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INTRODUCTION

The rate of movement of water through wood is directly dependent upon its porosity and permeability. Porosity is an expression of the amount of voids while permeability is determined by the frequency and size of the inter connections between the voids. Thus a wood may be relatively porous but have a low permeability to gases and liquids because of limitations in interconnections. In the swollen condition the interconnections between permanent voids (fiber cavities) consist of the transient capillaries within the cell walls and the pit structure in which the cell wall thins to a minutely perforated membrane. On drying to fiber saturation point, the transient capillaries begin to close and in the oven-dry condition are completely closed. The behavior and nature of the pit membrane on drying is still a matter for conjecture, but available evidence indicates that the perforations in pit membranes may open slightly more on drying below the fiber saturation point. With respect to the problem of increasing drying rates, the resistance of the pit membranes to moisture movement is the main obstacle.

Differences in permeability between woods of similar specific gravity (or porosity) are essentially due to the nature of the interconnecting paths. Thus it is well known that with most woods, heartwood is substantially less permeable than sapwood. Again the precise reasons for this have not been proven but there is the obvious suggestion that the deposition of extractives might play a part in partially blocking the fine structure as well as blocking cell cavities. Then too, it is possible that changes may occur during heartwood formation in the pit membrane rendering it less permeable. In hardwoods it has long been known that tyloses or gum deposits in the vessels substantially reduce permeability. In softwoods, particularly Douglas fir, aspiration, or sealing off the pits by displacement of the thickened torus before or during drying has been described as the major cause of reduced permeability. Particularly impervious woods, if certain other conditions are fulfilled are also prone to collapse during drying.

With the thought that it may be possible to increase the permeability of wood prior to drying, or perhaps during drying, and thus reduce overall drying times and minimize collapse, some investigations were begun at the University of California on the nature of wood permeability, particularly with respect to the influence of extractives.

The role of extractives in wood permeability

It is generally recognized in the redwood industry that heavy segregation lumber (i.e.,high moisture content containing material) is mainly found in the butt logs. This material is relatively slow to dry and if high drying temperatures are used to accelerate drying, then collapse can and does occur. It is also known that in the outer part of the heartwood in butt logs the amount of extractives is greater than in any other part of the tree.

In the case of incense cedar, the difficult to dry and collapse susceptible wood usually has a darker distinctive color due to heavy concentration of extractives. The category of western red cedar, known as "leopard wood" because of the color resulting from extractives in the wood, is also relatively slow to dry and susceptible to collapse. Similarly with certain pines, high contents of resin in the heartwood also slow drying. The question therefore raised, at least for some woods, is: does not permeability depend largely upon the amount and location of wood extractives? There is, some evidence to indicate that this may be so.

In the summer of 1958 exploratory work was begun at the Laboratory on permeability studies. The permeability to water of sapwood and heartwood of five species; namely, ponderosa and sugar pines, madrone, California black oak, and redwood were measured by Ellis(1). The permeability of the species decreased in the order listed. It was further found that their transverse permeability was greatest in the green condition as expected. Vacuum treatment of partially dry specimens tended to increase their permeability, while prolonged soaking in water prior to testing decreased their permeability.

In the following year Skaar (2) obtained data on the longitudinal permeability of incense cedar to air and found that extraction of relatively impervious incense cedar with hot water increased the permeability about 1000-fold whereas extraction with ethanol increased permeability 10,000-fold.

Besides increasing wood permeability by means of extractive removal the question also arises as to what can be done by means of simple physical treatments to perhaps change the nature of the extractives in wood or cause some relocation of their position. Recently some interesting drying results were obtained in the Laboratory, following steaming green lumber at 212°F. under saturated conditions which may be related to the influence of extractives. During work on stain control in heavy segregation California redwood it was found that, under laboratory conditions, kiln drying time for 1" thick boards was reduced by approximately 25 per cent. (See Fig.1) Further, the accelerated rate of moisture loss in the steamed material was only pronounced above the fiber saturation point indicating that probably the permeability, as it affects "free" water and moisture through pits movement, had been increased. Similar reductions of drying time have been reported recently by the Australian Forest Products Laboratory and in that country presteaming has been adopted as a commercial practice for certain hardwoods. Much more work has to be done in this area to determine why heat treatment causes this accelerated drying rate.

