Original Article

Eun-Suk Jang and Chun-Won Kang*

Sound absorption characteristics of three species (binuang, balsa and paulownia) of low density hardwood

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Abstract: In this study, the sound absorption coefficient of three low density hardwoods – binuang, balsa and paulownia – were investigated. Their gas permeability and pore size were measured, and their pore shapes were classified into through pore, blind pored, and closed pore, as specified by the International Union of Pure and Applied Chemistry (IUPAC). Among the three species, obvious that paulownia had lowest sound absorption when the two of others showed higher sound absorption. Although paulownia is a high porosity wood, most of its vessels are blocked by tyloses; it is therefore difficult for sound waves to enter its pores, which results in poor sound absorption performance. This study showed that the higher the through pore porosity, the higher was the gas permeability, which led to improvement of the sound absorption performance. It was also found that the sound absorption coefficient of the three species woods increased at low frequencies as the size of an air cavity between the specimens and tube's wall increased.

Keywords: blind pore; capillary flow porometry; closed pore; sound absorption coefficient; through pore.

1 Introduction

The elimination of outdoor noise pollution is one of the main concerns regarding the quality of housing. In designing or simulating the acoustics of building interiors,

it is necessary to consider the acoustic characteristics of a building's interior materials, in order to ensure a quiet housing environment (Cao et al. 2018; Jang et al. 2018a,b; Kang et al. 2019; Rutkevičius et al. 2015). While various kinds of sound-absorbing materials have been studied with the goal of improving the indoor noise environment, the current focus of research is on making them more sustainable (Arenas and Crocker 2010). Wood has been used as a sustainable material for innumerable applications since the industrialization of humankind (Matsubara and Kawai 2014; Micle 2018; Ragheb et al. 2016; Rowell 2006; Wang et al. 2014), while extensive research has been performed on sound-absorbing materials in construction (Amel et al. 2016; Asdrubali et al. 2017; Pöhler et al. 2016; Smardzewski et al. 2014; Taghiyari et al. 2016). Sound-absorbing materials can be categorized as porous, resonance, and panel vibration types (Shoshani 1990). Among these, wood is categorized as belonging to the porous sound absorber type (Jayamani et al. 2013; Kang et al. 2010a,b, 2018; Wassilieff 1996).

In the case of wood, the cell wall density is relatively constant, so if the density is low, the total porosity tends to increase. Smardzewski et al. (2014) reported that high porosity wood is effective as a sound-absorbing material because it exhibits a small specific impedance. Xu et al. (2004) reported that sound absorption properties depend on density and thickness in kenaf binderless particleboards. Kang et al. (2012) reported that the lower the density, the higher the sound absorption coefficient in board manufactured from miscanthus particles. This is because the lower the density, the higher the pore content, so that more sound waves are diffusely reflected and lose energy. Mohammad et al. (2010) investigated the sound absorption of Malaysian wood using the Delany-Bazley approximation method, and reported that high frequency sound absorption was high in low density wood.

As this previous research shows, low density is one of the major factors in improving sound absorption. The most important measurable parameter for determining the sound absorption coefficient in porous material is gas permeability

*Corresponding author: Chun-Won Kang, Department of Housing Environmental Design, Research Institute of Human Ecology, College of Human Ecology, Jeonbuk National University, Jeonju 54896, South Korea, E-mail: kcwon@jbnu.ac.kr

Eun-Suk Jang, Department of Housing Environmental Design, Research Institute of Human Ecology, College of Human Ecology, Jeonbuk National University, Jeonju 54896, South Korea

(Hong 1989; Kang et al. 2010a,b, 2011, 2018; Watanabe et al. 1967). The radial and tangential section of wood are acoustically reflective material with a sound absorption coefficient of less than 5%. However, cross-sectional wood has a higher sound absorption coefficient than the radial and tangential sections, since fluid can flow through vessels in hardwood or tracheids in softwood (Hong 1989; Kang et al. 2010a,b, 2011; 2018; Watanabe et al. 1967). In general, the sound absorption of hardwood is better than that of softwood because the vessels in hardwood are easier to permeate than the tracheids in softwood (Hong 1989; Kang et al. 2010a,b, 2011; Taghiyari et al. 2014a,b). Based on previous studies, it was expected that cross-section of low density hardwood would show excellent sound absorption performance.

