern hemlock.

The way in which permeability changes between quadrants at two different heights can be seen in Figure 6. At 38 feet the south quadrant is always more permeable than the north quadrant, whereas at 2 feet the converse is true. The reason for this is not known. The difference between quadrants is small compared with the main effects of heights and radial locations and will not be considered further here.

Permeability as affected by height averaged for radial location and quadrant is given in Figure 7. Permeability very definitely increases with height in the tree.

Heartwood Variability

The permeability of heartwood did not show much of the systematic pattern of variability that occurred in sapwood. An experiment of the same design used for sapwood was conducted with the result that only two variables were significant at the 90 percent level, as shown in Table 4. These were trees and radial locations. Figure 8 shows the effect of radial location on permeability at tree heights of 2 and 38 feet. In most cases, the outer heartwood was more permeable than the inner heartwood, but in several cases the difference was very small, and in one case the inner heartwood was more permeable.

One of the reasons that these variables are not more highly significant is the fact that the change in permeability with height is not consistent from tree to tree. As shown in Figure 9, trees II and III show a decrease in permeability with height, but tree I shows an increase. This interaction is included in the error term and, as a consequence, magnifies it considerably. Other variables also differ from tree to tree, and as a consequence the error term is much larger than the experimental error, which is shown as duplicates in Table 4.

It is evident from this experiment that substantial variation in the permeability of heartwood exists both within and between trees, but the variation appears to occur somewhat...
trees nor radial locations are significant in this analysis, which is probably due to the inconsistent effect of radial location from tree to tree. As shown in Figure 10, there is a definite decrease in permeability with distance from the heartwood-sapwood interface in tree III, whereas in trees I and II, there is no such trend. On the other hand, the effect of treatments on permeability is highly significant.

An experiment similar to the previous one was carried out on material at 20-foot heights. In this case, however, three radial locations were sampled from tree II, four from tree I, and five from tree III. The presence of shake near the pith of trees I and II caused insufficient width of sound heartwood to obtain five locations in each tree. The result at the 20-foot height along with those obtained at 11 feet are given in Table 6, which shows that the effect of both steaming and extracting on permeability is fairly uniform from tree to tree. Steaming appears to be somewhat more effective in increasing permeability than extraction, although the difference is not statistically significant.

Correlation with Other Properties
To determine whether permeability is correlated with other properties of the wood, several other physical properties were measured on end-matched specimens. The properties which were measured were green moisture content, specific gravity, percent summerwood, and growth rate. Least squares regressions were then run to determine whether any of these properties were correlated with permeability. Heartwood and sapwood were, of course, separated because of their large difference in permeability. Least squares regressions were determined both with permeability and the logarithm of permeability.

Table 7 gives the correlation coefficients between permeability and each of the properties measured for heartwood and sapwood. The only significant relationship with sapwood was with green moisture content. The relationship is shown graphically in Figure 11. There is considerable variation about the regression line, but the trend is for permeability to increase with increasing moisture content.

In heartwood, both specific gravity and percent summerwood were significantly related to permeability at the 99 percent level, although the correlation coefficients are quite low. Specific gravity was most highly correlated with the log of permeability, whereas the linear relationship was more significant with percent summerwood. The individual values are plotted in Figures 12 and 13, which indicate that permeability decreases with increases in either percent summerwood or specific gravity.

Conclusions
A technique has been developed for measuring the permeability of green wood with water which gives a true value of sapwood permeability and a reproducible, but not absolute, value of heartwood permeability. Constant rates of flow of water with time were observed consistently with sapwood, and constant or increasing rates of flow were obtained with heartwood.

The permeability of eastern hemlock sapwood is about 100 times greater than heartwood.

In sapwood, permeability decreases with distance from the bark and increases with height in the tree. Significant differences in permeability were found between trees.

The permeability of sapwood is significantly correlated with green moisture content.

In the heartwood, variations in permeability were observed, but there was little systematic variation with height, radial location, or quadrants. Heartwood permeability is significantly correlated with density and percent summerwood, but the correlation coefficients are quite low.

Both steaming and benzene-alcohol extraction approximately doubled the permeability of heartwood.

Literature Cited


