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Changes in Permeability and Sound Absorption Capability of Yellow Poplar Wood by Steam Explosion Treatment

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The possibility of improving the air permeability and sound absorption capability of wood by the low–pressure steam explosion of a wood disk was evaluated in this study. By means of comparing control and steam explosion treated specimens, the effects of steam explosion on the appearance, anatomical features, air permeability, and sound absorption capability of yellow poplar (*Liriodendron tulipifera*) were discussed.

The color of steam explosion–treated wood darkened, but significant anatomical changes were not observed by scanning electron microscope (SEM) on the treated sample specimen, as compared with the control.

The average air permeability in the fiber direction of treated woods was higher than that of control woods. The sound absorption capability of control and treated yellow poplar was 15% to 50% in the measured frequency range. The sound absorption coefficients of steam explosion–treated specimens were slightly higher than those of normal wood specimens at the high frequency range.

These results suggested that yellow poplar is highly sound absorptive in the fiber direction and that the low–pressure steam explosion treatment could be considered a technique for improving the permeability and sound absorption capability of wood in the fiber direction.

Keywords: low pressure steam explosion treatment, sound absorption capability, air permeability, yellow poplar (*Liriodendron tulipifera*)

INTRODUCTION

Wood is widely used as a housing material because of its environmental superiority, good mechanical properties, fine appearance, and high thermal insulation properties. However, wood is a sound reflecting material with a relatively low sound absorption capability. It is recognized that the sound absorption capability of wood is influenced by air permeability that varies by the sound incident surface structure. Wood is a porous material which has numerous cylindrical pores in the fiber direction. However, the permeability of wood is relatively low because there are very few continuous pores in wood. The pores in wood are classified into three types: through, blind, and closed. Among these pores, only the through pore has continuous vessel elements that readily permit fluid flow. Furthermore, the formation of pit–aspirations in softwoods or tylosis in hardwoods restricts the air or liquid flow in wood.

Improving the permeability of wood has been an interest of many wood researchers because highly permeable solid wood can be treated easily by a functional treatment that allows the good dimensional stability, fire proofing, and other traits. It is generally recognized that wood treatability increases with permeability. Several treatments, such as steaming, extraction with solvents, and degradation with enzymes or microorganisms, have been attempted to increase the permeability of wood. However these treatments did not have a sufficient effect on increasing permeability, and a useful method has not yet been developed.

In a previous paper, Kang *et al*. (2008 a) reported that the delignification treatment by Wise's method improved wood permeability in the fiber direction, and that the sound absorption capability on the cross sectional surface of *Larix kaemferi* increased, as compared with the control wood. Also, it was found that the sound absorption capability of a mushroom bed log of Mongolian oak degraded by fungus over four years was 2–3 times higher than that of control wood (Kang *et al*., 2008 b).

On the other hand, steam explosion is used in the field of pulp and fiberboard manufacturing or the wood–based biomass industry and is exposure to violent pressure and temperature changes via steam. For this treatment, the target material is mounted in a closed chamber, and then superheated steam is introduced from a boiler. The superheated steam heats the chamber and target material to a high temperature and pressure, which is maintained for a moment and then discharged abruptly by a blasting device. By this process, high–pressure

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steam changes the atmospheric pressure, part of boiling water changes from a liquid to a gas with extreme speed, and the volume increased dramatically by the extreme pressure change. In the case of steam explosion treatment of a wood disk, the increasing volume of steam may extend the pore volume and destroy obstacles, such as pits or tylosis in wood, thus increasing the permeability of wood.

Kanagawa *et al.* (1992) reported that the steam explosion treatment makes a number of fine fractures at the weakest part of the cells, such as the bordered pits; these fine fractures improve the drying rates of wood. It was found that the steam explosion treatment improved the drying ability of wood, and the effect of steam explosion treatment was not uniform in the longitudinal and transverse directions (Hayashi *et al.*, 1995). Lee *et al.* (2002) reported that the drying ability of Korean larch pillars treated with steam explosion was improved during radio–frequency/vacuum (RF/V) drying. Also, Lee *et al.* reported (2004) that the low–pressure steam explosion can prevent the resin exudation from wood under high–temperature surroundings.

