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Pressure Effect on Safranine Penetration in Some Hardwood Species[1]

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ABSTRACT

An experiment was conducted to know the safranine impregnation distance from surface to inward using 6 different hardwood species. During impregnation, 3 parameters were applied－vacuum, pressure and soaking time. Only vacuum treatment did not increase the permeability of wood. Vacuum followed by pressure increased the penetration depth of safranine in radial, tangential and longitudinal direction. Longitudinal penetration was found easy to impregnate. Comparing with radial and tangential direction, radial penetration was found easy. There was a striking difference among sapwood and heartwood permeability. Safranine input depth was found highest in diffused porous wood rather than in ring porous wood. At increased vacuum and pressure, safranine penetration was found easy.

Key words: Safranine penetration, Ring porous wood, Diffuse porous wood, Axial penetration, Lateral penetration.

INTRODUCTION

Wood is a heterogenous material and wood pore structure varies greatly among species, logs and different parts within the same log (Wang and Yan 2005). Hardwood is composed of different kinds of cells and all the components including the conducting channels and their connection contribute the treatability. The vessels are the main avenue in conducting fluids. Therefore, the size, distribution and condition of the vessels are important factor for treating the hardwood (Wang and DeGroot 1996). The rate and amount conducted by those cells varies from species to species. Capillary structures are very important to determine the liquid penetration which consists of vessel, wood fiber, ray cell and axial parenchyma. Those cells play an important role for liquid penetration in wood. Vasicentric tracheids can also function as communication means between the intervessel fluid transport (Wheeler and Thomas 1981). Beside the amount of liquid penetration is not same in sap and heartwood. The solution uptake is affected by the poor wettablility of the surface of the cell lumen (Iida et al. 2002). Tang et al. 2000 found that the permeability of liquid in wood was influenced by different factors like- size of the stain molecule, the affinity between stain solution and wood, tangential penetration is more difficult than longitudinal penetration. It also depends on molecular weight of solute molecule, low molecular weight solute penetrate into the cell wall easily (Furuno et al. 2004). It results in the differences of location and quantity of the penetrated liquid. As the impregnation of liquid in hardwood is difficult than that of softwood, vacuum along with increased pressure effect is also observed in this experiment.

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In this report, the impregnation path and distance covered from surface to inward by safranine in six different important hardwoods grown in Korea are described. This will help us to understand the causes responsible for the difficulty of impregnation. This knowledge can be applied for making the treatment easy for those considered species. Several factors are responsible for the impregnation of liquid in wood. This experiment is conducted to find out those factors and suitable combination of vacuum and pressure effect at which greater amount of liquid can be impregnated into wood at a shortest possible time.

MATERIALS AND METHODS

Wood block preparation

Six different kinds of wood were taken under consideration from ①*Populus tomentiglandulosa* T. Lee ②*Alnus hirsuta* Turcz. ③*Castanea crenata* Sieb. et Zucc. ④*Quercus* sp. ⑤*Betula davurica* Pallas ⑥*Robinia pseudoacacia* L. Wood blocks were made from both sapwood and heartwood maintaining the size 6cm (length) X 5cm (width) X 1.6cm (thickness). *B. davurica*, *C. crenata* and *R. pseudoacacia* are primarily heartwood, so only heartwood was selected for those species.

Coating of wood block with silicone resin

Wood blocks were weighed and dried in an oven for 24 hours maintaining the temperature 105℃. Moisture content of wood block in terms of wet weight basis was calculated.

As we want to know the penetration depth of liquid in three directions of wood blocks, we covered the entire surface with silicone resin except the considered surface to prevent the leakage of safranine through the other surfaces.

Impregnation of colored solution (1% safranine)

The air dried wood blocks were used for safranine impregnation through immersion and pressurized method by digester machine (Ahmed et al. 2005). After the vacuum pressure (-620 mmHg) was applied for 0, 5 and 10 minutes on wood blocks, they were allowed for soaking by safranine for 10 minutes. Another set of experiment was carried out where 5 minutes vacuum pressure was applied prior to the application of 30, 50 and 70 kgf/cm^2 pressure on wood block while soaking by safranine. It allowed us to observe the combine effect of vacuum and pressure on the penetration of safranine in wood blocks.

Data record

Data was recorded 7 times from sap and heartwood of considered species in 3 different directions. Total experiment was conducted for 3 times. Mean and SE (Standard Error) were estimated by a statistical analysis software, SPSS, Version 12.0.1, 2003.

