Improving the Sound Absorption Capacity of Wood by Microwave Treatment

Dong Wang, Limin Peng,* Guangyong Zhu, Feng Fu, Yongdong Zhou, and Boqi Song

Microwave treatment (MW) was used to improve the sound absorption capacity of *Pinus sylvestris* var. *mongolica* wood. The effects of the processing parameters such as MW intensity, processing time, and board thickness on the sound absorption of treated wood were investigated. Microstructure changes of the wood after microwave treatment were observed using scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP). It was found that the microwave treatment significantly enhanced the sound absorption capacity of the wood in the middle frequencies. The optimum microwave treatment parameters for *Pinus sylvestris* var. *mongolica* wood to achieve an improved permeability are: MW intensity of 18 Kw, board thickness of 30 mm, and processing time of 80 s. The maximum sound absorption coefficient of treated wood was 0.51. Micro-voids were formed in treated wood due to the destruction of the pit membranes, the wood ray cells, as well as the damage in the intercellular layer of the longitudinal tracheids. The number of micro-voids ranging from 7427.6 nm to 400 um increased, resulting in the increase in the air permeability and in sound absorption by the treated wood.

Keywords: Pinus sylvestris var. mongolica; Microwave treatment; Sound absorption capacity

Contact information: Research Institute of Wood Industry, Chinese Academy of Forestry, Key Lab of Wood Science and Technology of State Forestry Administration, Haidian District, Beijing 100091, China;
** Corresponding author: penglm@caf.ac.cn*

INTRODUCTION

Wood has been widely used as construction and decorative material due to its environmental sustainability, good mechanical and decorative properties, as well as high thermal insulation properties. Besides, the unique acoustic properties and aesthetic appeal of wood make it the material of choice for musical instruments and interiors of concert halls.

The wood acoustic properties such as the speed of sound (Wegst 2006), the characteristic impedance and air resistance (Chia *et al.* 1988), the sound radiation coefficient, and the loss coefficient as well as different treatment methods to modify the wood acoustic properties were investigated extensively in previous studies (Kang *et al.* 2008, 2010). Kang *et al.* (2010) reported the possibility of improving the air permeability and sound absorption capacity of wood by using low-pressure steam explosion. It was found that by using this approach, the treated wood displayed higher air permeability in the fiber direction than did its untreated counterpart; the difference resulted in a 15% to 50% increase in sound absorption for the treated wood in comparison to the untreated wood. In addition, Kang *et al.* (2008) also reported that the delignification treatment improved the wood air permeability in the longitudinal direction. They found that the intercellular substances were gushed out and numerous small cracks were formed on the surface of the delignification wood. The sound absorption coefficients of the delignification wood were found to be higher than those of normal wood in the entire frequency range. Itoh *et al.* (1998) developed an underwater shock technique to treat the Sugi (*Cryptomeria japonica* D. Don) wood in an attempt to improve the drying capacity of wood. An increase in air permeability was observed for the treated wood. However, none of the above-mentioned studies significantly improve the sound absorption capacity of the wood.

Although wood is a porous material with a variety of cylindrical pores in the fiber direction, the pit-aspirations in softwood or tyloses in hardwood result in poor interpore continuity and poor permeability and sound absorption properties (Fujii *et al*. 1997, Kanget *et al*. 2010).

Microwave treatment (MW) used for wood drying was found to significantly improve the wood liquid permeability (Torgovnikov and Vinden 2009; Hesheng *et al*. (2014). Microwave energy is delivered directly to wood through molecular interaction with an electromagnetic field. Microwave heating transfers the electromagnetic energy to thermal energy. Microwaves can penetrate materials and deposit energy, and the heat could be generated throughout the volume of the material. A microwave is able to rapidly and uniformly heat thick materials (Thostenson and Chou 1999). After wood microwave treatment, micro-checks were formed at the intercellular layer of ray cells, and the longitudinal tracheids and the pit membranes were damaged (Hesheng *et al*. 2014). These micro-checks might improve the air permeability of the treated wood. Very few studies have focused on improving the sound absorption capacities of wood using microwave treatment.

Scanning electron microscopy (SEM) is an effective and frequently used method to characterize the wood anatomical features at a microscopic level. The microstructural changes of wood before and after microwave treatment could be identified using SEM. Correlating these changes in wood microstructure could provide insights on how the microwave treatment improved the wood air permeability. Moreover, changes in microstructure could result in variation of the porosity, pore size and distribution, and inter-pores connectivity, which are important parameters for studying the sound absorption capacity.

The amount of porosity, pore size and distribution, and interpore connectivity strongly influence the material properties, particularly sound absorption capacity and air resistance. The total porosity has been found to decrease as the normal bulk density increases (Plötze and Niemz 2011). The sound absorption capacity would improve with increasing porosity and decreasing normal bulk density.

Measurements of porosity, pore size, and distribution are based on gas absorption (water vapor, nitrogen, *etc*.) and mercury intrusion porosimetry (MIP) (Lowell *et al.* 2004). The MIP method applies pressure to force mercury into the pores. The volume of the mercury entering the pores is used to determine the pore volume, and the pressure needed is used to determine the pore size. Mercury has the advantage of not wetting wood and not penetrating the pores through capillary action. Measurements of total intrusion volume, total pore surface area, pores size and distribution, bulk, and apparent specific density could be conducted using this method (Plötze and Niemz 2011).