In this study, we adopted the low–pressure steam explosion treatment on wood disks of yellow poplar (*Liriodendron tulipifera*) to estimate the possibility of wood as a sound absorbing material. Then, the changes of anatomical features, air permeability, and sound absorption properties were investigated. From these results, the influence of steam explosion on the air permeability and sound absorption capabilities on the cross–sectional surface of wood were discussed.

MATERIALS AND METHODS

Sample specimens

The specimens for measuring sound absorption coefficient and air permeability were prepared from a cross–sectional surface of yellow poplar. Sample cutting area was restricted only to the sapwood region, because cracks originated usually in the heartwood region when the wetted wood disks by the steam explosion treatment were redried. Moreover, the air permeability and sound absorption coefficients of heartwood were low, and those values were rarely affected by low–pressure steam explosion treatment. The dimensions of the test specimens for the sound absorption coefficient and air permeability were 28.9 mm×30.0 mm (diameter × thickness) and 35.0 mm×10.0 mm (diameter × thickness), respectively. The mean values of the specific gravity, moisture content, and width of the growth ring were 0.50, 14%, and 4 mm, respectively.

Steam explosion treatment

The steam explosion apparatus consists of a stainless steel cylinder, an electrically controlled steam blasting device, a silencer which can reduce the sound level at the moment of explosion, and a steam generating boiler, as shown in Fig. 1. In the figure, the tube induced the superheated steam from the boiler to the closed cylinder. The cylinder, with a removable bolted cap on one end, is 20 cm in diameter and 400 cm in length. The maximum pressure is 7 atm of absolute pressure. The explosion treatment was accomplished by superheated steam, at which the temperature and pressure were 158 ˚C and 6 atm, respectively. The one cycle explosion treatment was accomplished by six minutes of steam–heating and abrupt exhausting by an automatically controlled leak valve and one minute of breathing time. Three–cycle explosion treatments were repeated on the wood disk specimen.

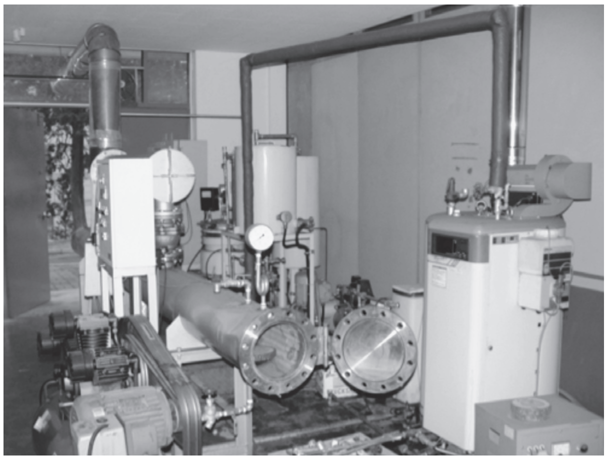


Fig. 1. Photograph of steam explosion apparatus.

Sound absorption coefficeint measuring

The sound absorption coefficient was measured a two microphone transfer function method, impedance tube, and pulse software used in a previous study (Kang *et al.*, 2008 a). The estimation frequency range was from 500 Hz to 6.4 kHz, and the environmental conditions, such as atmospheric pressure, temperature, relative humidity, sound velocity, and air density, were 1015 hPa, 15 ˚C, 36%, 340.30 m/s, and 1.225 kg/m^3, respectively.

Air permeability estimation by capillary flow porometry

Air permeability was estimated by capillary flow porometry designed by PMI (Porous Material Incorporated). This method estimates the pore structure and permeability by means of the liquid and gas flow rates as a function of differential pressure, as described in ASTM 316–03. For instance, wood samples were immersed into wetting liquid, its surface tension is 15.9 N/m, which is less than water with 72 N/m. Subsequently, wood having various diameter pores wetted spontaneously, because of its low surface tension. A fully wetted wood sample is placed in the sample chamber, and then the chamber is sealed. Non–reactive nitrogen gas is then allowed to flow into the chamber behind the sample. When the pressure reaches a point that can overcome the capillary action of the fluid within the largest pore, the bubble point has been found. After determination of the bubble point, the pressure is increased, and the flow is measured until all pores are empty, at which point the sample is considered dry. Gas pressure and flow rates through the dry sample are also measured. From these results, the air permeability and pore structure features of wood samples were estimated. In this study, air permeability changes by capillary flow porometry of normal and steam explosion treated woods were estimated, and the influences of low pressure steam explosion treatment were discussed.