RESULTS AND DISCUSSION

In hardwood species, both sap and heartwood were taken under consideration. Safranine penetration depth differed from heartwood to sapwood. The permeability is lower in heartwood compared with sapwood (Minato 2004). In this experiment, safranine penetration depth in sapwood was found higher than that of heartwood. Mainly ray, vessels and wood fiber were responsible for the liquid conduction. Many vessels connected longitudinally in series to form a capillary structure with definite length. All wood species possess a capillary structure and its effect on fluid permeability varied considerably. Wood is a capillary porous medium. The pore structure is defined by the cell lumen and the cell wall openings which interconnect them. If the pit membrane opening are large and numerous, the permeability is higher (Comstock 1967). The primary routes for liquid penetration into wood are provided by these capillaries (Smith and Banks 1971; Petty 1970).

Moisture content

Moisture in wood plays an important role for the penetration of liquid in wood block. Above the fiber saturation point, wood can also absorb water until the cell cavities are filled up with liquid water (Browning 1963).

Table 1. Average moisture content (mean±SE) in different wood species

Wood species	Moisture content (%)
P. tomentiglandulosa	6.2±0.1
A. hirsuta	6.6±0.1
B. davurica	6.5±0.1
Quercus sp.	6.4±0.2
R. pseudoacacia	6.9±0.1
C. crenata	8.2±0.1

The permeability of some wood species decrease with an increased moisture content (Comstock 1968). Excess moisture in wood voids may act as a physical barrier for the mass flow of liquid (Wirspa and Libby 1950). We tried to fill up the cell cavity of wood with an increased pressure.

Vacuum pressure effect

When liquid starts to enter in the wood block, the air present inside the void spaces begin to compress. Penetration of liquid is slowed down and eventually stops of the growing back pressure. After pressure equilibrium is achieved, further penetration can be possible either due to an increase in the pressure applied or a decrease in the pressure of gaseous mixture. It is known that the air present in cell lumen is the main obstacle for rapid penetration of liquid (Maass 1953). Removal of air from dry woodchip is found effective (Stamn 1953).When penetration is allowed from both side of woodchip, the back-pressure of trapped air becomes compressed by capillary forces which check the penetration soon (Rydholm 1965). Removal of air can be limited by the specific characteristics of wood capillaries as some air can be trapped with in the capillaries which are sealed up by extractive. It was found that at normal air pressure, safranine impregnation was lower from those wood blocks which were treated by vacuum pressure for 5 or 10 minutes (Table 2 and 3). This phenomenon can be explained by air trapped in capillaries which reduced the liquid penetration.

In every case, sapwood permeability was found higher than heartwood. This was due to lack of water conductive capacity of heartwood. Some hardwood species contain tyloses, which reduce the treatability (Thomas 1976). The factors attribute to the lowered heartwood treatability include the higher extractive content in heartwood. In this experiment it was found that diffuse porous wood like *A. hirsuta* and *B. davurica* absorbed safranine like softwood and penetration depth of safranine was found highest in almost all direction at 10 minutes of soaking time. Ray parenchyma conduct safranine faster than fiber in lateral impregnation. In radial direction, ray cells are joined together to form capillary structure which allow a safranine pathway for the impregnation. It has been reported that ray parenchyma cells are important channels for radial flow (Behr et al. 1969). In tangential direction, ray cells are not arranged in such way for easy penetration. In longitudinal penetration, vessel played an important role. A fluid flowing longitudinally does not have to pass through pits but only in transverse flow between vessels or other conducting cells, fluid has to pass through pits

Table 2. Safranine penetration depth (mean±SE) in sapwood. *Condition: After vacuum (-620 mmHg) treatment wood blocks were soaked in safranine for 10 minutes.*

Wood species	Vacuum pressure (-620 mmHg) treatment	Tangential direction (cm)	Radial direction (cm)	Longitudinal direction (cm)
	0 min	0.02±0.01	0.06±0.01	0.31±0.09
P. tomentiglandulosa	5 min	0.06±0.01	0.13±0.01	6.00±0.00
	10 min	0.11±0.01	0.21±0.01	6.00±0.00
	0 min	0.03±0.00	0.05±0.00	0.99±0.13
A. hirsuta	5 min	0.22±0.03	0.57±0.05	6.00±0.00
	10 min	0.32±0.03	0.65±0.05	6.00±0.00
	0 min	0.00±0.00	0.00±0.00	0.00±0.00
Quercus sp.	5 min	0.02±0.01	0.03±0.00	0.06±0.00
	10 min	0.00±0.00	0.07±0.01	0.09±0.03

