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INVESTIGATION ON THE MALAYSIAN *DUABANGA MOLUCCANA* CROSS SECTIONS AS SOUND ABSORBING FUNCTIONAL MATERIALS

EUN-SUK JANG, CHUN-WON KANG
JEONBUK NATIONAL UNIVERSITY
REPUBLIC OF KOREA

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ABSTRACT

This study focused on *Duabanga moluccana*, which is a fast-growing tropical tree native to Southeast Asia. *Duabanga moluccana* cross sectional specimens were analyzed to gas permeability, pore size, and open-pore porosity and also measured its sound absorption coefficients with an impedance tube. *Duabanga moluccana* showed a larger pore size and greater open-pore porosity than other hardwood species, and its sound absorbing performance was superior to that of the gypsum board currently used as a commercial ceiling material. Although this was a laboratory-scale investigation, we demonstrate that *Duabanga moluccana* cross sections have potential as a natural sound absorbing functional building material.

KEYWORDS: Eco-friendly materials, open-pore porosity, sound-absorbing performance, *Duabanga moluccana.*

INTRODUCTION

Environmental pollution can be categorized as soil, water, air, light, and noise pollution (Shirsath and Badole 2021). Among these, noise pollution first was considered an important environmental factor at the World Environment Congress in 1972 (Morillas et al. 2018). In particular, noise pollution in urban areas with high population and traffic density is expanding as a social problem (Zannin et al. 2002). According to a policy report published by the Seoul Institute (Korea) in 2014, the number of noise complaints in Seoul per year increased from 15,922 cases in 2009 to 27,558 cases in 2013. In addition, 33% of Seoul citizens perceived noise pollution as the most serious environmental pollution problem (Choi 2014). It is no different in China. In the annual environmental pollution complaints surveyed in China in 2019, noise issues ranked second after 2017 and 2018 (Xu et al. 2020). These noise problems cause a variety of health threats, such as sleep disturbance and cardiovascular, physiological, cognitive, and hearing effects (Van Kamp and Davies 2013). In addition, noise around residential areas has a significant effect on the decline in housing prices (Chasco and Gallo 2013, Theebe 2004, Zheng et al. 2020). Therefore, overall noise reduction is required to maintain a pleasant sound environment in urban areas (Sutcliffe et al. 2021).

There are two ways to reduce noise in a building: blocking external noise (sound insulation) and absorbing noise generated inside the building (sound absorption) (Zhu et al. 2014). Most commercial sound-absorbing materials are polyurethane foam or fibrous sound-absorbing materials made of synthetic fibers (Zhu et al. 2014). Recently, in consideration of the adverse effects of these sound-absorbing materials on the environment, studies to replace them using eco-friendly materials such as by-products of rice, kenaf fiber, coconut fiber, and wood materials are ongoing (Bhingare and Prakash 2021, Kang et al. 2018a, Taban et al. 2020).

Among the various natural sound-absorbing materials, this study focused on wood cross-sections. Considering climate-change impacts, wood products have environmental advantages over non-wood alternatives (Bergman et al. 2014). Essentially, wood is made up of carbon captured from the atmosphere, and the manufacture of wood products requires less fossil fuels than does that of non-natural products (Johnston and Radeloff 2019). Thus, use of wood products involves significant carbon emission savings (Bergman et al. 2014, Johnston and Radeloff 2019). Watanabe et al. (1967) first reported on the sound absorption capability of porous wood cross-sections in 1967. Since then, the sound absorption effects of various species of wood have been reported by many researchers. Kang et al. (2010) reported that the sound absorption effect was excellent in diffusely porous woods wherein the vessels are distributed over a wide area. Taghiyari et al. (2014) reported a positive correlation between specific gas permeability and sound absorption of wood. Highly permeable wood has an open-pore structure, which can facilitate absorption of sound energy (Kang et al. 2020). In contrast, closed-pore structures, which can interfere with sound absorption (Kang et al. 2020, Kang et al. 2010). Therefore, in order to utilize the cross section of wood as a sound-absorbing functional material, the discovery of species with an open pore structure, and various studies on physicochemical wood modification to destroy the closed pore structure of wood and reform it into a more permeable structure are being conducted (Chung et al. 2017, Kang et al. 2012, Kolya and Kang 2021, Wang et al. 2014).

As a basic study on tree species with potential for sound absorption, we focused on *Duabanga moluccana*, which is a fast-growing tropical tree native to Southeast Asia (Lestari 2020); it is known as Kalanggo in Indonesia, Loktob in the Philippines, and Magas in Malaysia. *Duabanga moluccana* is widely distributed in areas such as riverbanks, felled forests, forest edges, abandoned arable land, roadside, and limestone hills (Liew et al. 2015). This species is recognized as a very economically important species for box, firewood and boat production (Jamal et al. 2018). In Sarawak, Malaysia, *Duabanga moluccana* has been targeted as one of the fast-growing native tree species for planted forest development (Liew et al. 2015). But still, this species has not been used widely as a building material.