SEM observation

A specimen of 10 mm×10 mm×10 mm (tangential × radial × longitudinal) was cut from the control and steam explosion–treated yellow poplar wood. Samples with cross sectional surface, radial surface, and tangential surface wood were prepared using sharp blades. SEM observations were made on the three surfaces of the control and steam exploded wood specimens using a low vacuum scanning electron microscopy.

Color change analysis

The change in color of the explosion treated specimens was measured with a spectrophotometer (KONICA MINOLTA CR–400) using a D65 light source, which can estimate a color as its lightness and chromatic coordinates: lightness L* which varies from 0 (black) to 100 (white), and a* and b* coordinates, which define the chromaticity from green to magenta and from blue to yellow. This is named as the CIELAB color system. The CIELAB color parameters, L*, a*, and b* were used to represent the color change of steam explosion–treated wood.

RESULTS AND DISCUSSION

Changes of anatomical features by steam explosion treatmenat

Jhang and Cai (2006) reported that the changes of wood color during steam explosion treatments were caused by a series of chemical reactions between the chemical constituents of the wood cell wall and extractives under high temperature and humidity conditions. In this study as well, the color of the cross–sectional surface of yellow poplar changed slightly upon steam explosion treatment. Compared with the control group, the color of treated wood darkened. The value of L* decreased upon steam explosion treatment. For instance, the average lightness of sample specimens decreased from 74.07±3.15 to 61.15±2.11. The average values of a* and b* of the control were 3.7±0.66 and 17.11±2.21, while those values of treated specimens were 6.00±0.80 and 21.15±1.50, respectively. This means that the treated specimens more darkened, and more red and yellow colors were present than those of control specimens. If a higher temperature or longer duration time were accomplished, the wood color may darken further.

Figure 2 shows the three dimensional surface SEM images of treated yellow poplar. No significant structural differences between steam explosion–treated and control samples were observed using LV–SEM observation. However, the increased flow pathway enlargement and air permeability were detected by capillary flow porometry, as described in the following paragraph.