According to the International Association of Wood Anatomists (IAWA) committee, hardwood is classified by its basic specific gravity, whether low (≤ 0.40), medium ($0.40-0.75$), or high (≥ 0.75) (Wheeler et al. 1989). In this study, three species of low density timber (balsa, binuang, paulownia) were used that are easily distributed in the wood market. The sound absorption coefficient of each was measured using an impedance tube. We also investigated the three types of pore (through pore, blind pore, and closed pore) based on IUPAC (Rouquerol et al. 1994), pore size, and gas permeability, as well as the effect of the air cavity on the sound absorption coefficient of the wood.

The purpose of this study was to investigate the sound absorption characteristics of low density wood and to identify the factors that influence the sound absorption coefficient. It also examines the possibility of using low density wood as an eco-friendly sound-absorbing material and suggests how to improve its sound absorption coefficient.

2 Materials and methods

2.1 Specimen preparation

Three species of low density wood were obtained from Jeonil Timber Co., Ltd in the Republic of Korea. Figure 1 shows specimens for this

study. They were cut to the dimensions of 29 mm (diameter) $\times$ 10 mm (longitudinal). Their sizes are suitable for measuring small impedance tubes according to ISO 10534-2 (2001). 13 specimens of each species were used for the gas permeability, porosity, pore size and sound absorption coefficient. In addition, one sample for each species was taken from among the specimens, and cut into cubes approximately 5 mm (W) $\times$ 5 mm (L) $\times$ 5 mm (H).

All specimens were maintained in the laboratory at an ambient temperature of 20–25 °C and 50–60% relative humidity for two months prior to the experiment; equilibrium moisture content (MC) of the specimens was 12%. Table 1 provides details of specimen information (Meier 2015; Wong 2002).

2.2 SEM image of cross-sectional specimens

The morphology of the end-grains of the three species were examined in an SEM (model: Genesis-1000, Emcrafts, Korea). In order for the cross-sections to be well polished, they were immersed in water using a vacuum oven for approximately 10 min, after which their surfaces were sliced with a microtome and they were dried in an oven for 1 h. All specimens were gold coated using an ion sputter coater (model: SCM, Emcrafts, Korea), and the SEM was operated at an accelerating voltage of 20 kV in high-vacuum mode. The cross-sectional surfaces of the specimens were observed at 100 and 400 magnification and their radial sectional surfaces were observed at 400 magnification.

2.3 Gas permeability measurement

Gas permeability was measured using a capillary flow porometer (model: CFP-1200AEL, Porous Materials, Inc., USA). Differential pressure was increased from 0 to 15 psi (0.1 MPa), and the flow rate at each pressure was measured, while the Darcy permeability constant at each pressure was calculated by Eq. (1) (Jang et al. 2020; Sarangi et al. 2018; Siau 2012).

$$C = 8FTV / \pi d^2 (P^2 - 1) \quad (1)$$

where, C = Darcy permeability constant; F = flow; T = sample thickness; V = air viscosity; d = sample diameter; P = pressure.

2.4 Pore diameter measurement

The pore diameter of cylindrical specimens were measured using a capillary flow porometer (model: CFP-1200AEL, Porous Material Inc, USA). Originally based on ASTM F316-03 (2019), this is the standard

Figure 1: Cylindrical sample preparation of three species of low density wood: (top) binuang; (middle) balsa; (bottom) paulownia.

Table 1: Information of the three species of low density wood.