In this study, microwave treatment was developed to improve the air permeability and sound absorption of wood. The objective of this study was to develop appropriate processing parameters (MW intensity, processing time, and thickness of samples) in order to increase the sound absorption property of *Pinus sylvestris* var. *mongolica* wood. SEM was applied to correlate the microstructure changes with the changes in air permeability and sound absorption of the WM-treated wood. MIP was also used to understand the relationships between the microstructures such as the pore size and distribution and the air permeability and sound absorption of the WM-treated wood.

MATERIALS AND METHODS

Materials

Pinus sylvestris var. *mongolica* log was purchased from AoRui-yuan commercial and trade center, Beijing. (aory@163.com.). The wood oven dry density was 0.42 g/cm^3. The moisture contents (oven dry basis) of the sapwood and heartwood were about 127% and 31%, respectively. The sapwood was used for the experiment and cut into planks with the dimension of either 500 mm (length) × 120 (width) mm × 20mm (thickness) (denoted as Group I) or 500 mm (length) × 120 (width) mm × 30 mm (thickness) (denoted as Group II). Each group had at least 10 samples, and the reference samples were randomly selected and used as a control without microwave treatment.

Methods

Microwave treatment

The microwave treatment was carried out using the continuous belt MW equipment (Research Institute of Wood Industry, Chinese Academy of Forestry, WX20L-19). The microwave cavity was square in shape with a cross-sectional area of 120 mm × 120 mm. The drier was operated at a frequency of 0.915 GHz, with a maximum working power of 20 kW. The microwave intensity was set at 10 kW and 18 kW. The wood moisture content was about 30%, and the processing time was set at 80 s, 120 s, and 180 s. The optimized MW parameters were determined using optimized sound absorption property. The effects of thickness of the treated wood, microwave intensity, and processing time on the sound absorption of the treated wood were investigated using a full factorial experiment. The variables and their levels are listed in Table 1.

After the MW treatment, the MW-treated samples were dried in the vacuum drying oven at 50 ^{o}C. The final moisture content of the samples was approximately 10%. For each processing condition shown in Table 1, at least three samples were treated. For each sample, three replicate sound absorption measurements were made. Sample numbers are given in Table 5.

Table 1. Full Factorial Experimental Design for MW Treatment

Factors	Thickness (mm)	Power (kW)	Time (s)
Levels	20	10	80
			120
	30	18	160

Sound absorption coefficient

The sound absorption capacity of the treated wood was tested using Type SW 422 and Type SW 477 impedance tubes (BSWA Technology Co., Ltd., China. Fig. 1) based on the method of ISO 10534-2 (1998). During the sound absorption measurements, the samples were placed against the steel backing. The normal sound absorption coefficients at the 1/3-octave frequencies were measured using the large tube (SW 422, Φ 100 mm) in the frequency range of 63 to 1600 Hz. The sound absorption coefficients in the frequency range of 1000 to 6300 Hz were measured using the small tube (SW 477, Φ30 mm). The sound absorption coefficients in the full frequency range (63 to 6300 Hz) were the most curve-fitting of the values measured using the two tubes.

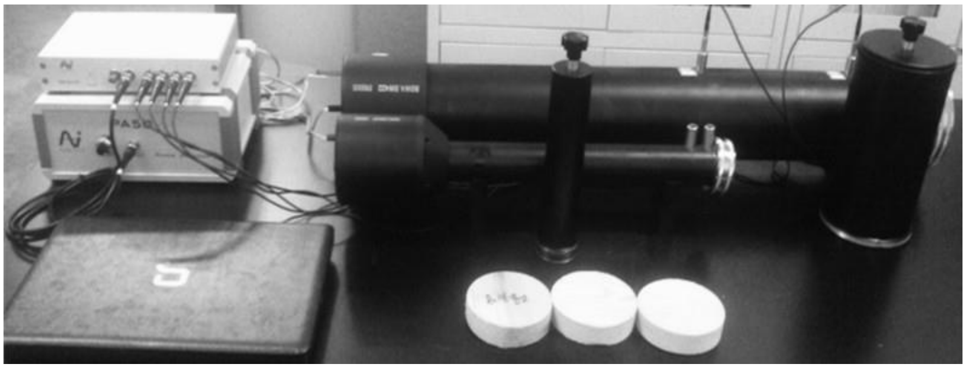

Fig. 1. Impedance tubes and samples

Scanning electron microscopy

The changes in the microstructure of MW-treated wood were examined using a Hitachi S-4800 Field Emission Scanning Electron Microscope (SEM) (Japan). The operation accelerating voltage was 10 kV. A rotary microtome (KD-2258, Wan Tong Precision Instruments Co., Ltd.; China) was used to cut the samples (5 mm × 5 mm) along the radial and tangential direction. Samples were mounted on aluminum stubs with double-sided tape, sputter-coated with gold, and analyzed for changes in microstructure in the radical and tangential sections.

Mercury Intrusion Porosimetry (MIP)

The mercury intrusion porosimetry (MIP, Autopore^{TM} IV 9500 Automated Mercury Porosimeter, Micromeritics Instrument Corp., US) was used to characterize the porosity and pore size of treated wood. It forced mercury into the pores using high pressure, with the volume of mercury that entered the pores used to determine pore volume and the pressure needed used to determine the pore size. Measurements of total intrusion volume, total pore surface area, pore size, and size distributions were all possible. About 0.16 g of air-dried samples with dimensions of 8 mm L × 6 mm T × 6 mm R were cut perpendicularly from the MW-treated wood and the control wood. The specimens were further oven-dried at 103 ± 2 °C, and measurements were conducted by increasing the pressure to 400 MPa on a sample immersed in the non-wetting mercury. The pressure increasing rate was automatically controlled with a lower rate at lower pressure levels. As the pressure increased, mercury progressively moved into smaller voids. The pore volume could be derived from the quantity of mercury used. The pore distribution was determined according to the Washburn equation, which gives a relationship between pressures and pore size,

$$r = -\frac{2\gamma \cos\theta}{p} \quad (1)$$

where *r* is the pore radius, *p* is pressure, *r* is the surface tension of mercury (0.48 N/m), and Φ is the wetting angle of mercury (141°) (Lowell *et al.* 2004; Junghans *et al.* 2005; Niemz *et al*. 2010).