Table 3. Safranine penetration depth (mean±SE) in heartwood. *Condition: After vacuum (-620 mmHg) treatment wood blocks were soaked in safranine for 10 minutes.*

Wood species	Vacuum pressure (-620 mmHg) treatment	Tangential direction (cm)	Radial direction (cm)	Longitudinal direction (cm)
	0 min	0.00±0.00	0.00±0.00	0.03±0.02
P. tomentiglandulosa	5 min	0.02±0.01	0.02±0.00	0.14±0.03
	10 min	0.00±0.00	0.02±0.00	0.07±0.01
	0 min	0.00±0.00	0.02±0.00	0.19±0.05
A. hirsuta	5 min	0.15±0.01	0.27±0.02	4.27±0.49
	10 min	0.20±0.03	0.32±0.03	4.71±0.52
	0 min	0.00±0.00	0.02±0.00	0.12±0.03
B. davurica	5 min	0.07±0.01	0.10±0.02	4.39±0.57
	10 min	0.14±0.03	0.24±0.01	6.00±0.00
	0 min	0.00±0.00	0.00±0.00	0.00±0.00
Quercus sp.	5 min	0.00±0.00	0.01±0.00	0.02±0.00
	10 min	0.00±0.00	0.00±0.00	0.00±0.00
	0 min	0.00±0.00	0.00±0.00	0.00±0.00
R. pseudoacacia	5 min	0.00±0.00	0.00±0.00	0.00±0.00
	10 min	0.00±0.00	0.00±0.00	0.25±0.00
	0 min	0.00±0.00	0.00±0.00	0.01±0.00
C. crenata	5 min	0.00±0.00	0.01±0.00	0.21±0.07
	10 min	0.00±0.00	0.00±0.00	0.24±0.03

(Bao 1999). So, safranine penetration depth was found the highest in longitudinal direction. Also time factor is important for safranine penetration depth. Long time exposure of wood to safranine solution will allow diffusing the solution form one cell to its neighboring cells. As wood is hygroscopic in nature and can still uptake liquid above the fiber saturation point, it can be concluded that the amount of liquid and penetration depth can be increased by prolonging the soaking time.

Table 4. Safranine penetration depth (mean±SE) in sapwood. *Condition: 5 minutes vacuum (-620 mmHg) treatment followed by pressure while soaking wood block in safranine for 10 minutes.*

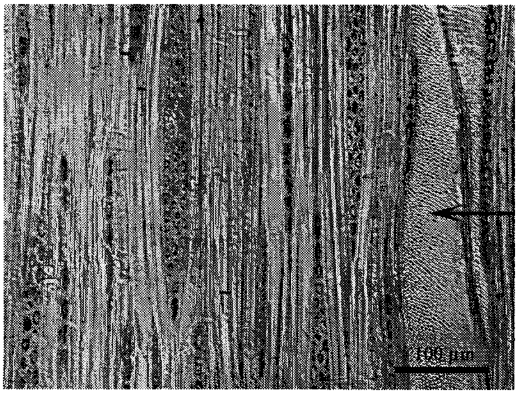
Wood species	Pressure	Tangential direction (cm)	Radial direction (cm)	Longitudinal direction (cm)
P. tomentiglandulosa	30 kgf/cm^2	0.21±0.03	0.35±0.04	6.00±0.00
	50 kgf/cm^2	0.21±0.02	0.51±0.02	6.00±0.00
	70 kgf/cm^2	0.38±0.03	0.57±0.01	6.00±0.00
A. hirsuta	30 kgf/cm^2	0.48±0.04	0.71±0.04	6.00±0.00
	50 kgf/cm^2	0.49±0.05	0.80±0.00	6.00±0.00
	70 kgf/cm^2	0.56±0.05	0.80±0.00	6.00±0.00
Quercus sp.	30 kgf/cm^2	0.04±0.01	0.14±0.02	4.21±0.59
	50 kgf/cm^2	0.08±0.01	0.15±0.05	6.00±0.00
	70 kgf/cm^2	0.11±0.02	0.24±0.04	6.00±0.00

Table 5. Safranine penetration depth (mean±SE) in heartwood. *Condition: 5 minutes vacuum (-620 mmHg) treatment followed by pressure while soaking wood block in safranine for 10 minutes.*

