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Air permeability and sound absorption coefficient changes from ultrasonic treatment in a cross section of Malas (*Homalium foetidum*)

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Abstract

We investigated the effect of ultrasonic treatment on Malas (*Homalium foetidum*) gas permeability and sound absorption coefficient using the transfer function method. Results showed a longitudinal average Darcy permeability constant of 2.02 (standard deviation SD 0.72) for untreated wood and 6.15 (SD 3.07) for ultrasound-treated wood, a permeability increase of 3.04 times. We also determined the average sound absorption coefficients in the range of 50 to 6.4 kHz and NRC (noise reduction coefficient: average value of sound absorption coefficient value at 250, 500, 1000, and 2000 Hz) of untreated Malas. Those values were 0.23 (SD 0.02) and 0.13 (SD 0.01), respectively, while those of ultrasonic-treated Malas were 0.28 (SD 0.02) and 0.14 (SD 0.02), a 19.74% increase in average sound absorption coefficient.

Keywords: Sound absorption coefficient, Transfer function method, Gas permeability, Ultrasonic treatment, Malas

Introduction

Wood permeability greatly influences drying characteristics [1], chemical impregnation [2–4], and sound absorption in the longitudinal direction [5, 6]. Kanagawa et al. reported that steam explosion treatments improve wood's permeability and drying rates [7]. Various researchers have reported that improving gas permeability increases the ability to treat wood chemically [2–4].

Jang et al. classified three kinds of yellow poplar wood's pore shapes, through pore, blind pore, and closed pore, and measured their contents [8]. In the same way, Jang et al. investigated the pore shapes of three species of conifer (hinoki, Douglas fir, and hemlock) [9]. Permeability increases were affected by pore size and through pore content [8, 9]. Jang and Kang also used heat treatment to investigate changes in gas permeability, pore size, and pore shape [10]. As the heat treatment temperature increased, pore size and through pore porosity increased,

which, in turn, caused an increase in gas permeability [10].

In previous research, Kang et al. reported that delignification treatment using Wise's method improved *Larix kaempferi*'s permeability and the cross-sectional surface sound absorption coefficient [11]. Permeability also improved after low-pressure steam explosion treatment [5], heat treatment [10], and organo-solvent treatment [6].

A high-frequency current flowing through a piezoelectric element with sound waves above the audible frequency creates ultrasonic waves. They can also be created by changing the magnetic field against a magnetic object, a method used in various industrial fields [12–14].

Although there have been few attempts to treat wood with ultrasound, Tanaka et al. reported that ultrasound increased Douglas fir (*Pseudotsuga menziesii*) permeability in both the radial and tangential directions due to ultrasonic pit de-aspiration or destruction [15]. The ultrasonic treatment removed intracellular lumen impurities in the direction of the wood cells, which improved the pores' air permeability (the pores are the fluid pathway between the wood cells) [15].

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Previous studies found that increasing wood permeability leads to an increase in sound absorption coefficient. Therefore, we expect ultrasonic treatment of wood to cause an increase in sound absorption performance.

In this study, Malas from Papua New Guinea (*Homalium foetidum*) was selected, which is popular because it is relatively inexpensive among Southeast Asian timber used in Korea [16]. The changes in gas permeability and sound absorption coefficient between untreated and ultrasonic-treated Malas were investigated.

Materials and methods

Sample preparation

Malas (*Homalium foetidum*) timbers were supplied from Jeonil Timber Co., Ltd in Korea. They cut logs into 20 cylindrical specimens with a 2.9 cm diameter and 1 cm cross-sectional thickness (Fig. 1). They were exposed to standard room conditions for one month. Their air-dried specific gravity and MC (moisture content) were 0.8 and 12%, respectively.

Ultrasonic treatment

We added 200 ml of water into an ultrasonic cleaner (model: SD-80H, SungDong Ultrasonic Co. Ltd.), and 20 cylindrical specimens were treated for about 25 min with a 40 kHz ultrasonic wave frequency and 50 W output power. After ultrasonic treatment, the specimens were dried at 40 °C for 8 h in a dryer and then equilibrated to the laboratory environment for 24 h. The MC of cylindrical specimens was similar between untreated and ultrasonic-treated samples.

