EFFECT OF BORDERED PIT TORUS POSITION ON PERMEABILITY IN CHINESE YEZO SPRUCE

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ABSTRACT

The effect of different bordered pit torus positions on wood permeability was studied by air-drying and ethanol-exchange drying for green wood and by soaking in water, then followed by ethanol-exchange drying for air-dried wood of Chinese yezo spruce (*Picea jezoensis* var. *komarovii*). The results showed that different treatments caused different pit torus positions and different wood permeability. The air-drying treatment resulted in pit torus aspiration and low permeability for sapwood. The ethanol-exchange drying treatment left the pit torus in an unaspirated position and resulted in high permeability for sapwood. Soaking in water followed by ethanol-exchange drying caused deaspiration of a part of pit torus and increased permeability for both sapwood and heartwood.

Keywords: Chinese yezo spruce, bordered pit torus, pit aspiration, pit in unaspirated position, pit deaspiration, permeability.

INTRODUCTION

As Siau (1995) indicated, the most important factor affecting softwood permeability is the pit system through which fluids flow. The key factors that affect efficiency of the pit in fluid transportation are: (1) pit aspiration, caused by the deflection of pit membrane; (2) pit blockage, due to the deposit of extractive in the pit membrane opening; and (3) pit clogging, caused by encrustation of amorphous substances on the pit membrane opening. Generally, the position of the torus in the bordered pit of a tracheid in the woods of Pinaceae plays a very important role in fluid transportation.

Various treatments associated with the pit torus position such as freeze-drying (Bramhall and Wilson 1971), critical point drying (Bolton and Petty 1977), solvent exchange drying (Comstock and Fate 1968), and soaking in water (Lu and Bao 1992; Thomas and Nicholas 1966) have been tried to improve permeability. However, all these treatments were focused on the efficiency of permeability improvement, while fundamental study on the mechanism of permeability improvement was neglected. This study focused on the effect on permeability of different torus positions caused by air-drying, solvent-exchange drying, and soaking in water then followed by solvent-exchange drying treatments. The permeability was measured, and also the pit torus position for the specimens from different treatments was determined. Therefore, it was possible to explore the relationship between wood

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permeability and pit torus position more exactly.

MATERIALS AND METHODS

The specimens tested were obtained from four trees of Chinese yezo spruce (*Picea jezoensis* var. *komarovii*). Specimens 2 by 2 cm and 10 cm in length (parallel to the grain) were made from fresh wood cut in winter. The position of the bordered pit torus was determined by microscope on the semi-sections. The proportion of pit aspiration was estimated from 200 pits in earlywood and 100 pits in latewood for each treatment specimen. The superficial specific air permeability was measured using the rising-water volume-displacement method (Siau 1981, 1995; Bao et al. 1999) after the moisture content of specimens treated by air-drying, ethanol-exchange drying, and soaking in water then followed by ethanol-exchange drying treatments was adjusted in a humidity conditioner to about 10% (Bao et al. 1999). The three aforementioned treatments are described as follows:

Air-drying of green specimens resulting in the pit torus in the aspirated position

The purpose of air-drying green specimens was to force the pits in tracheids into the aspirated position, due to the evaporation of free-water with high surface tension of 0.073 N/m so that the effect of pit aspiration on permeability could be studied. Two adjacent specimens within the same rings and end-matched were marked as a couple for comparison study. In total, 26 and 27 coupled specimens were selected from sapwood and heartwood, respectively. In each couple, one was air-dried and considered as control specimen for a following ethanol-exchange drying treatment, and the other was used for the ethanol-exchange drying.

Ethanol-exchange drying of green wood resulting in the pit torus in the unaspirated position

The purpose of ethanol with low surface tension of 0.022 N/m exchange drying for green specimens was to keep the pit torus in its original position during drying, so that the effect of unaspirated pit torus on permeability could be investigated. The green heartwood and sapwood groups were immersed in about 1,800~2,000 ml ethanol in 50%, 70%, 95% concentration successively, 2 days each concentration. After these 3 immersions, the ethanol in concentration 100% was then used several times for 2 days each time until the average moisture content was estimated to be below the fiber saturation point. After the ethanol-exchange drying treatment, the specimens were taken out from the container and allowed to evaporate the ethanol inside the specimen. Several specimens were weighed every day, and it was assumed that all the ethanol had been evaporated when the weight of the specimens approached a constant level. The moisture content of specimens after ethanol-exchange drying was also adjusted until the moisture content reached about 10%, and the permeability of the specimens was measured and compared with that of air-dried specimens mentioned above.