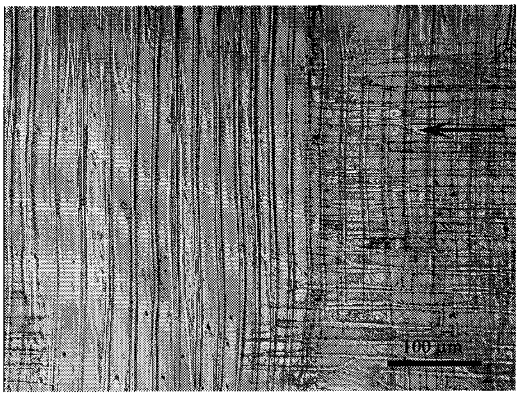
Wood species	Pressure	Tangential direction (cm)	Radial direction (cm)	Longitudinal direction (cm)
P. tomentiglandulosa	30 kgf/cm^2	0.16±0.01	0.30±0.02	6.00±0.00
	50 kgf/cm^2	0.20±0.02	0.36±0.06	6.00±0.00
	70 kgf/cm^2	0.22±0.03	0.36±0.01	6.00±0.00
A. hirsuta	30 kgf/cm^2	0.60±0.01	0.65±0.03	6.00±0.00
	50 kgf/cm^2	0.63±0.03	0.66±0.03	6.00±0.00
	70 kgf/cm^2	0.65±0.03	0.71±0.02	6.00±0.00
B. davurica	30 kgf/cm^2	0.13±0.02	0.18±0.01	6.00±0.00
	50 kgf/cm^2	0.25±0.05	0.27±0.04	6.00±0.00
	70 kgf/cm^2	0.25±0.02	0.28±0.02	6.00±0.00
Quercus sp.	30 kgf/cm^2	0.01±0.00	0.02±0.00	0.56±0.28
	50 kgf/cm^2	0.01±0.00	0.03±0.01	1.33±0.43
	70 kgf/cm^2	0.02±0.00	0.10±0.01	1.56±0.46
R. pseudoacacia	30 kgf/cm^2	0.04±0.01	0.08±0.01	0.23±0.05
	50 kgf/cm^2	0.04±0.00	0.08±0.01	0.39±0.13
	70 kgf/cm^2	0.05±0.00	0.10±0.02	0.52±0.13
C. crenata	30 kgf/cm^2	0.10±0.02	0.14±0.01	2.14±0.46
	50 kgf/cm^2	0.10±0.00	0.16±0.01	5.01±0.58
	70 kgf/cm^2	0.11±0.01	0.17±0.01	5.04±0.57

Combined effect of vacuum and pressure

Prime factors responsible for governing the flow are the amount of pressure, fluid viscosity, solvent contact angle, wood pore radius and wood capillary length (Bao 1999). An increase in pressure will result in faster penetration (Hoadley 2000). Pressure impregnation as the preservative is driven through the wood capillary system. High pressure is required to overcome the negative effect of surface tension in the liquid-air menisci, which are formed by the capillary condensation of vapour (Stamm 1963).



Tangential section



Radial section

Fig.1. Penetration trend of tangential and radial direction treated with safranine in *B. davurica. Arrow bar showing the safranine impregnated from radial surface (left) and tangential surface (right).*

After the vacuum treatment, three types of pressure were created on wood block during soaking time. And it was found that the wood which has difficulty for the impregnation only by vacuum treatment, that was overcome by increased pressure. Higher pressure results in solubility of air into liquid, thus allowing more air to be dissolved and a higher penetration degree to be reached. In both sap and heartwood, the liquid permeability was increased at pressure 70 kgf/cm^2 (Table 4 and 5). In this experiment it was found that safranine permeability was higher in heartwood of *A. hirsuta* in tangential, radial and longitudinal direction at pressure 30, 50 and 70 kgf/cm^2.