Statistical analysis

The obtained data were analyzed using the software program SAS, version 8 (USA), and the confidence degree was 0.95. The dependent variables were average sound absorption coefficient and maximum sound absorption coefficient within the measurable 1/3-octave frequency range. The independent variables were MW intensity, board thickness, and processing time.

RESULTS AND DISCUSSION

Sound Absorption Capacity

The effect of thickness

The average sound absorption coefficients for samples with the thicknesses of 20 mm and 30 mm were 0.08 and 0.15, respectively. Furthermore, the maximum sound absorption coefficient for samples of thickness 30 mm was higher than that of a 20 mm-thick sample (Fig. 2). The statistical analysis indicated that the thickness had a significant effect on the sound absorption of the treated wood (Table 2). For the sample with 20 mm thickness, when WM intensity was 10 Kw and 18 Kw, the sound absorption coefficient attained a local peak value of 0.26 at 2500 Hz and 0.22 at 1250 Hz, respectively (Fig. 2). However, for the sample of 30 mm thickness, when WM intensity was 10 Kw and 18 Kw, the sound absorption coefficient attained a local peak value of 0.33 at 1000 Hz and 0.51 at 800 Hz, respectively (Fig. 2). The results form Table 5 showed that the oven-dried density after treatment was different for different thickness of board. The greater the thickness of wood, the lower density of treated wood, when MW intensity was 18 Kw. However, when the microwave intensity was 10 Kw, no such relationship was found. Possible reasons could be that the microwave intensity was too small and the treatment effect was inefficient. The average sound absorption coefficient of the fifth sample was smaller than the eleventh, for which the densities were 0.373g/cm^3 and 0.358 g/cm^3, respectively. With the increase in sample thickness, the peak value of the sound absorption coefficient increased and the absorption peak was in the low-frequency range. The effect of thickness difference was insignificant at both low and high frequencies (Fig. 2).

Compared with the thin plates, the thick ones generated more steam and higher vaporized steam pressure at the same MW intensity and moisture content. In addition, the thicker plates were better than the thin ones in keeping pressure to form more and wider cracks. When sound waves were transmitted to the voids, they could follow the pores into the material and cause air molecules to vibrate. Mainly due to the viscous friction phenomena in the solid frame and at the interface between the solid frame and the air in the cracks, the sound energy was attenuated and partially transformed into heat energy (Chunhua *et al.* 2012). Furthermore, the sound pressure would also force the rigid frame of the voids to vibrate. When the frequency of the incident sound wave was close to the vibrational frequency of the rigid frame, the sound energy was converted into kinetic energy (Liu *et al.* 2008). The larger cracks containing more air could produce more frictional heat from sound energy.

Table 2. The Effect of Thickness of Treated Wood on Sound Absorption Coefficient

Thickness (mm)	Average-Absorbance	Max-Absorbance
20	0.08^{A} (0.01)	0.25^{A} (0.05)
30	0.15^{B} (0.06)	0.42^{B} (0.10)
*Mean values with the same letter in each column were not significantly different at the 5% level Standard deviations are in parentheses. Moisture content of the samples was about 10%.		

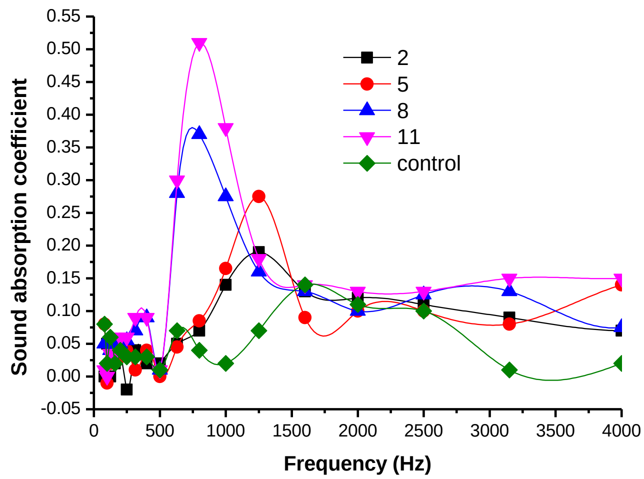

Fig. 2. Sound absorption coefficient for treatment wood of different thicknesses

The MW-treated wood could be considered as a type of porous material, consisting of many Helmholtz resonances in parallel. Every crack in the porous material could be seen as a Helmholtz resonance. Therefore, when the incident sound wave frequency matched the natural frequency of the resonator, the resonance frequency was:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{s_0}{Va}} \qquad (2)$$

In Eq. 2, c is the sound velocity (m/s), f_0 is the resonance frequency (Hz), S_0 is the cross-sectional area of the aperture (m^2), V is the void volume (m^3), and a is the effective length of an aperture (m). In this study, the treated wood was considered to consist of many Helmholtz resonances in parallel, and the resonance frequency was,

$$f = \frac{c}{2\pi}\sqrt{\frac{p}{DL}} \qquad (3)$$

where p is the porosity, D is the voids width (m), L is the effective length of an aperture (m), and f is the resonance frequency (Hz).