Experimental

(a) Procedure

To further evaluate the effect of extractive removal and heat treatment on longitudinal permeability, tests were done on two hardwoods (California black oak and madrone) and on one softwood (California redwood).

The permeability of the hardwoods was measured at 12 per cent moisture content using air, while the permeability of redwood was measured in the oven dry condition using nitrogen.

Permeability was expressed as ccs/sec cm^2 atmos/cm obtained from Darcy's law for streamline flow through a porous medium.

$$Q = \frac{K_a A}{L\,(P_1 - P_2)} \qquad \text{.................. (1)}$$

where A = cross sectional area of flow
L = length of specimen
P_1 = pressure at inlet
P_2 = pressure at outlet
K_a = permeability of wood to gas or vapor
Q = amount of air flow at mean pressure $\frac{P_1 + P_2}{2}$

The flow rates used in the experiment were determined to be in the streamline zone by ascertaining that the rate of flow was directly proportional to the pressure drop through the specimen as required to satisfy Darcy's Law.

The particular method used of expressing permeability has advantage as it enables comparisons to be readily made with other data such as the wood permeability survey made by Smith and Lee (3) who used this expression.

The specimens used were dowels 1 cm. along the grain and with 1 sq. cm. of cross section exposed for flow measurement. The specimens were cut from green cants, and treated as follows:

For the hardwoods a group of 3 specimen replications were used for each species for each of the following treatments: 1) kiln dried controls; 2) steam treatment in the green condition at 212°F. for 4 hours under saturated conditions; 3) replacement of water with n-propyl alcohol; 4) replacement of water with cellosolve, and 5) extraction with ethyl alcohol and benzene. All extractions and replacements were made on the specimens after they had been conditioned to 12 per cent moisture content. After treatment all specimens were conditioned to 12 per cent moisture content for permeability measurements.

For the redwood, six specimens from each of 4 logs were allocated to each treatment: 1) kiln dried controls; 2) extraction with hot water; 3) extraction with hot water followed by ethyl alcohol; and 4) steam treatment in the green condition at 212° F. under saturated conditions.

After extraction and heat treatment all specimens were kiln dried to 20 per cent moisture content at 110° F. and then oven dried at 220°F.

Air permeability measurements on the hardwoods were made by applying a vacuum to one end of the specimen which was sealed in a rubber tube and measuring the rate of water displacement in a graduated tube caused by the air flowing through the specimen.

Permeability of the redwood to nitrogen was obtained by passing nitrogen from a pressure bottle through a pressure regulating system connected to the specimen. Flow was measured with a flowmeter. A diagramatic view of the flow system is shown in Fig. 2.

(b) Results

Table 1 shows the air permeability coefficients (Ka) of California black oak and madrone according to the treatment used. All treatments increased permeability, extraction with ethyl alcohol and benzene being most effective resulting in 625-fold and 4-fold increases for black oak and madrone, respectively. The extracted and water replaced samples also contained residual amounts of the organic liquids used for extraction which would tend to reduce air flow through the specimens. Therefore the increase in permeability shown must be regarded as conservative. Heat treatment in the green condition was most effective for the California black oak, the specimens of which were particularly "impervious", causing a 20 fold increase in permeability.

Statistical analysis of the hardwood data showed that heat extraction and water replacement all resulted in significantly higher permeability with California black oak while for madrone although heat treatment showed a higher permeability only the extraction treatments were statistically different.

