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Effect of permeability on primary processing of wood

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Abstract
Wood, being hygroscopic in nature, its permeability affects the flow of liquid and gases. Permeability defines the ease of flow of fluid due to a pressure gradient. Various methods like falling water displacement method, rota meter method, etc. have been employed in measuring the variable traits of permeability. In wood, it depends upon the effectiveness of interconnecting capillaries such as pit, pores which constrict the passage from one cell cavity to the other. The size of openings connecting the wood cells determines the degree of permeability. Permeability is a function of porosity which in turn is dependent on the wood species. It varies with respect to the type of wood species i.e. hardwood and soft wood as well as in different directions within the wood. It can be altered by ponding, steaming, heat treatments, chemical treatments etc. Permeability is an integral part in determining the longevity influencing many other processes *viz.*, wood seasoning, preservatives treatment and pulping processes. Thus, its application in the field of wood science is justified.

Keywords: permeability, kiln seasoning, darcy's law, porosity, pulping, fibre saturation point (FSP)

Introduction

Wood has been used for thousands of years for fuel, as a construction material, for making tools and weapons, furniture and paper, and as a feedstock for the production of purified cellulose and its derivatives, such as cellophane and cellulose acetate. Wood is a porous and fibrous structural tissue found in the stems and roots of trees and other woody plants. It is an organic material; a natural composite of cellulose fibers that are strong in tension and embedded in a matrix of lignin that resists compression. Wood is sometimes defined as only the secondary xylem in the stems of trees (Hickey and King, 2001) [14]. In a living tree it performs a support function, enabling woody plants to grow large or to stand up by them. It also conveys water and nutrients between the leaves, other growing tissues, and the roots.

The moisture content of green wood is important because of its direct relation to the weight of logs and green lumber. When wood is dried all liquid water from the lumen comes out but the amount of water remains in the cell walls depend on the drying and the environment in which it is placed. The amount of water in wood or a wood product is usually expressed as the moisture content. The rate of flow of fluids through wood is highly affected by the presence of air or other gases. Moisture content (MC) is defined as the weight of the water expressed as a percentage of the moisture-free or oven-dry (OD) wood weight. Wood is a hygroscopic material with the ability to exchange water vapour with the surrounding air until it obtains moisture equilibrium with the air. Wood shrinks due to moisture loss, wood drying can be explain as the balance between heat transfer from air flow to wood surface and water transfer from wood surface to air. The point at which all the liquid water in the lumen has been removed but the cell wall is still saturated is termed the fiber saturation point (FSP). This is a critical level because below this point the properties of wood are altered by changes in moisture content (Shmulsky *et al.* 2011) [27]. The flow of liquid and gases through the porous media have been effect on the permeability of wood. The subject of permeability of wood has also mainly in physiological problem of sap conduction in plant, in pulping or in factors governing the drying of wood. Wood is complex biological material which is differentiated into hardwood and softwood. The hardwood have specialised structure called vessels which conduct sap upward. Vessels appear as holes and term as pores, the size shape and arrangement of pores are different according to species, but are relatively constant within the species. In the softwood sap passes through ray parenchyma cells through simple pits and tracheids. Bordered pits have their margin surrounded by the cell wall but function as passage for sap to move from one cell to other (Core *et al.* 1979) [10].

Permeability
Permeability is a measure of the ease of flow of fluid due to a pressure gradient. Permeability to liquid and gas is a property of wood that greatly influences its processing and its impregnation with preserving chemicals or its seasoning and conditioning for use as lumber (Walker, 2006) [34]. Evaluation of permeability will help to understand better the drying mechanism of wood above the fibre saturation point. The drying of wood results in high capillary forces as the moisture content decreases from the green condition to the fibre saturation point. Due to those forces, a large number of cell-wall pits become aspirated during drying which in turn reduce the permeability of wood (Ivaldo, 2005) [17].
Porosity is the fractional void volume of wood. This may be confused with permeability which refers to the ease with which fluids flow through wood, it depends on the condition of the pit and the opening of the void.

$$V_a = 1\text{-}V_w$$

V_a is the porosity and V_w is the volume fraction (calculated by the density of cell wall substance from helium displacement method 1.46) and the moisture content.