The purpose of study was evaluation of its sound-absorbing performance as an interior ceiling material. So, we investigated the morphology, permeability, porosity, and sound-absorbing performance of *Duabanga moluccana* cross sections and compared its sound absorption curve with that of gypsum board, which is used widely as a ceiling material.

MATERIALS AND METHODS

Specimen preparation

Air-dried Malaysian *Duabanga moluccana* timber was supplied by Jeonil Timber Co., Ltd. (Gimje, Korea). It was cut into cylindrical specimens (29 mm diameter x 10 mm thickness), and 10 defect-free specimens were selected. Their air-dried specific gravity and moisture content (MC) were 0.4 g.cm^{-3} and 6.9%, respectively.

Scanning electron microscopy

In order to observe the vessel structure of the *Duabanga moluccana* cross sections, a separate specimen was cut into approximately a 64 mm^3 cube and subjected to pretreatment (softening, surface cutting, and drying) (Jang et al. 2020) for scanning electron microscope (SEM) imaging (Genesis-1000; EmCrafts Co., Ltd., Sungnam, Korea). The observation magnification was 100× in high vacuum mode (7.5 × 10^{-5} torr).

Gas permeability, pore size, and open-pore porosity analysis

Previous studies have shown that the gas permeability, pore size, and open-pore porosity of porous materials are related to their sound absorption coefficient (Arenas and Crocker 2010, Kang et al. 2018b, Taghiyari et al. 2014). In this study, gas permeability and pore sizes were measured using a CFP (Capillary Flow Porometer, model: CFP-1200AEL; Porous Materials, Inc., Ithaca, NY, USA). The Darcy permeability constant of the specimens was calculated as shown in Eq. 1 (Jang et al. 2020):

$$DC = 8FTV/\pi d^2(P^2 - 1) \tag{1}$$

where: *DC* - Darcy permeability constant, *F* – flow (cm^3·s^{-1}), *T* - sample thickness (cm), *V* - viscosity of air (cp), *d* - sample diameter (cm), and *P* – pressure (psi).

The pore size of the specimens was calculated as shown in Eq. 2 (ASTM F316-03, 2019):

$$D = \frac{C\tau}{p} \tag{2}$$

where: *D* - limiting diameter, τ - surface tension (dyne/cm), *p* – pressure (psi), and *C* - constant of 0.415 when *p* is measured in psi units.

The open pore porosity of the specimens was calculated by gas pycnometer (PYC-100A-1; Porous Materials Inc., Ithaca, NY, USA) based on ISO 12154 (2014). First, the porosity of the specimen was calculated as shown in Eq. 3. The closed-pore porosity and open-pore porosity of the specimens were calculated as shown in Eqs. 4 and 5 (König et al. 2020):

$$\phi = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \tag{3}$$

where: ρ_b - density of the specimen (g.cm^{-3}), ρ_t - true density of wood was assumed to be 1.5 g.cm^{-3} (Lindgren 1991).

The closed-pore porosity and open-pore porosity of the specimens were calculated as shown in Eqs. 4 and 5 (König et al. 2020):

$$\phi_{closed} = \left(\frac{{\rho_p}^{-1} - {\rho_t}^{-1}}{{\rho_b}^{-1} - {\rho_t}^{-1}}\right) \times 100 \tag{4}$$

$$\phi_{open} = \phi - \phi_{closed} \tag{5}$$

where: ρ_p - density of the specimen using a gas pycnometer (g.cm^{-3}).

Measurement of sound absorption coefficient

The sound absorption coefficient was measured by an impedance tube (Type 4206, Bruel & Kjaer, Nærum, Denmark), which measures the sound absorption coefficient when applying 100-6400 Hz of white noise to the sample in the longitudinal direction (Fig. 1).

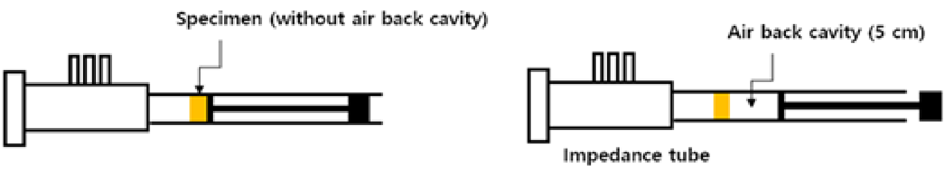


Fig. 1: Schematic diagram of the impedance tube.