With increasing width and quantity of voids, the peak value of the sound absorption coefficient increased and the resonance frequency or absorption peak would shift to the low-frequency region since the crack width was broadened according to Eq. 3.

Furthermore, the resonance absorption acoustic frequency bandwidths of treated wood with selected dimensions was less obvious at about 600 Hz (Note: f_1 and f_2 represent frequencies, the absorption coefficients were half of the maximum absorption coefficient in the high and low frequency band; the resonance absorption acoustic frequency bandwidth was the number of octaves between f_1 (1250) and f_2 (630)).

The effect of MW intensity

The impact of different MW intensities on sound absorption is shown in Fig. 3. A maximum sound absorption coefficient of 0.33 appeared at 1000 Hz when the specimens were exposed to a MW intensity of 10 kW. The maximum sound absorption coefficient increased to 0.53 at 800 Hz when the MW intensity was raised to 18 kW. With the increase in MW-intensity, the peak value of the sound absorption coefficient increased, and both the frequency bandwidth and the resonance frequency decreased (Fig. 3). The different MW intensities did not cause a significant increase ($p<0.05$) in the average sound absorption coefficient, but did have a significant effect on the maximum sound absorption coefficient. The density decreased with the MW intensity increased (Table 5). The seventh, tenth and control group samples densities were 0.398 g/cm^3, 0.362 g/cm^3, and 0.417g/cm^3, respectively. The improvement in the sound absorption capacity of the tenth sample with lower density was more significant than others.

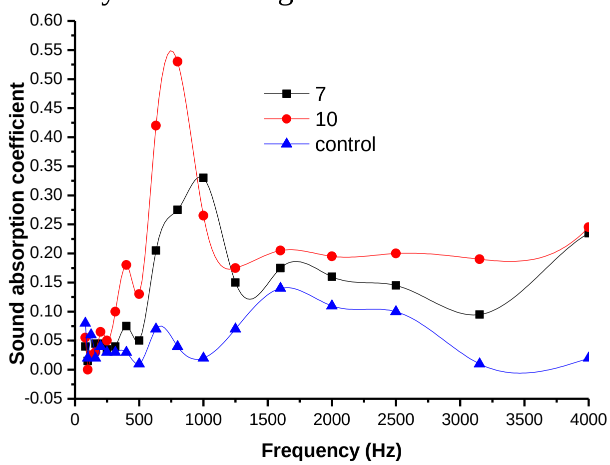

Fig. 3. Sound absorption coefficient at different microwave intensity

The steam pressure in the wood increased with the increase in microwave intensity. Therefore, the wood rays and the tracheid walls were ruptured more easily at higher intensities. When the samples were subjected to the microwave treatment, the resin in the wood was softened before melting. The steam pressure in the wood forced the soft resin to move out from the rays, leaving pores or cavities (Vinden *et al*. 2004). In comparison to the untreated wood, MW-treated wood had a significantly ($p<0.05$) better sound absorption at all frequencies (Fig. 3). It was observed that the increases in the MW intensity caused the peak to shift to a lower frequency and improved the low-frequency sound absorption. Due to the increase in the number and width of the cracks, there was a decrease in the flow resistance and specific acoustic resistance. Furthermore, with the increase in the number and width of cracks, the air quality in the void volume together with the quality factor (*Q*) were improved and resulted in a narrower frequency bandwidth. The MW intensity provided a significant contribution to the maximum sound absorption capacity of the treated wood, according to the data in Table 3. The energy absorption and the rate of water evaporation were mainly influenced by MW intensity when the wood moisture content and microwave processing time were constant (Zhang 2008).

Table 3. Effect of MW-Intensity on Sound Absorption Coefficient

Power (kW)	Average-Absorbance	Max-Absorbance
10	0.11^{A} (0.008)	0.17^{A} (0.02)
18	0.10^{A} (0.008)	0.40^{B} (0.02)

Mean values with the same letter in each column were not significantly different at the 5% level Standard deviations are in parentheses. (Board thickness was 30 mm and moisture content was about 10%)

The effect of processing time

Figure 4 shows the sound absorption capacity of wood at different MW treatment times. The sound absorption coefficient decreased as sound frequency increased. The trend was consistent at different processing times. The effect of processing time on sound absorption capacity was insignificant at the 5% level. The density of treated wood slightly decreased with the increase in the processing time. The processing time primarily affected the vaporization energy in the wood. When high frequency microwave was applied to the wood, an electrostatic field was created. The dipoles within the wood became polarized, and they rotated and frictionally moved during a short period of time. This will create a massive source of heat. With the increase in processing time, the water continued to absorb energy and evaporate, but the microstructure remained unchanged. Thus, the sound absorption coefficient decreased with increases in frequency, but remained constant when the processing times differed.