$$V_w = G\ (1/1.46{=}0.01M/G_s)$$

Here G = specific gravity of wood at moisture content M
G_s = specific gravity of bound water at moisture content M
The porosity can be calculated:

$$V_a = 1\text{-}G\ (0.685 + 0.01\ M/G_s)$$

Difference between permeability and porosity
Wood is highly porous but not a very permeable material. The void created primarily by fiber, vessels and capillaries together. If the cells are inter connected then air and water can escape when compressed and the material is porous and permeable, but where the cells are closed air or water can escape only by cell wall the materialis porous and impermeable. The size of openings connecting various wood cell determine the degree of permeability according to the poiseuille's law (Walker, 2006) [34].

$$Q = \Pi R^4 \Delta p/8\eta L \qquad \ldots (1)$$

Here Q is volume flow rate (cm^3/sec)
R is radius of capillary (cm)
ΔP is pressure difference (dyne/cm^2)
H is viscosity of fluid (dyne sec/cm^2)
Flow of fluid in wood is viscous, turbulent and molecular slip or Knudsen flows.
Viscous flow: It is a streamline flow which results from viscous forces during the flow and it is the property of both gases and liquids. In viscous flow the frictional force is proportional to the viscosity in accordance with Darcy's law.
Turbulent flow: When flow velocity increase laminar flow breaks down and disturbances occur which cause the friction force is proportional to the square of the velocity (Owoyemi, 2010) [26]. This flow is called turbulent flow. This flow is not likely in the lumens of tracheids and vessels in wood due to their relatively large diameter and resulting low flow velocities.
Molecular or Knudsen flow: It occurs in gases, when flow is viscous the velocity is zero at the wall of capillary and increase towards centre. The molecules of gas are able to move along the surface however resulting in a higher flow than Darcy's law.

Darcy's law for flow in wood
K = flux/gradient

$$= QL\eta\ /\ tA\Delta p \qquad \ldots (2)$$

Here K= permeability (darcy)
Q = flow rate of liquid through specimen (cm^3) = v/t
v=volume of liquid
t = time of flow (sec)
L= length of the specimen (cm)
A=cross sectional area of specimen
η = viscosity (centipose)
Darcy's law for gaseous flow in wood

$$K_g{=}vLP/\ tA\Delta p\ p \qquad \ldots (3)$$

Here K_g = superficial gas permeability
P= pressure (dyne/cm^2)
P= $\overline{p_1+p_2}/2$average pressure in specimen

Importance of permeability of wood
The variation on pressure permeability of wood is due to the variable structural of different species and the behaviour of wood substance with liquid and gases. The preservation and wood seasoning is the most important practices in wood science for the better product manufacture and this two operation is mainly depend on permeability of wood.

i) Wood seasoning
The basic principle of seasoning is the removal of remaining moisture from the wood by air seasoning or kiln seasoning. When dried below the fibre saturation point, wood becomes dimensionally unstable and its volume, area, and length become a function of its moisture content. This functional relationship is different along each of the three natural axes of wood. Tangential shrinkage is greatest. ranging from about 4 to 14 percent as wood dries from the green to the oven dry condition Comparable values for radial and longitudinal directions are 2 to 8 and 0.1 to 0.3 percent Respectively. Since in most of its uses will eventually come to equilibrium moisture content considerably less than the fibre saturation point (Eckelman, 1997) [11].

Air drying
Rate of drying largely depends on climatic conditions, and on the air movement. Air drying is the drying of timber by exposing it to the air. The technique of air drying consists mainly of making a stack of sawn timber (with the layers of boards separated by stickers) on raised foundations, in a clean, cool, dry and shady place.

Kiln seasoning
Artificial or oven drying consisting heat generated may be directly or by using natural gas and/or electricity or indirectly, through steam-heated heat exchangers, although solar energy is also possible.

ii) Wood pulping
The importance of proper chip impregnation in pulping has been accepted for many years. Numerous investigations have been conducted on the nature of penetration and the diffusion of gases into the wood. Researchers have noted a significant difference in permeability of coastal heartwood and mountain heartwood. Wood permeability is the significant variable in the process of pulping. Air or liquid permeability is related to

the process of penetrating pulp wood with cooking liquor (Noe, 1960) [25].

iii) Wood preservation: Wood preservatives are chemical substances that when suitably applied to wood, make it resistance to fungi, insect and woodborer. There are two general classes of wood preservatives: oils, such as creosote and petroleum solutions of pentachlorophenol; and waterborne salts that are applied as water solutions. The effectiveness of the preservatives varies greatly and can depend not only upon its composition and permeability, but also upon the quantity injected into the wood, the depth of penetration, and the conditions to which the treated material is exposed in service (Wood Preserving Industry Production Statistical Report, 1996) [2].