Impregnation difference in diffuse and ring porous wood

In this experiment, among the hardwood species *P. tomentiglandulosa*, *A. hirsuta* and *B. davurica* were diffused porous and *C. crenata*, *Quercus* sp. and *R. pseudoacacia* were ring porous wood. Diffuse porous wood has a higher permeability than ring porous wood (Bao 1999). Tyloses and various exudate often formed in the vessel lumens within the heartwood and transition zone. Formation of these materials subsequently reduces the permeability of the heartwood and the transition zone (Kumar and Dobriyal 1993). *C. crenata*, *Quercus* sp. and *R. pseudoacacia* contain tyloses in their heartwood (Fig. 2). As a result it was found that diffuse porous wood conducted more safranine than that of ring porous wood. Diffuse porous wood does not contain any obstacle like tyloses in its vessel elements to check the water conduction. Ray parenchyma played an important role for the lateral conduction (Fig. 1). Among the wood species, safranine impregnation in *R. pseudoacacia* was found the lowest. This is because it contains more air by volume compared with other species (Sparks 2000). As a result the void space hinder the penetration of liquid (Usta 2001). Besides tyloses was the important factor to resist the safranine movement. According to Kim and Park (1991) and Lee (1983), in hardwood penetration, the ease of permeability depending on the impregnation direction is longitudinal, radial and tangential order. Our experiment also supports this result. When woods were treated under vacuum and pressure, the safranine impregnation was found higher in diffused porous wood (Fig. 3 and 4).

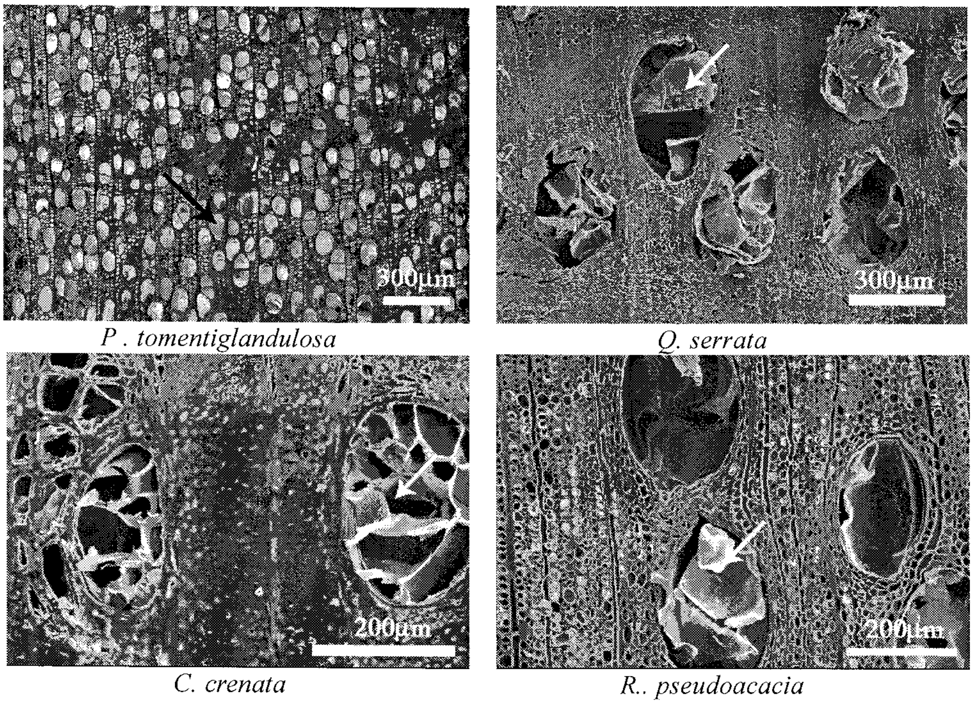


Fig.2. Cross section seen under FE-SEM. Black arrow showing vessel without tyloses while white arrow showing vessel with tyloses.