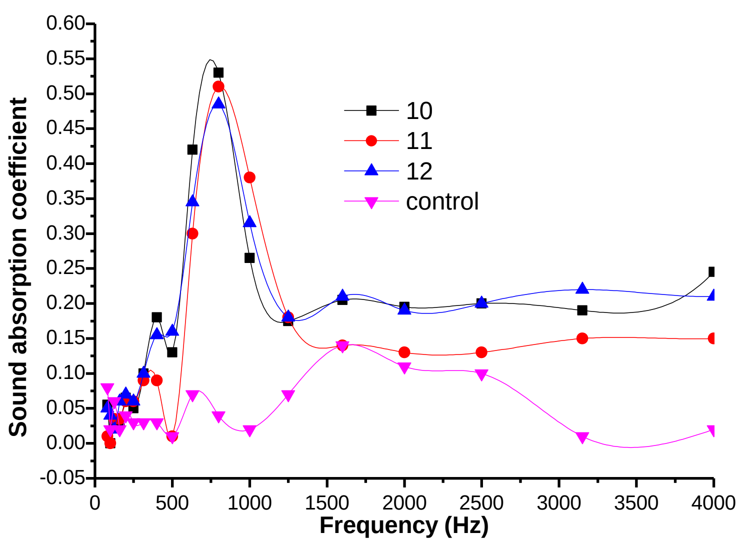

Fig. 4. Sound absorption coefficients at different microwave power

Table 4 shows that the magnitude of deviation was less obvious for different processing times because the mean values with the same letter in each column were insignificantly different at the 5% level. These results indicated that the selected microwave processing time were too long.

Table 4. Effect of Treatment Time on the Sound Absorption Coefficient

Time (s)	Average-Absorbance	Max-Absorbance
80	0.10^{A} (0.01)	0.37^{A} (0.02)
120	0.09^{A} (0.01)	0.31^{A} (0.02)
160	0.13^{A} (0.01)	0.31^{A} (0.02)
Mean values with the same letter in each column were not significantly different at the 5% level Standard deviations are in parentheses. (Board thickness was 30 mm and moisture content was about 10%)		

Changes in Anatomical Features of MW-treated Wood

Macro-cracks

Macro-cracks were observed for treated wood. The width of the cracks measured approximately 1.5 mm (Fig. 5) along with wood rays in the radical-longitudinal plane of wood. The cell walls of the ray cells are thinner than the cell walls of the main wood tissues (*i.e.*, tracheids, libriform) and run in a radical direction from the pith to the cambium of the tree stem. Macro-cavities of various sizes formed after the microwave treatment could help the acoustic waves to propagate freely through the system. The acoustic energy was carried through both the air in the cracks and through the solid frame of the materials. The density (oven-dry density) of the microwave-modified wood was reduced (Table 5).

Fig. 5. Treated wood

Table 5. Change of Density Before and After MW Treatment

NO.	Samples numbers	Density (before treatment) g/cm^3	Density (after treatment) g/cm^3
1	20 -10- 80	0.415	0.383
2	20-10-120	0.416	0.375
3	20-10-160	0.415	0.359
4	20 -18- 80	0.427	0.381
5	20-18-120	0.405	0.373
6	20-18-160	0.424	0.352
7	30- 10- 80	0.433	0.398
8	30-10-120	0.413	0.390
9	30-10-160	0.405	0.386
10	30 -18- 80	0.417	0.362
11	30-18-120	0.428	0.358
12	30-18-160	0.414	0.353

Note: samples numbers were MW treated parameters. 20-10-80 indicated thickness of treated wood was 20 mm, MW treated intensity was 10 kW, and processing time was 80 s.

Similar results were reported by Torgovnikov and Vinden (2009) on changes in the wood oven-dry density before and after microwave processing.

Micro-cracks

Micro-voids were observed at the intercellular layer of the longitudinal tracheids and wood rays in the treated wood using SEM (Figs. 6a and 6b). Figures 6b and 6e show that, in contrast to the control group, part of the pit membranes were destroyed in the treated wood. Furthermore, the wood ray cell walls and tyloses were broken compared with untreated wood (Figs. 6c and 6d). This is consistent with the findings of Torgovnikov and Vinden (2009). The micro-voids in the range of 5 μm to 50 μm were caused by the partial destruction of the pit membranes and damage to the intercellular layer of the longitudinal tracheids. These results agreed with the increasing trend of micro-voids from 7 μm to 30 μm (Fig. 7), which will be discussed later.