Flow of preservatives in wood

- Even if pressure is not used in a wood-preserving process, capillary suction creates a negative pressure or partial vacuum because of the narrow diameter of wood cell cavities, so some liquid chemicals will be absorbed.
- Air in wood cells can be compressed easily.
- Air (compressed or not) is an obstacle to full impregnation of wood with liquids.
- Rays and vessels in hardwoods and the fibre tracheids and rays in softwoods are the main routes for liquid flow into wood (*http://www.timber.lk*).

Permeability depends on direction

In transverse direction the rate of liquid flow in low permeable wood is extremely low and its measurement is difficult. Heartwood (redwood) is a material of extremely low permeability, particularly in directions across the grain. Permeability values for tangential and radial directions are about the same, while that along the grain is far greater. The presence of extractives in this wood is difficult to penetrate and their removal increases the permeability (Stamm, 1963) [31]. In Coniferous trees, water in sapwood is known to move longitudinally through the tracheid lumen, passing from one tracheid lumen to the next through the bordered pits. The same pathway is also used by preservative liquids when penetrating wood from a transverse surface. Both longitudinal and tangential flow paths in softwoods are predominantly by way of the bordered pits, when dried early wood bordered pits aspirate due to surface tension forces and permeability is reduced (Ellwood, 1957).

Measurement of permeability

The rate of flow through the wood is usually measured with a flow meter or rota meter.

If the permeability obtained in a thin sample and it is the representatives of thick sample then there is variation in the flow phenomenon in wood (Chong, 1974) [8].

By the flow meter the permeability can measured but as there is compressed gas is used in the system, provides chance for air introduction into the sample.

The experiment concluded that the absolute permeability of wood obtained from Darcy's law if the pressure gradient is constant. The flow rate is proportional to pressure gradient.

1. Falling water displacement method-Superficial air permeability was measured by a large aluminium water tank and a cylindrical glass column which is mounted on a wooden platform above the water tank (Siau, 1984) [29]. The glass column is connected to a vacuum pump and to the specimen holder by means of interchangeable vacuum tubes. When the vacuum is turned off, air flows through the rectangular specimens and into the glass column, which results in the drop of water in the glass column. the time required for the level of water to drop by Δz was recorded and used to measure the superficial permeability (k) in m3 (gas)/m s pa, by using the equation-

$$K_g = \frac{152VCL(P_a - \frac{\bar{h}}{13.6})}{ta(\frac{\bar{h}}{13.6})(2P_a - \frac{\bar{h}}{13.6})} \quad \ldots (4)$$

C is the correction factor for expansion of gas due to viscosity of water.

1. Raised-water volume displacement method-Time required to displace a known volume V_d measuring the pressure difference is determined by mercury monometer. The air volume V_r to greater flow through the specimen than that recorded as $V_{d.}$ Here use very small capillary for displacement tube in the measurement of very low permeability.

$$K_g = \frac{152VCL(2a - \frac{\bar{h}}{13.6})}{ta(\frac{\bar{h}}{13.6})(2P_a - \frac{\bar{h}}{13.6})} \quad \ldots (5)$$

2. Rota meter method (Flow meter):- The method utilised study state method since the flow rate and gradient are constant. It is assumed that the downstream end of specimen is at atmospheric pressure although this may be slightly in error due to the pressure drops across the rota meter.

$$K_g = \frac{152QLPa}{A\Delta Pm(2P_a - \Delta P_m)} \quad \ldots (6)$$

3. Measurement of permeability by monometer:

$$K_g = \frac{152QLPa}{A\Delta Pm(2P_a - \Delta P_m)} \quad \ldots (7)$$

Where K_g= air permeability of wood in $cm^3/sec.cm^2.atm/cm$.
Q =air flow through wood per unit of time in cm^3/sec.
A = cross sectional area in $cm^2=\pi/4$
L = length of the specimen in cm = 1cm.

4. Permeability test with nitrogen gas-permeability of test samples to nitrogen gas was measured in a specially build apparatus, the test sample positioned inside the specimen holder having 0.57cm bore was firmly tightened by a sliding plate having a similar bore corresponding to the sample holder at its centre (Narayanappa, 1990) [24].

Permeability in soft wood

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, mad rone, California black oak, and redwood were measured. 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 (Ellwood, 1957). The sapwood of conifers is much more permeable than either heartwood or wet wood (Ward *et al*. 1986). In the living tree the permeability of coniferous wood is higher than that of heartwood and is not influenced by season of the year (Markstorm *et al*. 1972) [21]. Pits are discontinuities in the secondary cell wall. There are two main types of pits-simple and bordered. All pits have two essential components-the pit cavity and the pit membrane.