The proportion of sound absorbed by *Duabanga moluccana* specimen is calculated using equations (Tudor et al. 2020).

$$\alpha = \frac{I_a}{I_i} = \frac{|P_a|^2 - |P_i|^2}{|P_i|^2} = 1 - R^2 = 1 - \left[\frac{n-1}{n+1}\right]^2 = \frac{4n}{(1+n^2)} \tag{6}$$

where: I_a - absorbed sound intensity, I_i - incident sound intensity, P_i - pressures of incident, R - reflectance factor P_a - pressure of reflected waves, n - ratio of maximum pressure to minimum pressure.

Additionally, NRC (Noise Reduction Coefficient) is calculated using equations.

$$\mathrm{NRC} = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} \tag{7}$$

where: α_{250} – sound absorption coefficient at 250 Hz, α_{500} – sound absorption coefficient at 500 Hz, α_{1000} – sound absorption coefficient at 1000 Hz, α_{2000} – sound absorption coefficient at 2000 Hz,

The sound absorption coefficients were measured in the 10 specimens, without an air back cavity or with a 5 cm air back cavity. In addition, we compared the sound absorption coefficient with that of gypsum board (10 mm thickness), which is widely used as a commercial ceiling material.

RESULTS AND DISCUSSION

SEM images of *Duabanga moluccana* cross section

Fig. 2 shows an SEM image of a *Duabanga moluccana* cross-section. The arrangement of vessels is as in diffuse porous wood without specific pattern. Average vessel diameter is > 100 μm and average number of vessels was 0.3 per cm². Tyloses are observed inside the vessels, and other deposits not observed.

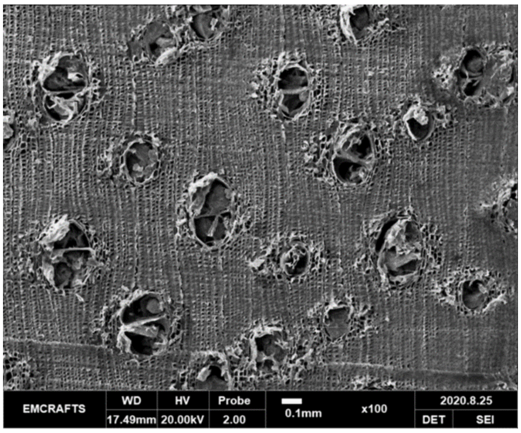
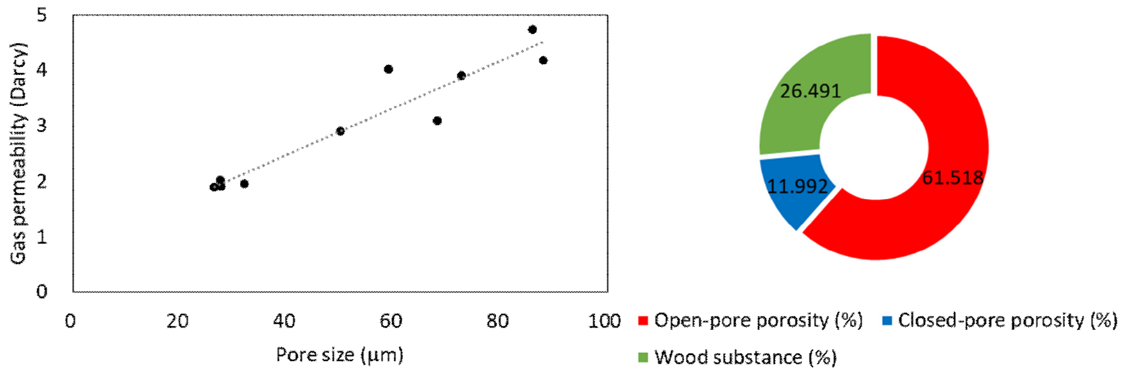


Fig. 2: SEM image of Duabanga moluccana cross-section.

Gas permeability and porosity analysis

Fig. 3 also depicts *Duabanga moluccana* gas permeability and porosity analysis. The average and standard deviation of gas permeability were 3.059 ± 1.032 Darcy, and the average pore size was 53.828 ± 23.234 μm. The vessel diameter measured by CFP was significantly smaller than that observed by SEM because the CFP measures the constricted parts of the through-pores (Jang et al. 2020). Pore size and gas permeability showed a linear relationship (Fig. 3a) because the CFP selectively measures only the pores contributing to the flow (Jang et al. 2020).



(a) (b)

Fig. 3: Results of Duabanga moluccana's gas permeability (a), and porosity analysis (b).