Gas permeability measurements

Gas permeability of untreated and ultrasonic-treated cylindrical specimens was measured by a capillary flow porometer (model: CFP-1200AEL, Porous Material Inc., Ithaca, NY, U.S.A). It measured the flow rate through the sample while pressing the sample vertically from atmospheric pressure to 1 atm.

Capillary flow porometer calculated automatically the Darcy permeability constant (K) using Eq. (1) and Eq. (2) [17]:

$$k = \frac{Q/A}{\Delta P/L} \quad (1)$$

$$K = 1.013 \times 10^8 k \eta \quad (2)$$

K =specific permeability (Darcy), k =permeability ($\text{cm}^3/\text{dyne s}$), η =viscosity of air ($=1.81 \times 10^{-4} \text{ dyne s/cm}^2$), Q =gas flow rate (cm^3/s), A =cross sectional area of the specimen (cm^2), ΔP =pressure difference (dyne/cm^2), L =length of the specimen (cm).

We sealed the samples' side surfaces with a silicon O-ring to prevent air leakage from the edges and estimated the same gas permeability direction both untreated and ultrasonic-treated cylindrical specimens.

Sound absorption coefficient measurements

Sound absorption coefficients of untreated and ultrasonic-treated cylindrical specimens were measured according to ISO 10534–2 using the two microphone transfer function method with an impedance tube kit (model: type 4706, B&K Company, nærum, Denmark), pulse analysis software, and a spectrum analyzer (model: type 3560, B&K Company, nærum, Denmark) [18]. We used a silicone O-ring to prevent experimental error from the air gap between the test specimen and impedance tube and, using the same direction for both, estimated the gas permeability before and after treatment. We used a frequency range of 50 Hz to 6.4 kHz. Prior to ultrasonic treatment, atmospheric pressure, temperature, relative humidity, sound velocity, air density, and acoustic impedance were 1030 hPa, 20.20 °C, 35%, 343.35 m/s, 1.221 kg/m³, and 419.2 Pa/(m/s), respectively. After treatment, conditions were 1021 hPa, 25.4 °C, 26%, 346.38 m/s, 1.189 kg/m³ and 411.9 Pa/(m/s), respectively.

Cross-sectional surface observations

To observe microscopic feature changes caused by ultrasonic treatment, we cut untreated and treated specimens into 7 mm (radial) × 7 mm (tangential) × 6 mm (longitudinal) samples using a microtome (model: HM400S, Microm GmbH, Germany). We coated the specimens with gold ions using an ion sputter-coater (model: SCM,

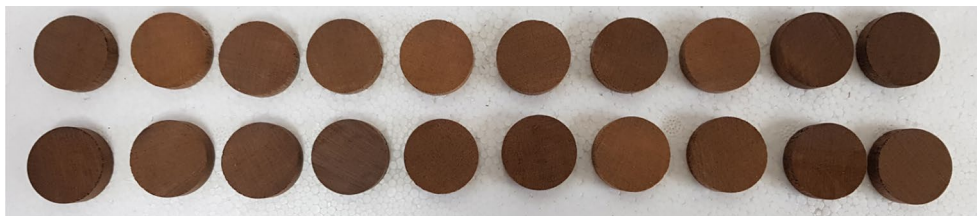
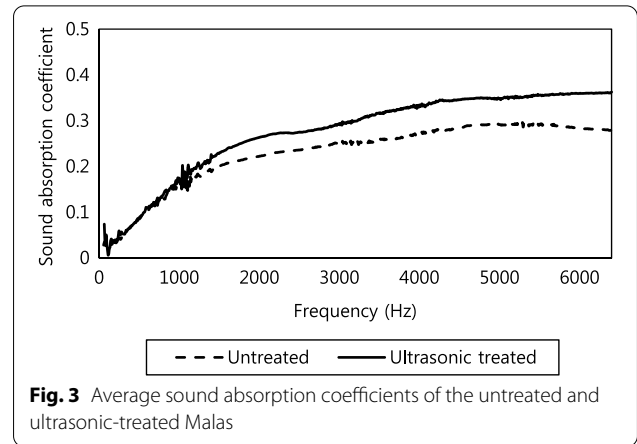
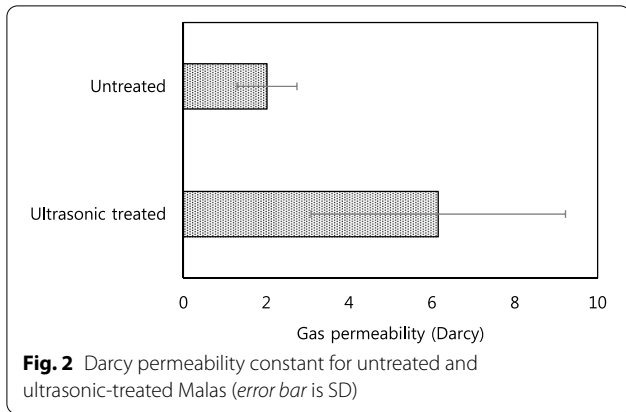