Spice	1	2	3
Common name	Binuang	Balsa	Paulownia
Scientific name	<i>Octomeles sumatrana</i>	<i>Ochroma lagopus Swartz</i>	<i>Paulownia coreana</i>
Number of specimen	13 (for gas permeability, pore size, porosity, and sound absorption coefficient) 1 (for SEM)	Same as binuang	Same as binuang
End-grain structure	Sometimes arranged in radial series, mostly circular in shape	Large pores in no specific arrangement solitary and radial multiples of 2–3 growth rings indistinct	3-5 rows of very large earlywood pores large to small latewood pores
Arrangement of vessels	Diffuse-porous	Semi diffuse-porous	Semi-ring-porous
Use	Plywood, light construction, furniture components, Cabinetwork, packing cases, etc.	Core in structural Sandwich panels, wind turbine blades, toys, etc.	Plywood, furniture, musical instruments, etc.
References	Wong (2002)	Meier (2015)	Meier (2015)

method for measuring the pore size of filters and membranes and can also be used to measure the diameter of softwood tracheids and hardwood vessels (Jang et al. 2018a,b, 2019; Jang and Kang 2019; Kang et al. 2018). A capillary flow porometer has the advantage of being able to selectively measure only the constricted parts of through pores associated with fluid flow. Wood permeability correlates with sound absorption (Kang et al. 2010a,b, 2011, 2018; Kolya and Kang 2021; Taghiyari et al. 2014a,b), while wood pore diameter measured by the capillary flow porometer is related to permeability (Jang et al. 2018a,b, 2019; Jang and Kang 2019). Therefore, this method is useful in this study because the wood pore size may be related to its sound absorption.

Testing with a capillary flow porometer uses a ‘dry up/wet up’ method that involves drawing first a ‘dry curve’ and then a ‘wet curve’ (Jang et al. 2018a,b, 2019, 2020, Jang and Kang 2019, 2020). Figure 2a shows dry curve, wet curve and half dry curve by the capillary flow porometer. The gas flow rates for both a ‘dry curve’ and a ‘wet curve’ were compared at the same pressures, while pore size was calculated as the relationship between pressure and pore size. Slowly increasing the gas on the wetted specimen correspondingly increases pressure. Depending on capillary pressure, it is extruded sequentially from large to small pores. The initial pressure is called the ‘bubble point’, and the

maximum pore size is obtained using Eq. (2). The mean flow pore diameter can be obtained from the point at which the ‘half dry curve’ and the ‘wet curve’ meet.

$$D = \frac{C\tau}{p}$$

(2)

where, D = limiting diameter; τ = surface tension; p = pressure; C = constant, 2860 when p is in Pa, 2.15 when p is in cm Hg, and 0.415 when p is in psi units.

2.5 Porosity measurement

In wood applications, density is often presented as air-dry density (ρ) which is the ratio of density including 12% MC. In this study, density was converted into air-dry density to obtain the porosity of wood. The air-dry density of specimens can be easily obtained by measuring their diameter, height, and weight according to KS F 2198 (2001). In previous research cell wall density (ρ_{cell}) has been reported as having a minimum value of 1.46 g/cm³ and a maximum value of 1.53 g/cm³, depending on the species (Plötze and Niemz 2011). For the sake of convenience, in the present study the cell wall density was assumed to

Figure 2: (a) Principle of capillary flow porometry; (b) three pore types of solid porous materials.

be 1.50 g/cm^3 (Tanaka et al. 2014), while total porosity can be obtained as shown in Eq. (3).

$$\phi_{\text{total}} (\%) = \left(1 - \frac{\rho}{\rho_{\text{cell wall}}}\right) \times 100 \quad (3)$$

where, $\rho_{\text{cell wall}}$: $1,500 \text{ kg/m}^3$.

The true density of cylindrical specimens was measured using a gas pycnometer (model: PYC-100A-1, Porous Material Inc. USA), based on the principle of Boyle's law whereby the pressure and volume of a given amount of gas in a container are inversely proportional to one another. This method has been widely used to measure the true density of wood specimens (Donato and Lazzara 2012; Jang et al. 2019; Jang and Kang 2019; Rouquerol et al. 1994; Stamm 2002).