a
b
c
d

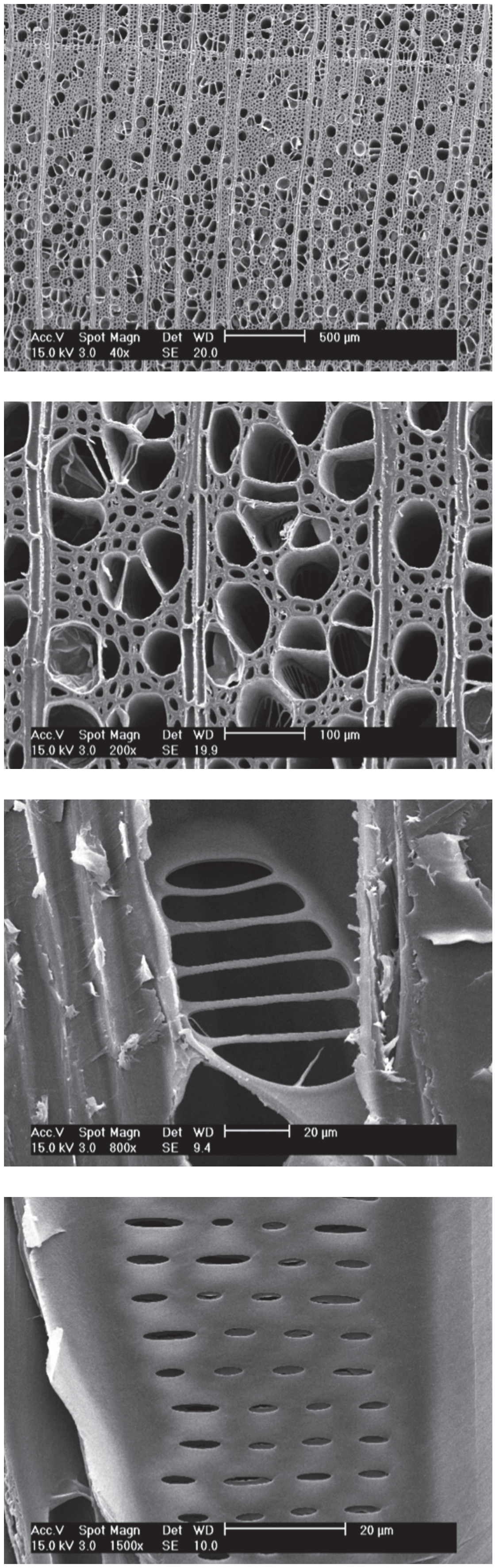


Fig. 2. Anatomical features of *Liriodendron tulipifera*. a, b : cross section, c: radial section, and d : tangential section

Air permeability changes by steam explosion treatment

In the case of capillary flow porometry, when the wetting liquid started to flow, the relation between pore diameter and the differential pressure required to displace the wetting liquid in the pore is obtained from the equation:

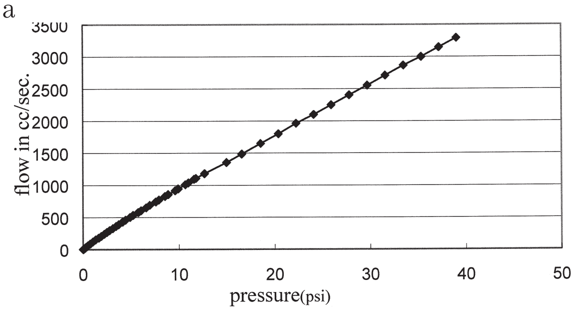
$$p = 4\ \gamma\ \cos\ \theta / D$$

where p is pressure, γ is surface tension, θ is contact angle, and D is pore diameter. This equation suggests that the largest pore is emptied first, and higher pressures are required to empty smaller pores. In this study, the typical relationship between flow rate as a function of differential pressure is shown in Fig. 3; 41.06 and 30.06 psi were needed to empty the smallest pores in control and steam–exploded wood, respectively. This means the treated specimens more easily permit flow than the control.

A comparison of the air permeability in the control and steam–exploded specimens in the fiber direction is shown in Figure 3. Air permeability is obtained from the gas flow rates through the wood in the fiber direction. The average air permeability of control and steam exploded specimens are 2.94 and 4.44 darcys, respectively. The pore diameter of the steam exploded specimen may be enlarged by the extreme steam flow. Capillary flow porometry estimates the constricted pore diameter of a porous material, which is the smallest pore diameter of one flow pathway. The constricted diameter of the largest pore and pore distribution determine the efficiency of fluid flow in porous materials. This constricted pore may be enlarged by steam explosion treatment, because the extreme volume increase of steam removes obstacles or enlarges the flow pathway. Zhang and Cai (2006) reported that the pit aspirations of soft wood were reopened by steam explosion treatment. Hence, Kanagawa *et al.* (1988) reported that the permeability increased by steam explosion treatment was due to resin eruption in the case of hardwood. In this study, the pore size distribution as a function of average pore diameter by CFP represent that the number of permeable pores in treated wood increased, as compared to control wood, as shown in Fig. 4. This result means that the constricted diameter was enlarged by the steam explosion treatment, thereby increasing air permeability. For example, when the differential pressure was in the range of 0.02 to 41.06 psi, the apparent average air permeability of control wood was about 2.94 darcy, while that of treated wood was about 4.44 darcy at a differential pressure range of 0.01 to 30.06 psi.