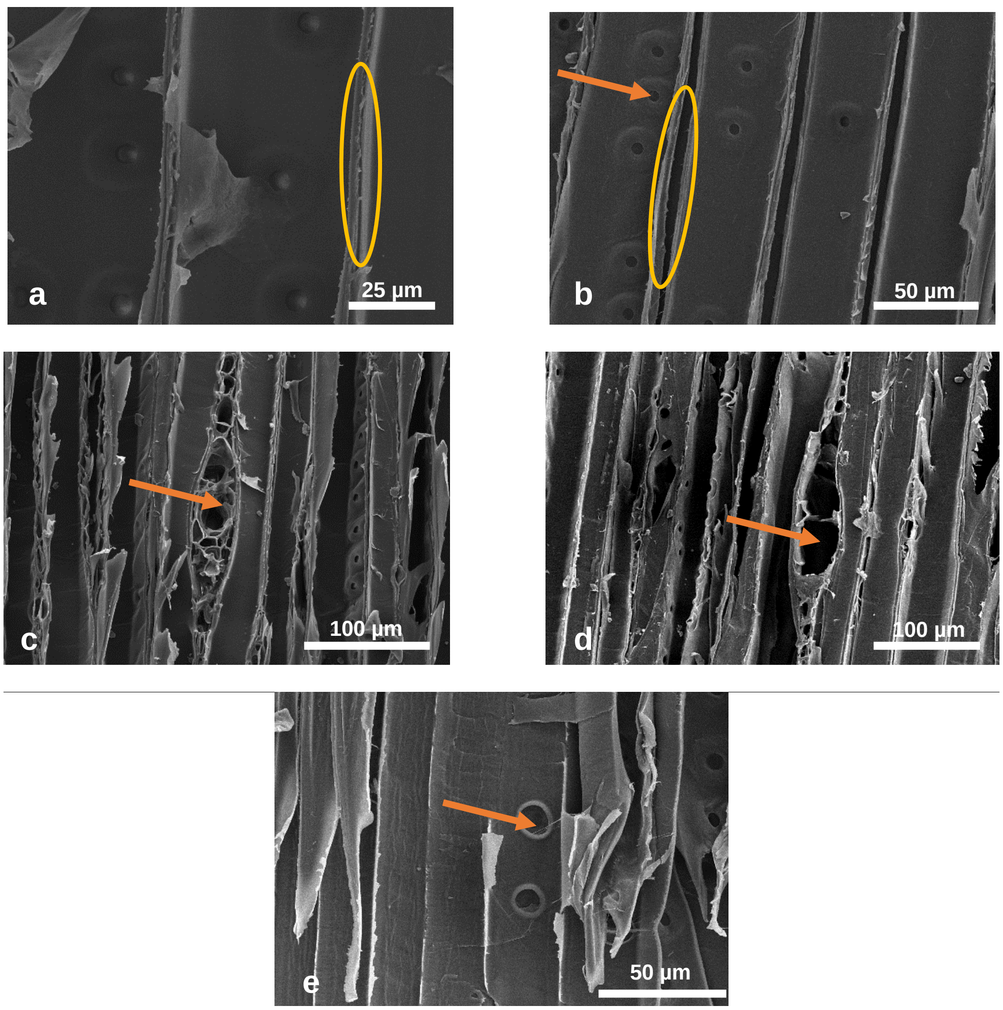

Fig. 6. SEM images of MW-treated wood and control group. (a) Control; intercellular layer of longitudinal tracheids without checks; (b) Treated (30 mm, 18 kw, 30%, 80 s); micro-checks in intercellular layer of longitudinal tracheids; (c) Control; resin trapped in the canals; (d) Treated (30 mm, 18 kw, 30%, 80 s); resin moved and disappeared; and (e) Treated (30 mm, 18 kw, 30%, 80 s); damaged pit membranes. Arrows denote the change of resin in the canals (c,d), and destruction of the pit membrane (e).

Airflow in softwood can occur in both the longitudinal and transverse directions. Airflow in the transverse (tangential) direction is mainly through inter tracheid-bordered pits, while horizontally aligned rays constitute the main pathways for flow in the radial direction. The air permeability of treated wood can be improved through these micro-voids. Zhang and Cai (2006) reported that the pit aspirations of soft wood were reopened by steam explosion treatment. Kanagawa (1988) found that the increase in permeability after the steam explosion treatment was due to resin eruption, which led to the enhancement of inter-cells connectivity, the decrease in flow resistance, and thus the improvement of sound absorption.

The anatomical feature changes in the microstructure of treated wood offered insights on the mechanism of the improvement in sound absorption after the MW treatment. These macro-cracks and micro-pores contributed to the improvement of porosity and inter-cells connectivity of treated wood and decreased the resistance to airflow. It reflected the resistance of air through material voids. When sound waves enter the treated wood, they can follow pores into material and cause air molecules in the voids to vibrate. The air flow velocity was slower near the wall of voids due to resistance and friction. It caused part of the sound energy to be attenuated and transformed into heat energy. The sound absorption capacity of treated wood was superior to that of the control sample in the whole band frequency. It could be explained by the fact that the sound waves entered the treated wood materials by diffraction, whereas at the untreated wood surface, instead of diffraction, reflection of sound waves was more likely to occur. In order to estimate the degree of modification and the improvement in sound absorption, it is necessary to know the quantity and dimensions of the cracks appearing in the wood. Further investigation should establish the relationship between the quantity even dimensions of the cracks and the sound absorption coefficient.

Changes in Pore Size and Distribution after MW treatment

The values of total intrusion volume, total pore area, median pore diameter (volume), median pore diameter (area), average pore diameter (4 V/A), and bulk density at 0.43 psi are shown in Table 6. The parameters of median pore diameter (volume), median pore diameter (area), and average pore diameter were improved significantly at the 5% level after the MW treatment (Table 6), even though the bulk densities of the control and MW treated wood taken for the MIP test were almost the same (0.4064 g/cm^3 and 0.3940 g/cm^3, respectively).

Table 6. MIP Test Results Before and After MW Treatment

	Total intrusion volume mL/g	Total pore area m^2/g	Median pore diameter (volume)/nm	Median pore diameter (area)/nm	Average pore diameter (4V/A)/nm	Bulk density at (0.43 psi) g/cm^3
MW-treated	1.5226	13.720	1217.5	209.7	443.9	0.3940
Control	1.5005	16.539	463.2	199.6	362.9	0.4064

Figures 7 and 8 show the relationship between the cumulative pore volume and the pore size distribution. The results indicated that the increase in the cumulative pore of volume ranged from 3.1 nm to 40 μm after the MW treatment. The contribution of dominant pore radius to cumulative pore of volume for treated wood was 7427.6 nm and 40 μm (shown in Fig. 8), which was about 34% of volume contribution. Figure 9 displays the pore volume calculated using the logarithm of the differential pore diameters; the pore diameter distributions before and after treatment are also shown. The segment of the curve with the higher slope, corresponding to the pore sizes of 7427.6 to 33004.4 nm (Figs. 7, 8, and 9), might reflect the occurrence of damage to the pit membranes. It might be the result of resin in the cell having been shifted out. This result was consistent with the increasing trend of micro-voids in the range from 7 µm to 30 µm (Fig. 6). In accordance with Schneider's research on the pore size distribution of 30 different wood species, characterized using MIP, the pore radii were classified into three classes: <0.1 µm for micro-voids or cell wall capillaries; 0.1 to 5 µm for some small tracheid openings; and >5 µm for large lumens (Schneider 1979). Pores with diameters ranging from 7247.6 nm to 416598.3 nm were found in the tracheid lumens to the microwave treatment. The present results were consistent with previous studies. (He *et al.* 2014).