The nitrogen permeability coefficients (k_n) of California redwood (table 2) shows that again although heat treatment in most instances increased permeability, the most effective treatment was extraction with hot water. All treatments produced statistically greater permeability coefficients than those of the controls except the alcohol extracted and heat treatment on specimens from log 2 and the heat treatment on specimens from log 4. The relatively lower values of the water-ethanol extracted specimens were increased after steam distillation as a result of removal of the residual alcohol. The final value did not attain that for the water extracted specimens as somewhat less water soluble extractive was removed in the water-ethanol extracted specimens. For convenience in interpreting the differences between treatments Table 3 shows the relative percentage effectiveness of the treatments. No good correlation exists between the permeability of the specimens and the extractive contents determined from the cant from which the specimens were cut.

(c) Discussion

In hardwoods the condition of the vessels with respect to the presence of tyloses and/or extractive deposits determine longitudinal permeability. Tyloses, which occur in black oak, are actually proliferations of cell wall material and it is not expected that they would be affected by the treatments done in the present tests. Because of the nature of hardwood pits, blocking of pit membranes by aspiration as in the softwoods, does not occur. It is therefore most probable that extractives removed from the vessels in the extraction process were responsible for the increased permeability although removal of extractives in the pit areas cannot be discounted because the relatively low overall permeability suggests that the vessels were almost completely blocked. Comparatively little can be said on the reason why heat treatment affected permeability until this aspect is studied more thoroughly. However, the possibilities do exist that the pit membranes could be reptured somewhat by the treatment or that there may be some relocation of extractives in critical areas. Also heat treatment may render certain extractive components insoluble so that their migration and subsequent deposition in and around pits in the zone of evaporation is prevented. In certain woods heat treatment may volatilize extractives. Whatever the cause, the increase in permeability as a result of heat treatment does provide some basis for expectations of an effect on drying rate.

Considering redwood permeability to nitrogen, the influence of the organic liquids used for extraction on pit aspiration needs to be separated from their effect of removing extractives. Recently Erickson and Crawford (4) made some interesting experiments on the permeability to water of Douglas fir and western hemlock sapwood before and after several different methods of seasoning. All permeability measurements on dried specimens made by Erickson and Crawford were done after the specimens had been soaked back to the green condition. Bearing in mind that the sapwood of these two species contains comparatively little extractive, these workers showed that air drying reduced specimen permeability to water to approximately 1.1-2.7 percent of that in the green condition. The decrease in permeability was essentially due to aspiration of pits during drying as had been pointed out by previous workers. On the other hand, when green sapwood specimens were solvent dried using alcohol or acetone the permeability decreased very little or even increased compared to the permeability of specimens in the green condition. The authors ascribed this behavior to prevention of pit aspiration by the solvents. Data from previous workers and microscopical examination of several specimens supported this contention.

In the present work on redwood, the fact that the hot water extracted specimens showed a higher permeability that those extracted by water and alcohol indicates that in redwood heartwood, reduction of pit aspiration by alcohol is not a major factor in changing permeability. The permeability behavior of the specimens indicates that water soluble, rather than water insoluble extractives, are primarily responsible for the change in permeability. Further work on the comparison between sapwood and heartwood extracted with water and organic solvents would clarify the point.

With respect to the increase in permeability as a result of heat treatment in the green condition, again no causes can be definitely assigned until this phase is further investigated. In addition to the possible ways that heat treatment may affect permeability as listed previously for the hardwoods, there is the additional possibility in softwoods, that pit aspiration may be influenced.