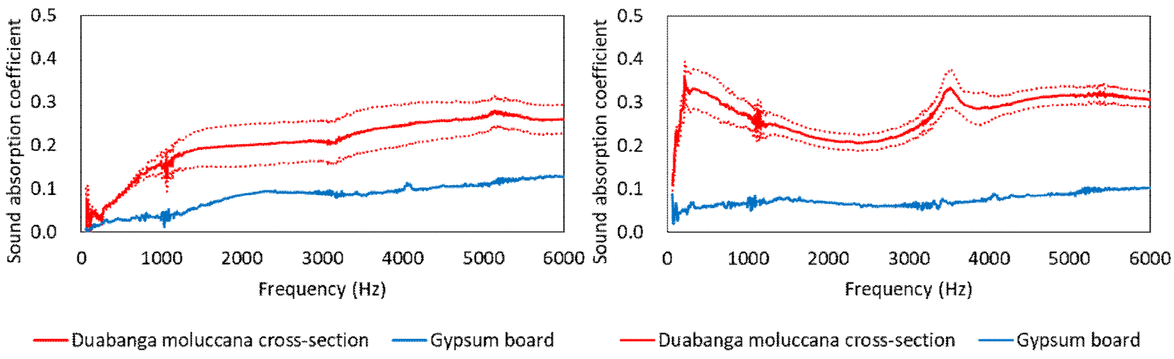
Kolya and Kang (2020) investigated the gas permeability of 10 domestic and overseas hardwoods in the same way as in the present study: hackberry (9.78 Darcy), light balsa (7.51 Darcy), heavy balsa (7.39 Darcy), hard maple (7.38 Darcy), platanus (4.76 Darcy), cherry (3.85 Darcy), sinensis (2.58 Darcy), chestnut (0.32 Darcy), paulownia (0.07 Darcy), and silver poplar (0.04 Darcy). In comparison with these results, *Duabanga moluccana* at 3.059 Darcy showed an intermediate level of permeability.

Duabanga moluccana's total porosity was 73.509 ± 0.552%, and its open-pore porosity was 61.518 ± 2.403% (Fig. 3b). Plötze and Niemz (2011) investigated the porosity of various hardwoods, ranging from 22.1% of *Diospyros celebica Bakh* to 69.69% of *Acer campestre L.* Although their sample size and measurement method were different from those of this study, *Duabanga moluccana*'s total porosity was relatively high among those hardwoods.

Sound-absorbing performance

Fig. 4 compares the sound absorption curves of *Duabanga moluccana* cross-sections and gypsum board. As the sound absorption curves progress from low to high frequency, the sound absorption coefficient gradually increases. This is because the high-frequency sound wave can penetrate deep inside the pores. Most wood cross sections show a similar sound absorption curve pattern (Arenas and Crocker 2010, Kang et al. 2010, 2018b,2020, Taghiyari et al. 2014, Watanabe et al. 1967).

When an air back cavity was applied to the samples, the sound absorption coefficient at low frequencies was significantly increased. This is because of the resonance phenomenon caused by the open pores of *Duabanga moluccana*. The NRC in the specimen without an air back cavity was 0.114 ± 0.007, but increased by 99.8% to 0.282 ± 0.031 when an air back cavity was applied.



(a) *(b)*

Fig. 4: Comparison of sound absorption curves of Duabanga moluccana cross sections and gypsum board with no air back cavity (a), or 5 cm air back cavity (b). Dashed lines are standard deviations.

In comparing the sound absorption curve of gypsum board used as a commercial ceiling material, the *Duabanga moluccana* cross section showed excellent sound-absorbing performance. However, it is lower than that of commercial sound absorption materials. Nevertheless, these results suggest the availability of *Duabanga moluccana* as a natural sound-absorbing functional material for interior ceiling material. From these studies, it will be possible to contribute to increasing the added value of *Duabanga moluccana*, which had low utilization as a building material.

CONCLUSIONS

This study investigated the sound absorbing performance of *Duabanga moluccana* cross sections, and we present the following conclusions. The *Duabanga moluccana*'s gas permeability was 3.059 ± 1.032 Darcy, its average pore size was 53.828 ± 23.234 µm, its total porosity was 73.509 ± 0.552%, and its open-pore porosity was 61.518 ± 2.403%, which were superior to those of other hardwoods studied elsewhere. The noise reduction coefficient of a *Duabanga moluccana* cross section without an air back cavity was 0.114 ± 0.007, but increased by 99.8% to 0.282 ± 0.031 with a 5 cm air back cavity. Overall, the *Duabanga moluccana* cross section had superior sound-absorbing performance compared to gypsum board used as a commercial ceiling material.

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EUN-SUK JANG, CHUN-WON KANG*
JEONBUK NATIONAL UNIVERSITY
COLLEGE OF HUMAN ECOLOGY
DEPARTMENT OF HOUSING ENVIRONMENTAL DESIGN AND RESEARCH
INSTITUTE OF HUMAN ECOLOGY
567, BAEKJE-DAERO, DEOKJIN-GU 54896
JEONJU-SI, JEOLLABUK-DO.
REPUBLIC OF KOREA
*Corresponding author: kcwon@jbnu.ac.kr