In the view of the relationship between permeability and sound absorption capability, Wassilieff (1996) reported that the air flow resistivity is closely related to the sound absorption capability, and Xie *et al.* (2004) reported that the sound absorption capability increased with decreasing air flow resistivity. Air flow resistivity also represents the fluid flow efficiency through porous material as the ratio of pressure per unit flow in spite of air permeability, representing flow efficiency as the ratio of flux per differential pressure. The air permeability of

a



b

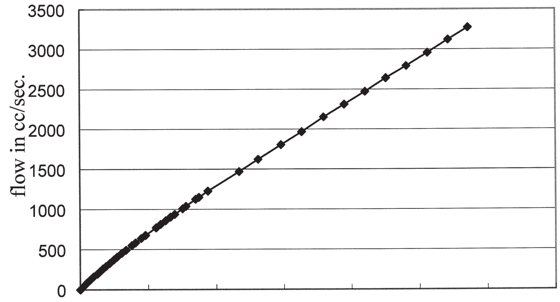
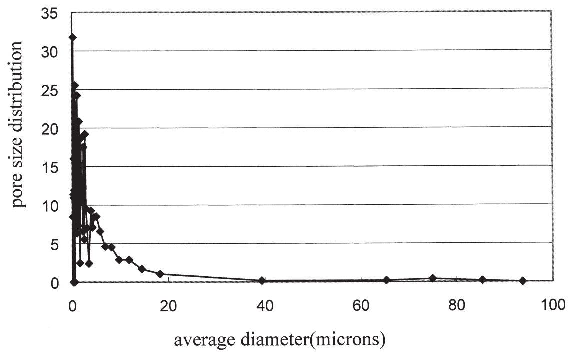


Fig. 3. Examples of pressure versus airflow in fiber direction of *Liriodendron tulipifera*. a. normal wood and b. steam exploded wood

a



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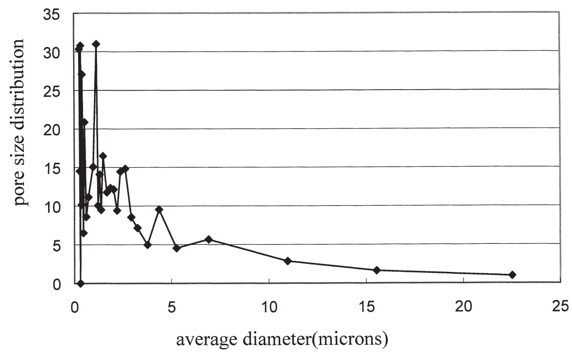


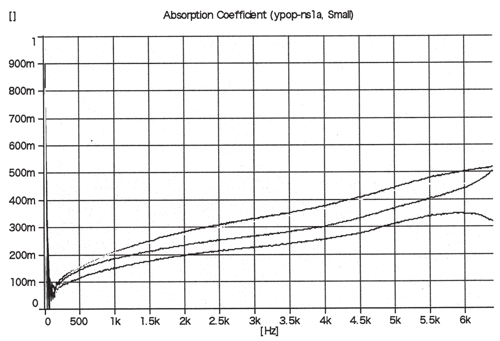
Fig. 4. Examples of pore size distribution as a function of average pore diameter of *Liriodendron tulipifera*. a. normal wood and b. steam exploded wood.

wood in the fiber direction increased by steam explosion treatment, and the sound absorption capability of treated wood increased, as described in the next paragraph.

Sound absorption capability changes by steam explosion treatment

As shown in Figure 5, a and b represent the sound absorption coefficients of control and treated wood, those values were high over the entire frequency range (500–6400 Hz). The sound absorption coefficients of the control and steam explosion treated samples of yellow poplar wood disks increased with the frequency. The sound absorption coefficient of control and treated wood over all estimated frequencies were about 15% to 50%. These values are higher than those of other construction materials, such as concrete, marble, fiberboard, and gypsum board, which is broadly used as sound absorbing board. The high sound absorption coefficient of yellow poplar is due to the high permeability in the fiber direction resulting from its cross–sectional pore structures. From the SEM observation, it was found that there were abundant and large multiple pore vessels, whose diameters were about from 50 μm to 100 μm on the cross section surface, and a thin bar associated scalariform perforation plate on the longitudinal surface of the wood, as shown in Fig. 2 c. Moreover, there was only a few tylosis formations, which restrict the fluid flow in the fiber direction of the wood. These anatomical features, such as abundant large diameter vessel, continuous vessel connection, and a little tylosis contributed to the high air permeability, low air flow resistivity, and high sound absorbing capability.