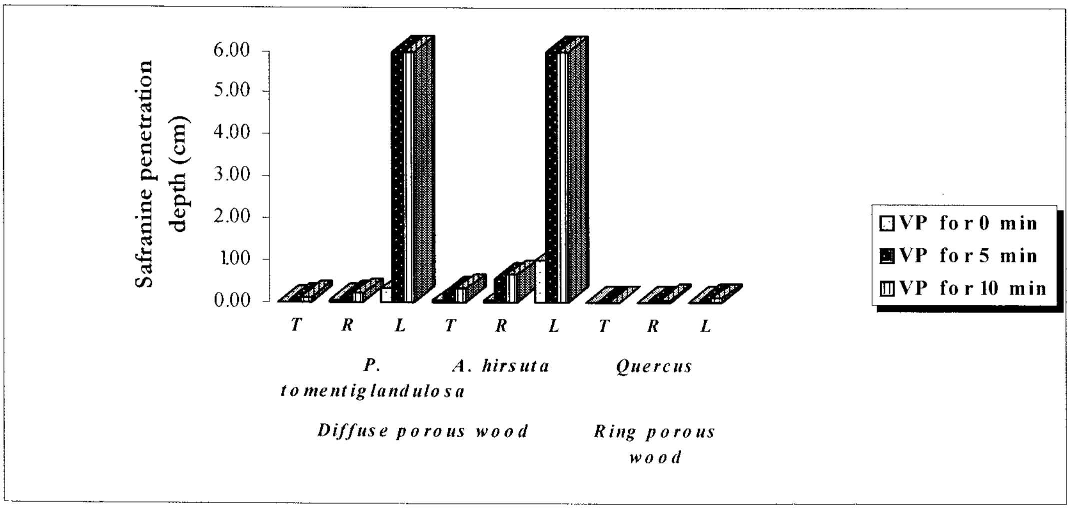


Fig.3. Comparison of safranine penetration depth differences in sapwood between diffuse and ring porous wood. *Condition: After vacuum treatment, (-620 mmHg) wood blocks were soaked in safranine for 10 minutes. VP-Vacuum pressure. T- Tangential; R- Radial and L- Longitudinal direction.*

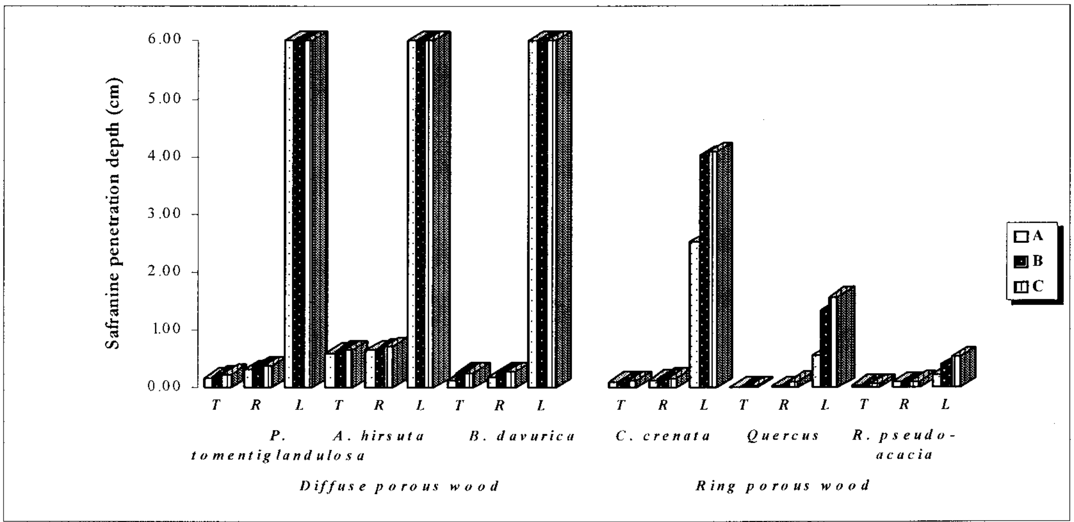


Fig.4. Comparison of safranine penetration depth in heartwood between diffuse and ring porous wood. *Condition: 5 minutes vacuum (-620 mmHg) treatment followed by pressure while soaking of wood block in safranine for 10 minutes. A=30 kgf/cm^2, B=50 kgf/cm^2 and C=70 kgf/cm^2. T-Tangential, R- Radial and L- Longitudinal direction.*

The variability between ring and diffused porous wood can be explained by varying proportion of latewood within the sample. Wood block with large proportion of high density latewood would not absorb safranine as much as one with relatively small proportion of latewood (Laks 1996). Ring porous wood in this experiment, contained large proportion of high density late wood compared with diffuse porous woods which result in low penetration depth of safranine.

CONCLUSIONS

The main objective of this research was to find out the appropriate condition for liquid penetration. It was found that only vacuum treatment did not increase the permeability to a higher extent. Vacuum treatment followed by an increased pressure showed an excellent result for the impregnation of safranine. Sapwood and heartwood permeability was found remarkably different. Longitudinal penetration of safranine was found easier than radial and tangential direction. Radial penetration was found higher than tangential direction. Diffuse porous wood was found more permeable than ring porous wood. Based on experimental condition it can be concluded that safranine impregnation in different hardwoods depend on- species, vacuum and pressure during impregnation time, wood surface, soaking time and moisture content in wood . At a given condition, permeability of liquid in wood can be increased by lengthening the soaking time.

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