In the above studies, emphasis has been placed on the movement of fluids through pits and pit membranes which create the major resistance to rapid movement of fluids through wood. However, during drying, diffusion of bound moisture through the transient capillaries of the fiber walls accounts for some proportion of fluid movement through wood. As Stamm (5) has recently shown in moisture diffusion studies on redwood, the removal of extractives from the cell walls actually halves the rate of moisture diffusion within cell walls. This is because the extractives act as a bulking agent and create larger transient capillaries than expected from the moisture content of the wood. While in this instance removal of extractives may appear to be a retrograde step as far as drying rates are concerned it should be recognized that continuous bound water diffusion within the cell walls accounts only for a proportion of the total moisture movement. Both capillary flow of water and diffusion of water vapor occur through pits. If the removal of extractives also substantially increased the effective openings through pits, it is expected that the increased rate of moisture movement resulting would substantially outweigh the reduced rate of movement of bound water through the cell walls. The particular benefits of increased drying rate resulting from more effective pit permeability would be most pronounced above the fiber saturation point where liquid flow is operative and also at higher drying temperatures because of the greater importance of vapor diffusion.

Significance of Permeability Studies in Drying

Many questions are left unanswered in attempting to predict changes in drying rates that might be expected from changes in wood permeability detected from longitudinal fluid flow studies. It is well recognized that the lumber drying problem is concerned mainly with moisture movement across the grain in which direction permeability is much less than along the grain. However the same pits are effective for both transverse and longitudinal fluid movement. Longitudinal measurements have some experimental advantages in ease of evaluation of pit behavior. Good techniques for evaluating across the grain permeability must be developed and changes in permeability in both grain directions correlated with changes in drying rates. Present information indicates that pit permeability may have to be increased manyfold to significantly affect drying rates (6). Also the relation of gas to liquid permeability must be evaluated.

At this stage sufficient information is available from permeability studies to indicate some possibilities of significantly increasing drying rate. Concurrent advantages may also be reduction of the occurrence of wetspots, the extent of case hardening type stresses and drying degrade.

Pit aspiration in softwoods can be reduced or prevented by means of certain organic liquids. It is probable that the reduced pit aspiration caused by drying from organic liquids is due to the lower surface tension of the liquids compared to water. The relatively rapid drying rates obtained in solvent seasoning are no doubt related to this.

Removal of extractives, at least in some woods, increase permeability to the extent that an increase in drying rate might be expected. Depending upon the species of wood concerned the extractives may be mainly water soluble or insoluble. Advantage of this may also be taken in solvent seasoning by using water together with the solvent in the extraction phase.

Presteaming treatment of specimens in the green condition was shown to have some effect on permeability, at least on some woods, which indicates that an improvement in drying rate might be expected. The effect of other treatments prior to drying (including log or lumber storage conditions) are also suggested for study.

Table 1.- LONGITUDINAL PERMEABILITY TO AIR AT 12 PER CENT MOISTURE CONTENT OF CALIFORNIA BLACK OAK AND MADRONE (ccs/sec cm^2 atm/cm).

Species	Untreated control	Treatments: Presteamed at 212° F.	Propyl alcohol replacement	Cellosolve replacement	Ethyl alcohol and benzene extraction
California black oak	0.02	0.40	7.0	11.9	12.5
Madrone	70.0	91.4	132.7	171.0	293.1

Table 2.- LONGITUDINAL PERMEABILITY TO NITROGEN AT OVEN DRY CONDITIONS OF CALIFORNIA REDWOOD (ccs/sec cm^2 atm/cm)

Log	Extractive content of original cant	Untreated control	Treatments: Presteamed at 212° F.	Hot water extraction	Water and Ethyl alcohol extraction
1	16	136.0	182.0	238.7	159.5 (198.0) 1/
2	25	181.0	174.1	330.9	180.2 (227.2)
3	32	257.9	341.6	452.5	369.3 (445.9)
4	34	155.4	175.9	377.3	255.6 (339.1)

1/ Note: Figures in parenthesis are values obtained after steam distillation of the dried specimens to remove residual alcohol.