As prescribed in an IUPAC technical report (Rouquerol et al. 1994), the pores of solid porous materials are classified as open pores or closed pores depending on their availability to an external fluid. Open pores are divided into blind pores (open only at one end) and through pores (open at both ends). Since helium gas does not penetrate closed pores, only the open-pore porosity of cylindrical specimens is obtained from the gas pycnometer, Eq. (4) expressed open pore porosity (ϕ_{open}) as the sum of through-pore porosity (ϕ_{through}) and blind-pore porosity (ϕ_{blind}). Closed-pore porosity (ϕ_{closed}) can be found by subtracting open-pore porosity (ϕ_{open}) from total porosity (ϕ_{total}) (Eq. (5)).

$$\phi_{\text{open}} = \phi_{\text{through}} + \phi_{\text{blind}} \quad (4)$$

$$\phi_{\text{closed}} = \phi_{\text{total}} - \phi_{\text{open}} \quad (5)$$

Previous studies have proposed a method for distinguishing through-pore porosity (ϕ_{through}) and blind-pore porosity (ϕ_{blind}) from open-pore porosity in cylindrical wood specimens (Jang et al. 2019, 2020; Jang and Kang 2019), and this method was applied in the present study. First, the cylindrical specimen was immersed in a beaker containing Galwick solution (surface tension: 0.159 mN/m) and placed in the vacuum chamber for 10 min. Since the liquid has a very low surface tension, it can easily permeate the blind pores and through pores of the specimen.

Next, the cylindrical specimens were placed in a chamber that was sealed using two O-rings at the top and bottom of the specimen to prevent air leakage between the edge of the specimen and the chamber wall. Air pressure was then increased in a longitudinal direction, so that only the Galwick solution in through pores could be extruded. The through pore content can be calculated by observing the amount of Galwick solution impregnating the sample. From Eq. (6), through-pore porosity was calculated

$$\phi_{\text{through}} = \phi_{\text{open}} - \phi_{\text{blind}} \quad (6)$$

2.6 Sound absorption coefficient

The sound absorption coefficient of the specimens was measured by the pulse acoustic material testing system, a device that consists of three components: an impedance tube (Model: Type 4206, Bruel & Kjaer, Denmark), a dual-channel signal analyzer (Model: Type 2302, Bruel & Kjaer, Denmark), and a power amplifier (Model: Type 2706, Bruel & Kjaer, Denmark). The measuring processes are integrated in the system, which follows the standard of ISO 10534-2 (2001). Each specimen was affixed to the interior wall of the tube and sealed with an O-ring to prevent micro-cavities between its edges and the wall of the tube. White noise was then transmitted from a loudspeaker towards

the specimen. Two microphones in the impedance tube received the signal converted to FFT (fast fourier transform). Since the sound absorption coefficient of sound-absorbing materials varies according to frequency, it is necessary to represent a single index. ISO 11654 (1997) has suggested noise reduction coefficient (NRC), which is the average of sound absorption measured at 250, 500, 1000 and 2500 Hz (Eq. (7)).

$$\text{NRC} = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} \quad (7)$$

To analyze the sound absorption characteristics for each frequency range, the average value of sound absorption coefficient for 250–500, 500–1000, 1000–2000, and 2000–6400 Hz was also calculated. Additionally, to investigate the effects of the sound absorption coefficient in the air cavity of the specimen, sound absorption coefficients at a distance of 10, 20, and 30 mm from the wall of the specimen.

The environmental variables of sound absorption coefficient testing in this study were as follows; Sound velocity was 344.93 m/s , air density was 1.206 kg/m^3 , and acoustic impedance was 416.1 Pa/(m/s) .

3 Results and discussion

3.1 Morphology and pore structure

Figure 3 shows cross-sections of the three wood species by SEM. Binuang showed a diffuse porous structure with a wide distribution of vessels with some tyloses. Balsa showed a semi-diffuse porous structure with smaller distribution of vessels than binuang and only rare tyloses. Paulownia showed a ring porous structure in which vessels were distributed mostly in late wood, and consisted mostly of tyloses. These structures were similar to what has previously been observed (Meier 2015; Wong 2002).