Pit aspiration in soft wood:

A common modification of bordered pit-pairs is the lateral displacement of the membrane. This phenomenon, called aspiration, usually occurs when sapwood is transformed into heartwood or when wood dries. In softwoods, the torus seals one of the pit apertures and, therefore blocks the passage through the pit. Aspiration makes the wood of fir, spruce and Douglas-fir difficult to impregnate with preservatives (Walker, 2006) [34].

Aspiration makes the most of the softwood species difficult to impregnate with preservative solutions under pressure, and hence this species became refracted, i.e. resistant to fluid flow and require a long period of treatment (Ilkar, 2005) [15].

Permeability in Hard Wood

Longitudinal permeability of *Casuarina equisetifolia* sap wood was found to be increased by both pre-steaming and ponding of wood in green condition. The improvement was more by pre-steaming than the ponding. Pre-steaming also improves permeability in the refractory middle heartwood of this species but the effect of ponding was insignificant (Narayanappa, 1990) [24].

Measurements of longitudinal permeability of water in trembling aspen showed to be very permeable, while most samples of wet wood and heartwood were completely impermeable. The rate of tangential moisture loss from sapwood was distinctly greater than from heartwood and wet wood (Kemp, 1957) [18].

Eucalyptus hybrid from various locations when tested for gas permeability in a single stem variability occurs, sap wood showed a permeability more than the heartwood (Elvin *et al.* 1997). In the heartwood also variation occurs. Middle heartwood exhibited slightly lower permeability than the inner heart wood. The permeability variation in the heart wood due to the extractive content and higher amount of extractives in the middle part is responsible for the low permeability (Bahri *et al*. 1982) [3]. The permeability of Brazilian *Eucalyptus grandis* and *Eucalyptus citriodora* wood was measured in a custom build gas analysis chamber in order to determine which species could be successfully treated with preservatives (Sonaya *et al*, 1982) [30]. The statistically significant difference to the permeability of two fluids is strong enough to indicate that *E. grandis* may be a slightly better candidate for preservative impregnation. Due to the zero or near zero permeability of heartwood from both *Eucalyptus* species, this part of the tree is not recommended for fluid impregnation (Marcio *et al*. 2010) [20].

Table 1: Difference between soft wood and hard wood on the basis of permeability.

Soft wood	Hard wood
• When drying of wood the longitudinal permeability is dominant than the transverse permeability.	• In hard wood transverse flow is small in comparison to longitudinal flow.
• Radial permeability of *Pinus radiate* Sapwood increase on drying due to resin canals.	• Hard wood having ray cells which isn’t efficient in radial flow and also having pits which are inefficient in tangential flow.
• But in *Dacrydium cupressinum* racheids and resin canals	• In hard wood tyloses increase the resistance to flow along vessels and they
• Absent so decrease in permeability on drying (Booker, 1990) [6].	• Account low permeability of white oaks such as
	• *Quercusalba* (Comstock, 1967).

Examples according to permeability

Liquid permeability

Under this the liquid permeability in radial direction was compared to *Pinus radiate, Tsuga heterophylla, T. mertensiana, Cryptomeria japonica.* By pressure process and by light microscopy the co relation between liquid retention in wood by both capillary penetration and the rate of air exhust in initial stages were highly significant. The difference in permeability occurs due to the structure and the degree of blocking by cell inclusion in the ray parenchyma cells and the size and structure of cross field pit membranes and the resin penetration inside it (Tanikawa *et al*. 1995) [33].

In both heart wood and sapwood gas permeability increased with increasing severity of drying the increase being about 100% for sap wood and about 250% for heartwood. The increase in permeability is due to movement and modification of the resin (Booker, 1990) [6].

Gas permeability

Gas permeability of *Pinustauda* sapwood was determined for samples from 6 plantation grown trees. Samples are solvent dry to obtained green equivalent state or air dried. Permeability was also measured in the tangential and radial directions. Longitudinal permeability was significantly less in the lower part of the tree than the upper part. Mature wood was more permeable than juvenile wood for both green and air dried wood (Milota, 1995) [23]. The permeability and water transfer during high temperature drying are related in mocsson pine (*Pinus massoniana*), Permeability of wood has a very big effect on water transfer above FSP and less effect on water transfer under FSP during high temperature drying (Miao *et al*. 2000) [22].