a



b

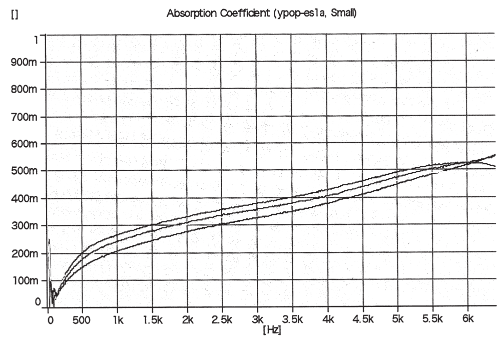


Fig. 5. Frequency versus sound absorption coefficients of *Liriodendron tulipifera* in fiber direction.
a : normal wood and b : steam–exploded wood.

The sound absorption coefficient of the steam explosion treated wood was slightly higher than that of control wood in the high frequency range. In Fig. 5, control and steam exploded wood, four graphs of a and b graphs represent four samples tests, the sound absorption coefficient of steam explosion treated wood was found to be higher than that of the normal wood, and this trend increased as the frequency increased. In the frequency range of 2–6 KHz, the sound absorption coefficient of steam explosion–treated wood is approximately 5–10% higher than that of normal wood.

We performed a statistical analysis in order to determine whether our results were statistically significant. Excel was used for statistical analysis. The F–value, 30.28, was greater than the F–limit, 3.84, which meant that the two groups had a statistically significant difference in sound absorption coefficients within a 95% confidence interval as shown in Table 1. This statistically significant difference between the two groups indicates that the steam explosion treatment contributes to the increase of the sound absorption coefficient of wood in the fiber direction.

From these results, it is surmised that the steam explosion treatment enlarges the flow pathway in the fiber direction of sapwood, and improved the air permeability and sound absorption coefficient of yellow poplar. Therefore, control and steam explosion–treated yellow poplar wood can be used as construction materials when considering a more successful acoustic structure design. Moreover, sound absorption capability of wood was improved by low–pressure steam explosion treatment.

It is concluded that the steam explosion treatment could be used as a technique to improve the sound absorbing capability of wood, but further investigation is required on the relationship among pore structure, air permeability, and sound absorption capability of wood. Additionally, further investigation related to selecting highly absorptive wood species, radial variation, and operational parameters of steam explosion, treatment such as pressure, temperature, and cycles should be investigated.

Table 1. ANOVA table for the comparison between control and treated groups

Summary

Groups	Count	Sum	Mean	Variance
Column 1	3204	1096.716	0.342296	0.13758
Column 2	3204	908.0077	0.283398	0.229438

Anova

Factor	SS	DF	MS	F	P–value	F–limit
Treatment	5.557266	1	5.557266	30.28332	3.88E–08	3.842911
Error	1175.56	6406	0.183509			
Total	1181.117	6407				

CONCLUSION

By the low pressure steam explosion treatment on the wood disk of yellow poplar, the wood color darkened by 158 ˚C, 6 bars, and three steam explosions.

There were abundant, large–diameter, multiple–pore vessel elements observed on the cross–sectional surface of yellow poplar wood disks and vessel elements connected with the thin bar scalariform perforation plate. It is considered that these large pores and continuous vessel element interconnections contributed to the high air permeability and sound absorption capability in the fiber direction. However, significant anatomical changes were not observed by scanning electron microscope (SEM) on treated sample specimens, as compared to control wood, with this treatment condition.

The air permeability in the fiber direction of treated wood was higher than those of control wood, and the sound absorption coefficients of treated specimens were slightly higher than those of normal wood specimens at the high–frequency range. These experimental results show that the steam explosion treatment could be considered a technique to improve the permeability and sound absorption capability of wood on the cross–sectional surface.

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