3.2 Gas permeability and pore diameter

Figure 4a shows, the Darcy permeability constant of the three wood species investigated. While the difference in gas permeability between binuang and balsa was not statistically significant ($p = 0.350$, by Tukey's test), paulownia showed significantly lower gas permeability than the other two species, and this difference was statistically significant ($p < 0.01$, by Tukey's test).

In engineering applications, density is often presented as air-dry density (ρ) which is the ratio of density including 12% MC. In this study, density was converted into air-dry density to obtain the porosity of wood (Taghiyari et al. 2014a,b).

The development of tyloses in vessels causes the poor fluid flow as tyloses act as impermeable barriers in wood and interfere with permeability (Taghiyari et al. 2014a,b). Wood with low permeability such as paulownia has a long

Figure 3: SEM image of three species of low densitywood: (a) binuang (left: cross-section of 100×, middle: cross-section of 400×, right: Radial section of 400×); (b) balsa (left: cross-section of 100×, middle: cross-section of 400×, right: radial section of 400×); (c) paulownia (left: cross-section of 100×, middle: cross-section of 400×, right: radial section of 400×).

Figure 4: Gas permeability and pore size of three species wood (error bar standard deviation): (a) gas permeability; (b) pore size analysis.

Figure 5: Results of porosity analysis of three species wood (error bar standard deviation): (a) analysis of air dried-density and porosity; (b) analysis of porosity (through pore, blind pore, and closed pore).

drying time and makes it difficult to have preservatives or resins impregnated. To destroy tyloses and improve permeability, a variety of wood modification has been attempted (Esmailpour et al. 2019; Kolya and Kang 2021; Torgovnikov and Vinden 2009).

Figure 4b shows the pore diameter of cross-sectional specimens was measured by capillary flow porometer, and maximum pore size and mean flow pore diameter were calculated. Rankings for vessel diameter size were balsa, binuang, and paulownia ($p < 0.01$, by Tukey's test). The pore size of paulownia was substantially smaller than that of the other two species. The reason for the large difference in pore size between the two species is the same as in the case of the results for gas permeability. The difference in gas permeability between binuang and balsa can be inferred as not statistically significant, since while pore size for balsa was larger than for binuang, pore frequency for binuang was greater than for balsa. As a tradeoff between the two parameters, it can be assumed that there is no difference in gas permeability between the two species. Thus, the pore size and frequency affect the gas permeability (Jang et al. 2018a,b; Jang et al. 2019; Jang et al. 2020).

3.3 Porosity analysis

Figure 5a shows density of three species wood specimens. Rankings of density were balsa, binuang, and paulownia. Their total porosity was calculated as follows: balsa > binuang > paulownia. Differences in porosity between the three species were statistically significant ($p < 0.01$ by Tukey's test).

Figure 5b shows through-pore porosity, blind-pore porosity, and closed-pore porosity of three species wood specimens. Rankings for through-pore porosity were binuang, balsa, and paulownia, with the three differences being statistically significant ($p < 0.01$, by Tukey's test).

Gas permeability may not be related to total porosity, because total porosity include not only through-pore porosity but blind-pore porosity and closed-pore porosity. The fluid can only flow through the gas through-pore. Blind and closed pores impede gas flow (Jang et al. 2019, 2020; Jang and Kang 2019). As a result of this study, it was also found that gas permeability of cross-sectional wood was affected by through-pore porosity.

3.4 Sound absorption characteristics

The sound absorption coefficient for each frequency was measured using an impedance tube. Figure 6 shows the average of the sound absorption coefficient graphs measured for the 13 specimens of each wood species. Table 2 shows the average NRC for each wood species and the average sound absorption coefficient for each frequency section.