Soaking in water followed by ethanol-exchange drying for air-dried specimens resulting in pit torus deaspiration

Soaking air-dried specimens in water followed by ethanol-exchange drying aimed to move the aspirated pits due to air-drying back to the central position by resaturating them with water, and to keep the pit torus in the central position with ethanol-exchange drying the resaturated specimens. In this experiment, 16 heartwood and 16 sapwood specimens were made from the spruce that had been air-dried for 18 months. After that, the moisture content of the specimens was adjusted to about 10%. The weight of the specimens was determined, and the permeability was measured, which was used as control for that of the soaking specimens. Soaking in water took place as soon as the measurement of permeability was completed.

This treatment included two steps: the first step was the resaturation of air-dried specimens with water. The air-dried specimens were immersed in distilled water until they sank to the bottom of the container. Two weeks' soaking was required before all the specimens had completely sunk to the bottom of the container. The specimens were taken out and the surface water was wiped off. These specimens were weighed again, and the moisture content of sapwood and heartwood at this time was about 242% and 235%, respectively. The second step was ethanol-exchange drying. The ethanol-exchange drying carried out for resaturating specimens in this treatment was exactly the same as for green specimens described earlier. In total, 7 times (3 days each time) of ethanol-exchange treatment was carried on, after which the moisture content of the specimens in sapwood and heartwood was approximately 22% and 24%, respectively. Then the moisture content adjustment procedure was followed after the ethanol was totally evaporated. Permeability was measured again on the same specimen when the moisture content was adjusted again to about 10%.

RESULTS AND DISCUSSION

Permeability in the case of pit aspiration

As the moisture content in woods of Pinaceae decreases from green to the fiber saturation point, most of the free-water in the lumen of tracheids is removed. Therefore, a meniscus of free-water to air interface resulting in high capillary forces is formed across the pit aperture. When the meniscus moves to the pit-membrane openings in the margo, the resulting much higher tension due to smaller diameter (0.02~4 μm) can cause the membrane to become aspirated to where the tori close off the flow path. Therefore, the aspiration of pits reduces the permeability of wood and increases the difficulty of fluid flow in wood.

Table 1 lists the proportion of aspirated pits in the earlywood and latewood of the spruce sapwood and heartwood at green, air-dried, ethanol-exchange dried, and soaked in water followed by ethanol-exchange drying state.

TABLE 1. *The proportion of aspirated pits in Chinese yezo spruce wood at green state, and after air-drying, ethanol exchange drying, and soaking in water (%).*

Specimen types	At green state		After air-drying		After ethanol-exchange drying		After soaking in water followed by ethanol-exchange drying	
	Early-wood	Late-wood	Early-wood	Late-wood	Early-wood	Late-wood	Early-wood	Late-wood
Sapwood	4.76	12.30	99.50	80.60	8.35	17.50	81.20	63.10
Heartwood	97.90	86.70	97.50	86.30	97.00	85.80	97.20	69.50

The proportion of aspirated pits in the earlywood and latewood of green sapwood was about 5% and 12%, respectively. However, the proportion of aspirated pits in the earlywood and latewood of green heartwood was about 98% and 87%, respectively. Therefore, it could be concluded that, in the case of green wood, most of the pit tori were in the unaspirated or central position for sapwood, while for heartwood most of the pit tori had already been aspirated. This is in agreement with other studies (Jiang et al. 1993; Lin 1989; Comstock and Côté 1968; Liese and Bauch 1967; Thomas and Nicholas 1966). Côté (1963) explained that pit aspiration in green heartwood is attributed to heartwood formation in living trees.

Air-drying the spruce green sapwood and heartwood in this study had the expected effect of causing pit aspiration. After air-drying, the proportion of aspirated pits in the earlywood and latewood of sapwood increased from 5% and 12% at green state to 99% and 81%, respectively (Table 1), and the corresponding average air permeability was about 0.114×10^{-12} m^3/m (Table 2). This pit aspiration decreased the permeability of sapwood after drying. For heartwood, the proportion of aspirated pits in the earlywood and latewood after air-drying was almost the same as before drying, about 98% and 87%, respectively (Table 1), and its average air permeability was as low as 0.045×10^{-12} m^3/m (Table 2). This showed that air-drying had no effect on the proportion of pit aspiration in heartwood, and the low permeability in heartwood was its intrinsic attribute, since most of the bordered pits were aspirated in the living tree.