It is reasonable to predict that these microstructure changes in the pit membranes and wood rays, *i.e.*, the increase in cumulative pore volume and in intrusion volume, would lead to increased air permeability. Air permeability, the smallest pore diameter of one flow pathway, is estimated on the basis of the constricted pore diameter of a porous material. The constricted diameter of the largest pore and the pore distribution determine the efficiency of fluid flow in a porous material. This constricted pore might be enlarged by microwave treatment, as the extreme volume increase of the steam within the material has the effect of removing obstacles and enlarging the volume of pathways (Kang *et al.* 2010). The checks and voids, with dimensions ranging from 7 um to 1500 um, contributed to the improvement in the sound absorption capacity of treated wood at mid-frequency, since they decreased the flow resistance. Furthermore, the micro-voids enhanced the inter-cells connectivity of the wood, resulting in augmented transmission and reduced reflection of sound waves at the wood surface. When sound waves enter treated wood, they can follow pores into the material and cause air molecules in the voids to vibrate. The air flow rate and air molecules vibration were slower near the wall of voids, resulting from viscous resistance and friction, which caused the sound energy to be attenuated or partially transformed into heat energy.

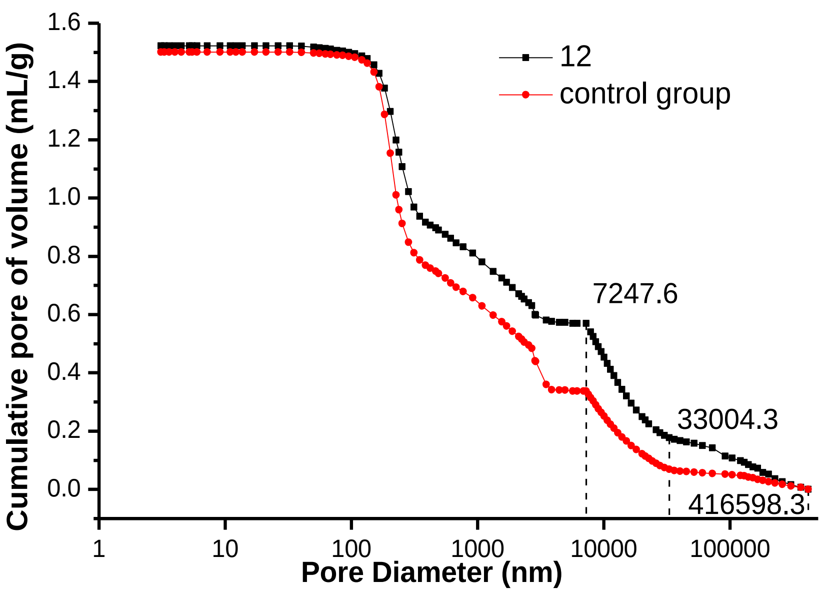

Fig. 7. Cumulative pore volume as a function of the pore diameter of wood before and after MW treatment

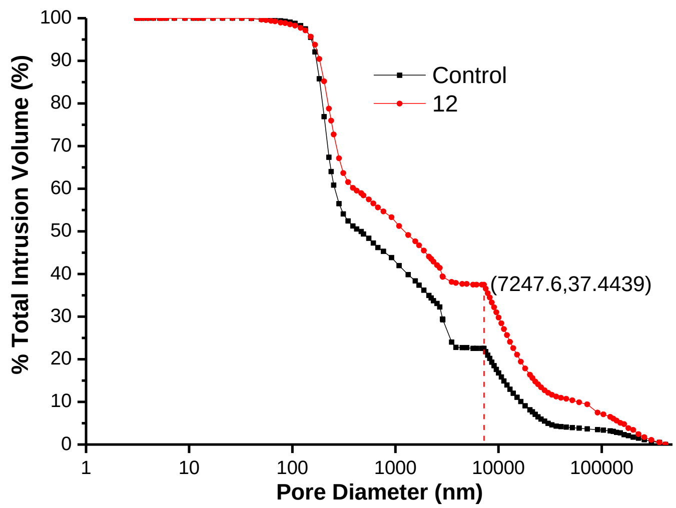

Fig. 8. Percentage of intrusion volume versus pore diameter of MW-Treated and control group

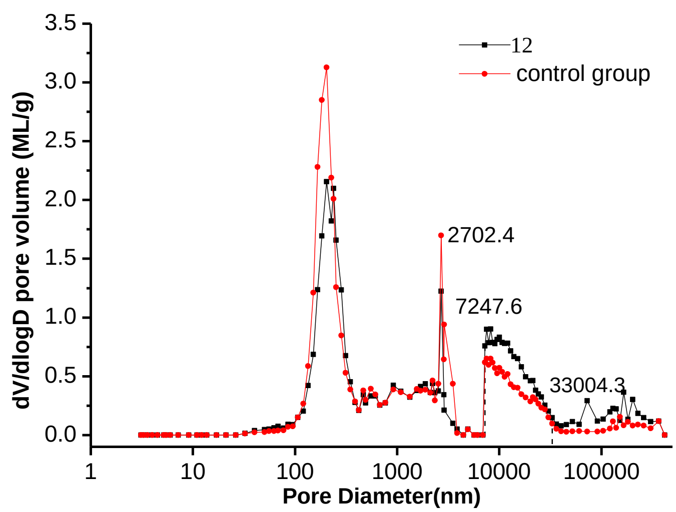

Fig. 9. Log differential intrusion as a function of the pore diameter of wood before and after MW treatment