The sound absorption coefficient of binuang increased with increasing frequency, which is typically similar to that of a cross-section of diffuse-porous hardwood with high permeability (Kang et al. 2011, 2018). Overall, the sound absorption coefficient of balsa was lower than that of binuang, showing statistically significant differences ($p < 0.01$, by Tukey's test). Among the three species, the paulownia showed the lowest sound absorption. Gas permeability, pore size and through-pore porosity decreased due to the effect of tyloses in the vessels which makes it difficult to absorb sound.

Figure 6: Results of average sound absorption coefficient graph of three species wood depending on air back cavity: (a) binuang; (b) balsa; and (c) paulownia.

Table 2: Results of NRC and average sound absorption coefficient for each frequency range of three species low density wood (parenthesis are standard deviation).

Average sound absorption coefficient						
Species	Air back cavity	Average NRC	250–500 Hz	500–1000 Hz	1000–2000 Hz	2000–6400 Hz
Binuang	N/A	0.155 (0.015)	0.074 (0.004)	0.133 (0.007)	0.239 (0.028)	0.332 (0.053)
	1 cm	0.270 (0.033)	0.192 (0.005)	0.342 (0.037)	0.358 (0.070)	0.303 (0.038)
	2 cm	0.316 (0.050)	0.309 (0.032)	0.384 (0.075)	0.333 (0.070)	0.306 (0.037)
	3 cm	0.323 (0.056)	0.346 (0.057)	0.371 (0.076)	0.312 (0.061)	0.302 (0.040)
	N/A	0.109 (0.005)	0.039 (0.001)	0.067 (0.003)	0.171 (0.008)	0.323 (0.038)
Balsa	1 cm	0.261 (0.014)	0.148 (0.015)	0.365 (0.015)	0.376 (0.047)	0.224 (0.026)
	2 cm	0.320 (0.020)	0.325 (0.012)	0.438 (0.040)	0.317 (0.031)	0.216 (0.022)
	3 cm	0.349 (0.017)	0.407 (0.017)	0.433 (0.033)	0.304 (0.025)	0.225 (0.020)
	N/A	0.088 (0.018)	0.059 (0.012)	0.046 (0.005)	0.067 (0.018)	0.105 (0.031)
	1 cm	0.098 (0.021)	0.092 (0.023)	0.107 (0.028)	0.109 (0.022)	0.112 (0.013)
Paulownia	2 cm	0.091 (0.028)	0.094 (0.034)	0.099 (0.031)	0.097 (0.023)	0.110 (0.016)
	3 cm	0.119 (0.028)	0.126 (0.036)	0.130 (0.035)	0.111 (0.020)	0.123 (0.016)

Comparing the results of binuang and balsa, while balsa showed higher total porosity binuang showed higher sound absorption coefficients, leading to the conclusion that density cannot be used as a catch-all variable for estimating sound absorption. Among the three species, binuang is characterized by large vessel diameter and diffuse porosity.

Previous studies reported that gas permeability was improved through a variety of wood modification such as

heat treatment, microwave treatment, and steam explosion (Esmailpour et al. 2019; Jang et al. 2019; Kang et al. 2021; Kolya and Kang 2021; Torgovnikov and Vinden 2009). If such modifications could be applied to binuang, the through-pore porosity could be more improved and gas permeability increased. This may lead to improvement in sound absorption performance making binuang viable for use as a natural sound-absorbing material.

Table 3: Results of the Pearson correlation analysis ($n = 39$).

	NRC	TPP	BPP	CPP	MPS	GP
NRC	–	0.823 ^a	0.161	–0.388 ^b	0.172	0.773 ^a
TPP		–	–0.046	–0.254	0.340 ^b	0.715 ^a
BPP			–	–0.952 ^a	–0.905 ^a	–0.339 ^b
CPP				–	0.778 ^a	0.112
MPS					–	0.592 ^a
GP						–

^aRepresent significance 1% levels; ^brepresent significance 5% levels. Denotations of variables are as follows: NCR, noise reduction coefficient; TPP, through-pore porosity; BPP, blind-pore porosity; CPP, closed-pore porosity; MPS, mean pore size; and GP, gas permeability.