The permeability in the case of pits in the unaspirated condition

Table 1 shows that the proportion of aspirated pits in the earlywood and latewood of the spruce sapwood after ethanol-exchange drying was as low as approximately 8% and 17%, respectively, which was almost the same low value as for green wood. However, the proportion of aspirated pits in the earlywood

TABLE 2. *The permeability of Chinese yezo spruce wood after air-drying, ethanol-exchange drying, and soaking in water.*

Treatment types	Specimen types	No. of specimen	Permeability of control group Aver. (10^{-12} m^3/m)	Permeability of control group CV (%)	Permeability of treatment group Aver. (10^{-12} m^3/m)	Permeability of treatment group CV (%)	Increase rate (%)	t-test	Significant level (α)
Air-drying	Green sapwood	26			0.114	29.2			
	Green heartwood	27			0.045	54.0			
Ethanol-exchange drying	Green sapwood	26	0.114	29.2	11.713	46	10150	11.0	0.001
	Green heartwood	27	0.045	54.0	0.0738	130	62.44	1.69	0.200
Soaking in water followed by ethanol-exchange drying	Air-dried sapwood	16	0.238	60.4	0.4399	34.6	84.56	5.88	0.001
	Air-dried heartwood	16	0.040	67.9	0.0600	42.7	48.75	11.6	0.001

and latewood of heartwood after ethanol-exchange drying was as high as approximately 97% and 86%, respectively, about the same high value as the degree of aspiration in green wood. Therefore, the ethanol-exchange drying treatment in this study effectively prevented aspiration of the pit membranes in sapwood. Since most of the pits in heartwood had already been aspirated in green wood, ethanol-exchange drying failed to keep the pits in the unaspirated position, as expected.

The results shown in Table 2 indicated that the average air permeability of green sapwood after ethanol-exchange drying was approximately 11.713×10^{-12} m^3/m. Compared with the permeability after air-drying, the air permeability increased about 100 times. The *t*-test of paired comparative test showed that the difference in permeability between two groups was highly statistically significant at the 0.1% level (Table 2).

The increased rate of air permeability in the spruce green sapwood after ethanol-exchange drying compared with its permeability after air-drying in this study was very close to the values reported by other scientists. Bramhall and Wilson (1971) found that the gas permeability of alcohol-benzene exchange dried sapwood increased 10 to 100 times compared with the air-dried wood in coastal type and 4 to 20 times in interior type *Pseudotsuga menziesii.* Comstock and Côté (1968) compared the water permeability of the green sapwood of *Pinus resinosa* and *Tsuga canadensis,* which had been solvent-exchange dried with several organic solvents with surface tensions between 0.017–0.044 N/m, such as ethanol, methanol, and acetone etc, with that of air-dried specimens. They found that the water permeability at green state was about 5.3×10^{-12} m^3/m for both species, and the specimens dried with organic solvents were essentially unchanged in permeability. However, the air-dried *Pinus resinosa* had a permeability of only 4.5% of the value at green state, while that of the *Tsuga canadensis* was only about 0.3%. Erickson and Crawford (1959) investigated the influence of several drying methods on the liquid permeability of *Pseudotsuga menziesii* and *Tsuga heterophylla* sapwood. They observed that there was essentially no change in the liquid permeability of sapwood dried with ethanol, alcohol-benzene, and acetone compared with the liquid permeability in the green specimens for both species. However, the liquid permeability of the air-dried specimens was found to decrease significantly, in which the liquid permeabilities of air-dried specimens were approximately 1.3% and 3% of those of green specimen for *Pseudotsuga menziesii and Tsuga heterophylla,* respectively. Therefore, it can be concluded that the ethanol-exchange drying in this experiment greatly increased the permeability of sapwood.

As to heartwood in this study, the average air permeability of heartwood dried with ethanol was 0.074×10^{-12} m^3/m and was increased by about 62% compared with that of air-dried specimens. The *t*-test showed that the difference in permeability between two groups was not statistically significant (Table 2). This indicated that the ethanol-exchange drying in this study failed to improve the permeability of green heartwood after drying, which agrees with the results of Bramhall and Wilson (1971) and Petty (1978).

From the above discussion, it is evident that the much higher permeabilities in the spruce sapwood dried with ethanol compared with those air-dried is a result of a much lower proportion of aspirated pits in the former condition. In other words, the ethanol-exchange drying can effectively prevent the complete aspiration of pits in sapwood; thus most of the pits remained in the unaspirated position. The lack of significant change in permeability resulting from ethanol-exchange drying for heartwood may be due to the high proportion of aspirated pits in the specimens.