CONCLUSIONS

1. In accordance with the experimental results, a method was provided to increase the sound absorption capacity of wood. When microwave intensity, thickness of the wood, and processing time were controlled at 18 kW, 30 mm, and 80 s, respectively, the optimal sound absorption was achieved for the treated wood.
2. The microwave treatment significantly increased the sound absorption of wood in the middle frequencies. The peak sound absorption coefficient increased to 0.55 at 800 Hz under the optimized microwave treatment parameters.
3. The micro-voids caused by the partial destruction of the pit membranes and wood rays and the damaged intercellular layer of the longitudinal tracheids were observed using SEM. Those micro-voids enhanced the intercell connectivity of the treated wood, resulting in the improved air permeability and sound absorption of the treated wood.

ACKNOWLEDGMENTS

This work was supported by the key project of "Twelfth Five-year Plan" of National Science and Technology (Grant No. 2012BAD24B02).

REFERENCES CITED

Chia, L. H. L., Teoh, S. H., Tharmaratnam, K., and Tan, L. C. (1988). "Sound absorption of tropical woods and their radiation-induced composites," *International Journal of Radiation Applications and Instrumentation. Part C. Radiation Physics and Chemistry* 32(5), 677-682. DOI: 10.1016/1359-0197(88)90087-2

Fujii, T., Suzuki, Y., and Kuroda, N. (1997). "Bordered pit aspiration in the wood of *Cryptomeria japonica* in relation to air permeability," *Iawa Journal* 18(1), 69-76. DOI: 10.1163/22941932-90001462

He, S., Lin, L., Fu, F., Zhou, Y., and Fan, M. (2014). "Microwave treatment for enhancing the liquid permeability of Chinese fir," *BioResources* 9(2), 1924-1938.

ISO 10534-2 (1998). "Acoustics-Determination of sound absorption coefficient and impedance in impedance tubes. Part 2," *International Organization of Standardization*, Geneva, Switzerland.

Itoh, S., Nagano, S., and Fujita, M. (1998). "The improvement of the permeability of wood by underwater shock wave," *Metals and Materials* 4(4), 843-846. DOI: 10.1007/BF03026410

Kang, C. W., Kim, G. C., and Park, H. J. (2010). "Changes in permeability and sound absorption capability of yellow poplar wood by steam explosion treatment," *Journal of the Faculty of Agriculture* 55(2), 327-332.

Kang, C., Kang, W., and Chung, W. (2008). "Changes in anatomical features, air permeability and sound absorption capability of wood induced by delignification treatment," *Journal of the Faculty of Agriculture* 53(2), 479-483.

Kanagawa, Y. (1989). "Resin distribution in lumber dried by vacuum drying combined with radio frequency," *IUFRO 1989 Wood Drying Symposium*, Seattle, WA.

Liu, K., Qing C., and Tian, J. (2008). "Resonance sound-absorbing structure for sheet," *Chinese patent NO. CN 101329865A*.

Lowell, S., Shields, J. E., Thomas, M. A., and Thommes, M. (2004). "Pore size and surface characteristics of porous solids by mercury porosimetry," *Characterization of Porous Solids and Powders: Surface Area, Pore Size and Density* 16, 189-212.

Plötze, M., and Niemz, P. (2011). "Porosity and pore size distribution of different wood types as determined by mercury intrusion porosimetry," *European Journal of Wood and Wood Products* 69(4), 649-657. DOI: 10.1007/s00107-010-0504-0

Schneider, A. (1979). "Beitrag zur Porositätsanalyse von Holz mit dem Quecksilber-Porosimeter," *Holz als Roh-und Werkstoff* 37(8), 295-302, DOI: 10.1007/BF02607491

Thostenson, E. T., and Chou, T. W. (1999). "Microwave processing: Fundamentals and applications," *Composites Part A: Applied Science and Manufacturing* 30(9), 1055-1071. DOI: 10.1016/S1359-835X (99) 00020-2

Torgovnikov, G., and Vinden, P. (2009). "High-intensity microwave wood modification for increasing permeability," *Forest Products Journal* 59(4), 84-92.

Vinden, P., Romero, F. J., and Torgovnikov, G. (2004). "Method for increasing the permeability of wood," *U.S. Patent 6,742,278 B2*.

Wegst, U. G. K. (2006). "Wood for sound," *American Journal of Botany* 93(10), 1439-1448. DOI:10.3732/ajb.93.10.1439

Zhang, W. H. (2008). "Techniques of thick wood drying by microwave," *Journal of Fujian College of Forestry* 27(4), 370-375. DOI: 1001-389X (2007)04-0370-06

Zhang, Y., and Cai, L. (2006). "Effects of steam explosion on wood appearance and structure of sub-alpine fir," *Wood Science and Technology* 40(5), 427-436. DOI: 10.1007/s00226-005-0053-6

Article submitted: June 3, 2014; Peer view completed August 25, 2014; Revised version received and accepted: October 2, 2014; Published: October 27, 2014.