Fig. 1

DRYING RATES OF 1" THICK PRESTEAMED AND UNTREATED REDWOOD DURING KILN DRYING

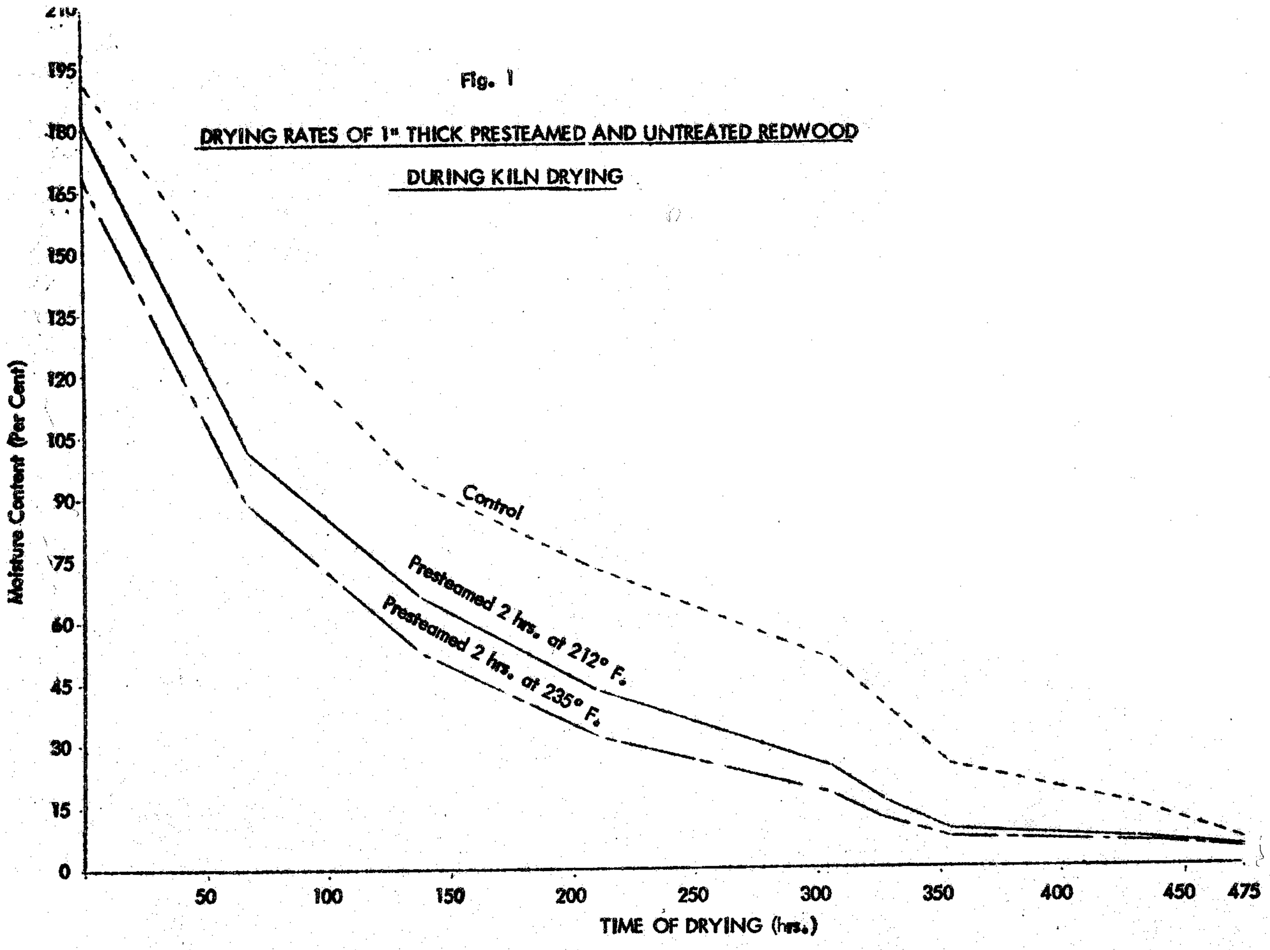

Fig. 2

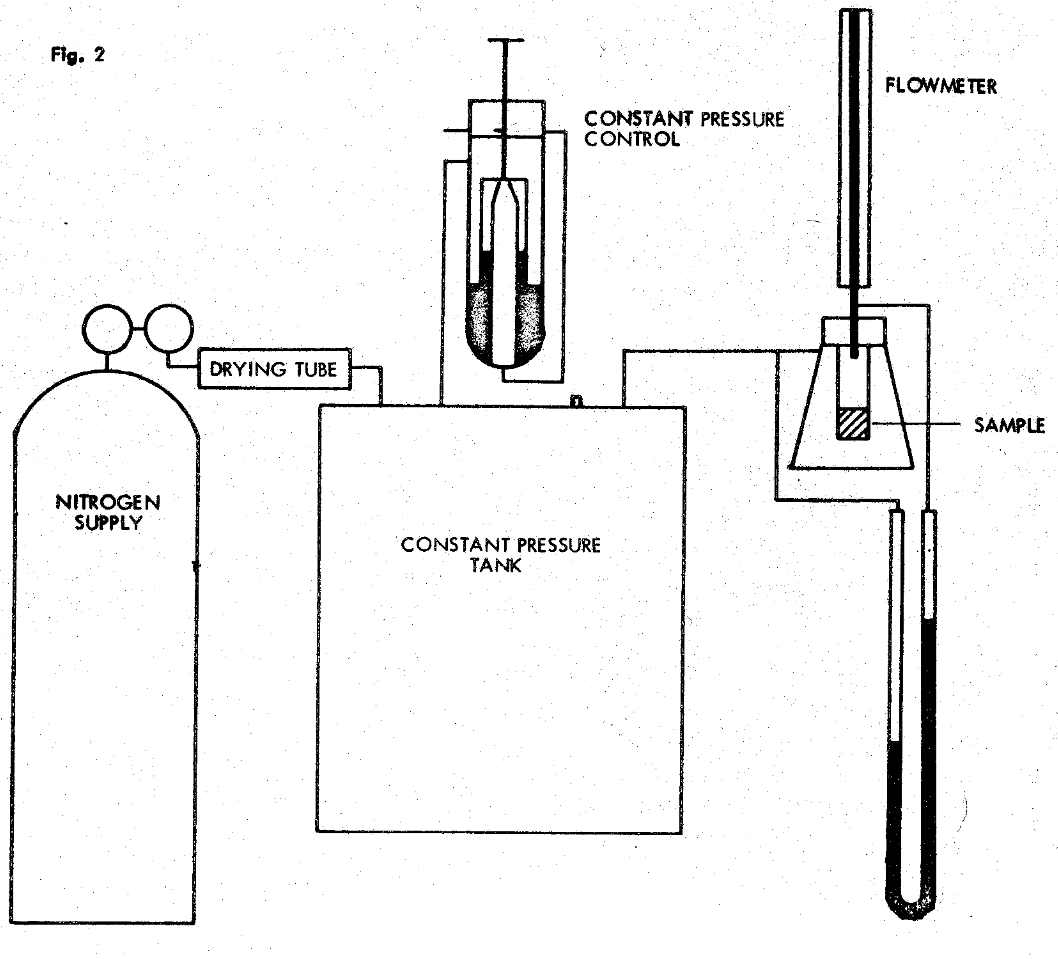

Table 3. - RELATIVE PER CENT EFFECTIVENESS OF TREATMENTS ON LONGITUDINAL PERMEABILITY TO NITROGEN OF CALIFORNIA REDWOOD COMPARED TO UNTREATED CONTROLS.

Log	Untreated control	Presteamed at 212° F.	Hot water extraction	Water and Ethyl alcohol extraction
1	100	134.0	175.5	117.3 (145.6) 1/
2	100	96.1	182.7	99.5 (125.5)
3	100	132.5	175.5	143.2 (172.9)
4	100	113.2	242.8	164.5 (218.2)
Mean	100	118.9	194.1	131.1 (165.5)

1/ Note: Figures in parenthesis are values obtained after steam distillation of the dried specimens to remove residual alcohol.

References

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