The permeability in the case of pit deaspiration

It is clear from Table 1 that the proportion of aspirated pits in air-dried sapwood and heartwood stored for 18 months decreased after soaking in water for 2 weeks followed by ethanol-exchange drying. However, the proportion of pit aspiration in earlywood and latewood was still high, about 81% and 63% for sapwood, respectively, and 97 and 70% for heartwood, respectively (Table 1). Compared with the proportion of pit aspiration in earlywood and latewood before soaking, it decreased by 18% and 17%, respectively, for sapwood, and 0 and 17%, respectively, for heartwood. According to the air permeability values measured before and after soaking, it was evident that the air permeability in sapwood and heartwood increased because of the soaking. Specifically, for sapwood the permeability of 5 specimens increased by more than 100%, and the average air permeability from all 16 specimens increased approximately 85%. In heartwood there were also 5 specimens with an increase in permeability of more than 100%, and the average air permeability from all 16 specimens increased about 49% over their controls (Table 2). The permeability difference of soaked specimens versus their controls was highly statistically significant at the 0.1% level by *t*-test of paired comparative test (Table 2). This indicated that the soaking could render some aspirated pits to become deaspirated, and the deaspiration could be kept with ethanol-exchange drying, thus improving the permeability of the specimens after redrying.

Although the proportion of aspirated pits decreased due to soaking, only a small portion of the aspirated pits were deaspirated. This may be a result of a too long air-dried period (18 months) and too short a soaking time (2 weeks) in this study. Thomas and Kringstad (1971) reported that air-dried *Pinus taeda* sapwood stored for 3 months was soaked in water for 1 week and followed by pentane-exchange drying resulting in the deaspiration of all the pits. However, for air-dried specimens stored for 13 months, only about 40% of the pits were deaspirated when the same treatment was used. This suggested that the bonding between the torus and border was strengthened by the longer storage period, and therefore, the required soaking time should be increased corresponding to the time in the aspirated state. Since the specimens of sapwood and heartwood used in this study had been air-dried for 18 months before soaking, resulting in more hydrogen bonds between the torus and border, it was more difficult to break those hydrogen bonds by soaking (Thomas and Kringstad 1971). Moreover, stress relaxation could occur in the pit membrane during the long air-dried period and thus develop permanent deflection. In this case, even if the hydrogen bonds between the torus and border were broken by soaking in water, the aspirated pits couldn't be restored to the unaspirated position because of the stress relaxation of pit membranes (Nicholas 1973). Based on the above discussion, it may be possible that more aspirated pits could be deaspirated by soaking in water for a longer time.

CONCLUSIONS

The results showed that different treatments caused different pit torus positions and different wood permeability.

1. Air-drying Chinese yezo spruce sapwood had the effect of causing pit torus aspiration and low permeability. After air-drying, the proportion of aspirated pits in the earlywood and latewood of the sapwood increased from 5% and 12% at green state to 99% and 81%, respectively, and the corresponding permeability was low, about 0.114×10^{-12} m³/m. For heartwood, the air-drying had no effect on the propertion of pit torus aspiration and permeability. The proportion of aspirated pits in the earlywood and latewood of the heartwood after air-drying was the same as before drying, about 98% and 87%, respectively, and the permeability was as low as 0.045×10^{-12} m³/m.
2. Ethanol-exchange drying the spruce sapwood effectively prevented aspiration of the pit torus and resulted in high permeability. Compared with the value of controls, the proportion of aspirated pits in the

earlywood and latewood of sapwood after ethanol-exchange drying decreased by 91% and 65%, respectively, and the permeability was increased by about 100 times. For heartwood, the ethanol-exchange drying failed to keep the pits in the unaspirated position and to improve permeability. The proportion of aspirated pits in the early-wood and latewood of heartwood after ethanol-exchange drying was the same high value as that of controls, abut 97% and 86%, respectively, and the permeability of heartwood was the same low value as that of controls, about 0.014×10^{-12} m³/m.

3. Soaking the spruce sapwood and heartwood in water followed by ethanol-exchange drying caused deaspiration of a part of pit torus and increased permeability. The proportion of aspirated pits in earlywood and latewood of the sapwood and heartwood decreased by 18% and 17% for sapwood, respectively, and by 0 and 17% for heartwood, respectively, compared with the value of controls. The permeability of the sapwood and heartwood after soaking was increased by approximately 85% and 49% over their controls.

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