Fig. 1 Malas sample preparation



Emcrafts, Korea) and observed the samples at a 20 kV acceleration voltage and 200× magnification using a scanning electron microscope (SEM) (model: Genesis-1000, Emcrafts, Korea).

Results and discussion

Gas permeability

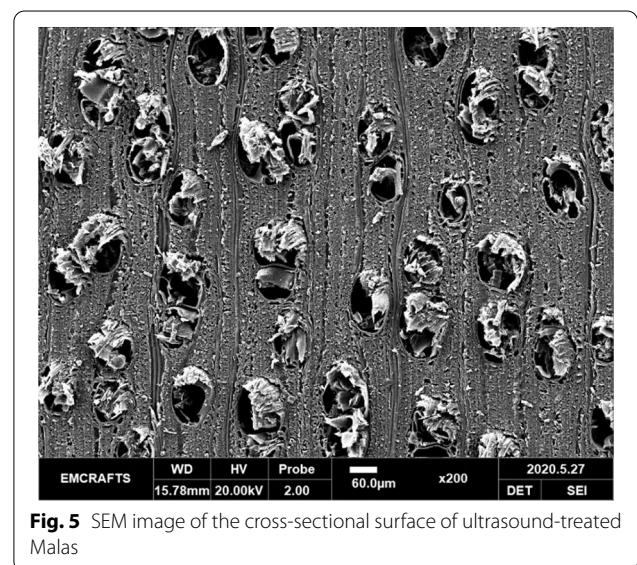
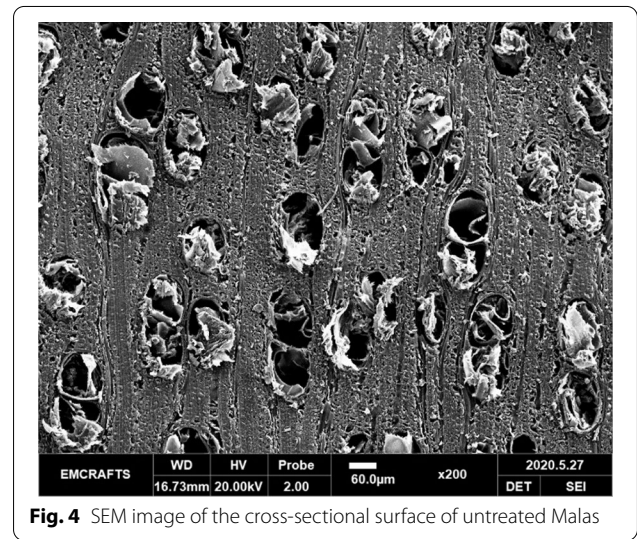
Figure 2 shows gas permeability changes between untreated and ultrasonic-treated Malas. A change of 2.02 (standard deviation SD 0.72) was measured for untreated wood and 6.15 (SD 3.07) for ultrasound-treated wood. Paired *t* test was performed to statistically determine the difference in gas permeability between untreated and ultrasonic-treated cylindrical specimens. Results of $t = -6.709$ and $p = 0.000$ indicate a statistically significant difference in gas permeability before and after ultrasonic treatment. The treated wood’s gas permeability was 3.04 times higher than that of the control. Tanaka et al. found the permeability in the radial and tangential directions to increase 15.3 and 16.2 times when treated with 20 kHz ultrasound for 80 min [15]. These results show that the ultrasonic sound treatment influences permeability changes [15]. The high permeability increases are due to the Malas’s many diffuse, porous, large-diameter vessels on the cross-sectional surface (Figs. 4 and 5) which leads them to behave as through pores. Kang et al. reported that vessel and the single perforation plate of hardwood behave as through pores that are effective for sound absorption [19].