Sound absorption of porous material is achieved by converting incoming sound waves from sonic energy to thermal energy due to friction within pores. For this reason, pore structure of wood may affect the sound absorption coefficient. In this study, the effects of these parameters on NRC were statistically investigated. Pearson's correlation analysis was used to understand the univariate associations between variables.

Table 3 provides Pearson's correlation between variables. NRC showed a positive correlation with through-pore porosity (0.823) and gas permeability (0.773) at 1% significance level, closed-pore porosity (0.388) was negative correlation with NRC at 5% significance level. The correlation coefficient between through-pore porosity and gas permeability is 0.715, which shows a positive correlation at 1% significance level. Of course, that of between through-pore porosity and mean pore size is also 0.592, which shows a positive correlation at 1% significance level. However, through-pore porosity's degree of correlation is greater than that of mean pore size. In conclusion, wood with high through-pore porosity has high gas permeability, which can be a condition for high sound absorption performance.

3.5 Changes in sound absorption coefficient due to air cavities

The introduction of an air cavity behind specimens shifted the maximum sound absorption coefficient in the direction of lower frequencies (Table 3). This is a common phenomenon in porous sound-absorbing materials (Lim et al. 2018). However, in the case of paulownia, there was little change in the frequency of the maximum absorption coefficient in relation to the size of the air cavity. The paulownia seems to have been less affected by the air cavity because of its basically low sound absorption performance.

Changes in the sound absorption coefficient of balsa according to the size of the air cavity showed the same tendency as with binuang; as air cavity size increases, the sound absorption coefficient at low frequencies increases, while the sound absorption coefficient at high frequencies tends to decrease slightly.

3.6 The availability of sound-absorbing materials with cross-sections of wood

In recent years, floors made of cross-section of wood, which is called 'end-grain wood block,' have become popular (DRAKKAR 2021; Kaswell 2021; Oregonlumber 2021). End-grain wood block was used in housing being inspired by what was already used in European and American road construction dated back to World War I. However, on end grain wood floors, their pore structure or sound absorption performance is not considered important.

This study proposes that end-grain wood blocks can be produced using wood species with excellent sound-absorbing properties and can be used as eco-friendly sound-absorbing materials. The sound absorption performance of wood cross-sections shown in the present study is the result of small specimens at laboratory scale. Therefore, in the future, it is necessary to evaluate the sound absorption characteristics by installing it on the wall or ceiling inside a building using an end grain wood block with excellent sound absorption characteristics.

4 Conclusions

In this study, among the three species, binuang shows the highest sound absorption, demonstrating its applicability as a natural sound-absorbing material. The sound absorption coefficient of balsa was lower than that of binuang without an air cavity, but it showed similar sound absorption performance to binuang with an air cavity. Where an air cavity was present, the sound absorption coefficient tended to be greatly increased at low frequencies. Paulownia showed large vessels but low through-pore porosity due to the large number of tyloses in the vessels. For this reason, gas permeability was low, while the sound absorption coefficient was poor. The cross-section of paulownia is thus concluded to be inadequate for use as a sound-absorbing material. The NRC of all three species of wood sample tested in this study was positively correlated with through-pore porosity, gas permeability.

Variations in the sound absorption characteristics of the cross-sectional wood are dependent upon the size and

distribution of vessels and the number of tyloses. In other words, even if the diameter of vessels is large, if the vessels include a large number of tyloses or the number of vessels themselves is small, the sound absorption rate will be poor. Since the anatomical structure of wood is not uniform, the method may be of limited effectiveness in predicting its sound absorption characteristics. In the future, a wider range of species of wood needs to be investigated in order to clarify their sound absorption coefficient as well as its physical and anatomical correlation with the wood itself. With further testing to confirm estimations, natural wood can be considered to be a viable sustainably sourced material for sound dampening applications in both residential and industrial markets.

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