Permeability of different species

1. **Cotton wood tree (*Populuse deltoids*):** Permeability varied with height in tree and in heartwood also the stem quadrate and radial location. Variation with height was irregular but longitudinal permeability was highest adjacent to the core wood and then dropped rapidly towards the periphery of the tree. In constant flow of fluid in the longitudinal directions of hardwood is largely controlled by the size and number of vessels that are not clogged by tyloses or other obstraction. This study was undertaken primarily to determine the variation of longitudinal and transfer gas permeability with in populous tree (Issacs *et al*. 1971) [16].

2. ***Hevea brasiliensis* (rubber wood)**
The rubber wood is hard wood species. This wood is diffuse porous which are having straight and slightly

interlocked grain (Bossherd, 1966). The occurrence of tyloses is an important character of rubber wood. Gas permeability in rubber wood samples was conducted at 9% moisture content using nitrogen gases as a flow medium. Permeability was found to be significantly higher in longitudinal directions due to the conductivity of vessels present in the wood other than low in radial and tangential directions.

3. ***Abies pindrow***

This is a soft wood species where the flow occurs through the longitudinal tracheids. *Trichoderma* moulds improve the treatability of the southern pine wood which observed through researches. (Lindgren *et al*. 1952) [19]. There are various types of bacteria present in soft wood which increase the permeability when stored in log pond (Ward *et al*. 1968) [35]. Heavy degradation of pit membrane observed during the laboratory pre-treatment with bacteria and enzyme (Bauch *et al*. 1970) [4].

Table 2: Difference between Liquid and Gas permeability

Liquid permeability	Gas permeability
• The flow of aqueous solution through wood obeys Darcy's law with respect to viscosity, length of sample and pressure.	• The flow of gases through wood doesn't strictly obey Darcy's law.
• Permeability shown to be quadratric function of pressure when flow velocity is large. (Sucoff *et al.* 1965).	• Molecular slip or Knudsen flow occurs in gases where the opening sizes is in the order of mean free path of gas.
• The variation in permeability to various liquids caused by removal of extractives or by different degrees of swelling of wood. (Comstock 1967).	• The molecule of gas are able to move along the surface however resulting in a higher flow than that predicted by Darcy's law
• Permeability to nitrogen gas decrease with increasing moisture content.	• K_g= VLP/taΔp P
• Permeability to liquid inversely vary with degree of swelling of the wood by liquid.	• P= $p_1+p_2/2$
• K=VL/tAΔp	• Δp= p_2-p_1

Factor affecting the permeability of wood

The most common methods are ponding, steam conditioning and incising.

Ponding or water spraying: This can't increase the strength of wood. It increases the wood permeability. The action of bacteria growing within the cells is responsible for this extra permeability. But sometimes it creates an unusually high absorbtion of preservatives. High permeability can be achieved by ponding of logs in lakes, tanks or rivers where bacterial water is available and sprinkling stacks of logs in a timber yard with water rich in bacteria. Earlier work on ponding and related subject was done by (Adolf *et al*. 1972) [1].

Steam conditioning: It is the method which can increase the natural permeability of wood. The duration of the treatment depends on the initial moisture content, species and thickness of the timber. The permeability of all timbers can't increase by this method as the disadvantage is high cost and the tendency to reduce the strength (Ilkar Usta 2005) [15].

Other factors

Specific gravity- As the density is high or the specific gravity of wood is high the permeability of wood is low (Benvenuti, 1963) [5].

Moisture content- The permeability wood generally increases with loss of moisture (Chong, 1974) [8].

Effect of high temperature on drying: Rapid drying could have significant effects on the permeability of the finished product, by increasing the frequency of pit aspiration and reducing the ability of the finished product to take up preservatives or finishes (Siau JF, 1971) [28]. Western hemlock is generally viewed as being among the more treatable of western wood species and any changes in permeability as a result of drying could have important implication for the preservatives treating industry.

Conclusion

Permeability is influenced by the cells which are interconnected in nature. When wood is compressed, air and water escape and the material become porous and permeable. But when the cells are closed, air and water escape only from the cell wall, so the wood is porous but impermeable. The permeability to water in sapwood and heartwood of five species (softwood) namely, ponderosa and sugar pines, madrone, California black oak and redwood were measured and the permeability of these species decrease in the order listed. The sapwood of conifers is much more permeable than heartwood.

The permeability in case of hardwood species in transverse direction is extremely low and its measurement is difficult because the rate of liquid flow is also meagre. Longitudinal permeability of *Casuarina equisatifloia* sapwood was found to be increased in green condition by both pre-steaming and ponding but in rapid drying process, permeability is reduced.

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