This is because the ultrasonic treatment removed impurities present in the vessels.

Sound absorption coefficient

Figure 3 shows the average sound absorption coefficients calculated between 50 Hz and 6.4 kHz for the untreated and ultrasonic-treated Malas specimens.

The untreated specimen’s average sound absorption coefficient is 0.23 (SD 0.02) and NRC (noise reduction



coefficient: average value of sound absorption coefficient value at 250, 500, 1000, and 2000 Hz) is 0.13 (SD 0.01). The ultrasonic-treated specimen's average sound absorption coefficient is 0.28 (SD 0.06) and NRC is 0.14 (SD 0.02), and paired t test was performed to statistically determine the difference in average sound absorption coefficient between untreated and ultrasonic-treated cylindrical specimens. Results of $t = -3.232$ and $p = 0.002$ indicate a significant difference in average sound absorption coefficient before and after ultrasonic treatment.

The sound absorption coefficient increased with frequency for both the untreated and ultrasonic-treated specimen. The sound absorption coefficient of the porous material showed a tendency to increase at high frequencies, and porous material with a high specific gravity and small porosity exhibited low sound absorption characteristics [20]. The Malas's sound absorption coefficient was only 10% at low frequencies, but over 2 kHz, it reached 0.3 to 0.5. These are relatively high values and demonstrate that this wood could be used as sound-absorbing material. A large amount of diffuse porous vessels with little tylosis formation can be seen in Malas's cross section. The void volume of hardwood can be anatomically classified into vessels, perforation plates, and pit. In previous studies, void volume of wood was classified into through pores, blind pores, and closed pores [8–10]. This is in accordance with IUPAC's definition of physical pore types of solid porous material. Since both ends are open, a pore through which the fluid can flow is defined as a through pore, a pore with one side blocked as a blind pore, and a pore impregnated within the material as a closed pore [21]. The size of the through pore affects wood permeability [8–10, 22], and the sound absorption coefficient increases when the through pore porosity increases.

We found that the sound absorption coefficient increased after ultrasonic treatment, most effectively in the high-frequency range. The ultrasonic forces enlarged the through pore diameter and eliminated obstacles on the wood's cross-sectional surface.

The sound absorption coefficient did not increase in proportion to the gas permeability increase. Other factors, in addition to gas permeability, can affect wood cross-sectional permeability. Further studies are needed in this area.

Anatomical features

As shown in Figs. 4 and 5, we confirmed that Malas contains a typical wood-diffuse porous structure. We observed many vessels on the cross-sectional surface, which led to the high sound absorption coefficient.

Wood-diffuse porous structures seem to absorb sound energy effectively [23].

Although the ultrasonic-treated specimens showed a 2.87 times gas permeability increase, we saw little difference in the cross-sectional SEM images. SEM did not show any internal pathway changes related to ultrasonic treatment [10].

Conclusion

We measured changes to gas permeability and sound absorption coefficient using an ultrasonic treatment on Malas wood. We obtained the following conclusions:

1. The ultrasonic treatment increased gas permeability in the fiber direction of a Malas cross section by 2.87 times.
2. The ultrasonic treatment increased the sound absorption coefficient by 19.74%.

Abbreviations

K: Specific permeability; *k*: Permeability; η : Viscosity of air; *Q*: Gas flow rate; *A*: Cross-sectional area of the specimen; ΔP : Pressure difference; *L*: Length of the specimen; *MC*: Moisture content; *NRC*: Noise reduction coefficient: average value of sound absorption coefficient value at 250, 500, 1000, and 2000 Hz; *SD*: Standard deviation.

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Authors' contributions

CWK: Conceptualization, Methodology, and Writing—original draft. ESJ: Experiment, Data analysis, and Writing—original draft. NHL: Supervision and Writing—review & editing, SSJ and ML: Writing—review & editing. All authors read and approved the final manuscript.

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Competing interests

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