Acoustical Properties of Wood Fiberboards Prepared with Different Densities and Resin Contents

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The demand for noise control in residential environments is steadily increasing, but the currently available noise-reducing materials used in walls and floors are unsustainable and expensive. As an alternative, wood-fiber could be a good resource to manufacture eco-friendly acoustic materials. In this study, fiberboards were prepared by mixing wood-fibers (*Pinus densiflora*) with melamine-urea-formaldehyde resin adhesive, obtaining specimens with different final densities and resin contents. The acoustic, physical, and morphological properties of the fiberboards were investigated. The sound absorption was greatly influenced by the density of the fiberboard: lower densities showed higher sound absorption performances. Furthermore, the low-frequency absorption coefficient was higher for lower resin contents. The materials met all the criteria required by the Korean standards for fiberboards. As the density increased, the dimensional stability and the bending strength increased; in contrast, the physical properties were not affected by the resin content. Microscopy observations confirmed that specimens with different densities and resin contents had different porosities; the porosity was assumed to be the main property that governs the noise-reducing ability. Due to their eco-friendliness and inexpensiveness, these fiberboards offer themselves as efficient and effective alternative sound-absorbing materials.

Keywords: Fiberboard; Density; Resin content; Sound absorption; Transmission loss

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INTRODUCTION

Recently, increasing attention has been devoted to the concept of "quality of life" and its improvement. In the context of efforts towards better life conditions, environmental noise is an increasing problem, and the demand for noise control in residential areas is on the rise. Noise control is a new concept in residential maintenance and is often overlooked in many construction projects (Souza 2019). In the last few decades, cities have experienced a rapid increase in population density due to urbanization, and the apartment has become the residential environment of choice of this modern society. Apartments are designed to accommodate a large amount of people in a small surface area and are hence densely populated, leaving limited space for each household. Consequently, different family units are only separated by a floor/ceiling and walls, which can only minimally avoid noise propagation. This problem is getting worse with the rise of individualism and the decrease of interpersonal relationships, the diversification of sound sources according to the improvement of living standards, and the advancement of the performance of residents (Grimwood 1997). As domestic disturbance incidents and quarrels between neighbors due to noise problems keep increasing, noise and vibration have been recognized as important social problems and various regulations and methods have been developed and implemented to control them. The Ministry of Environment and the Ministry of Land, Infrastructure and Transport in Korea jointly enacted rules on the scope and standards of floor noise in multi-unit housing on June 3, 2014 (Ministry of Environment Act no. 559; Ministry of Land, Infrastructure and Transport Act no. 97 2020).

To reduce noise in apartments and other residential buildings, directly blocking or removing outside noise and absorbing the sounds generated inside the housing units would be ideal; however, the complete shielding or removal of sound coming from inside and outside buildings is obviously a hard task (Godshall and Davis 1969). Usually, noise is controlled by installing sound-absorbing panels on the exterior and interior walls of apartment complexes and condominiums. Accordingly, research on the development of building materials with excellent sound absorption, as well as on how to quantify these sound-absorbing properties, is increasing.

The sound absorptivity of a wall or panel depends on the raw material employed to build it and its structural characteristics; this is because frictional resistance (which causes sound energy attenuation) depends on the porosity of the raw material (Godshall and Davis 1969). When sound is first generated, it propagates in space; when it encounters a heavy medium, it can be reflected/scattered, or pass through it and is converted into sound energy. Sound energy is transmitted in the form of vibrations and produces sound when it contacts a fluid. However, sound transmittance can be interrupted or hindered by sound-absorbing materials, which effectively reduce sound energy due to frictional resistance (Woodruff and Ehrenreich 1961). For instance, in construction sites, the “floating” floor method or the floor buffer material insulation method generally reduce the reflection of sound (Lesovik *et al*. 2014).

In Korea's sound-absorbing panel market, aluminum soundproof walls and petrochemical derivatives take up approximately 90% of the market due to their price competitiveness, pleasant aesthetics, performance, and durability (Kang *et al*. 2010). In addition, for indoor sound shielding, porous composites made of rock wool and glass wool, or polyurethane foamed sponges, are also employed (Wassilieff 1996). Plastic-based sound-absorbing materials include polyester and polyurethane, which can be produced in various colors, patterns, and shapes, and implemented in various construction methods, in addition to having outstanding sound absorption abilities. These properties make them the sound-absorbing materials of choice in the field. Depending on the application, and to further improve their sound absorption performance, they can be shaped as pyramids, egg crates, interlocking blocks, and more. Their main areas of application as sound-absorbing materials include interior wall finishes, music rooms, piano rooms, performance rooms, studios, offices, factories, special vehicles, containers, machine rooms, and electric rooms. However, their use is limited due to some fundamental problems such as safety hazards, low durability, flammability, and high cost (Kang *et al*. 2010).

In addition, the growing global interest towards the reduction of greenhouse gas emissions to mitigate climate change is broadcasting a negative image of petrochemical derivatives. Wood is a natural building material and has been used for interior finishes or ceilings for centuries. Watanabe *et al*. (1967) and Zhou *et al*. (2006) both studied the sound absorption properties of wood and wood-based panels, and they found that the sound absorption performance is lower compared to that of currently employed sound-absorbing materials; thus, it is more suitable to use wood and its derivatives as sound-reflecting materials, rather than sound-absorbing materials. The lower sound absorption performance of wood and wood-based panels is due to their higher density and the porosity of their surfaces. However, many attempts have been conducted to improve the sound absorptivity of these more eco-friendly materials, and perforation has been found to be one of the most simple and effective methods (Lee *et al*. 2005; Hwang *et al*. 2008; Byeon *et al*. 2010).

Wood fiber, the raw material of fiberboards, is a natural resource and can be advantageously constructed into panels for sound absorption applications as these constructs often present a porous morphology, both open-cell and closed-cell, which is desirable in a sound absorbing material. Natural wood fiber- and cotton-based panels have demonstrated good absorption performances (Berardi and Iannace 2015); however, their properties can be further enhanced by controlling their density. In this paper, fiberboards were fabricated with different densities and melamine-formaldehyde-urea (MFU) resin contents, and their physical and sound absorption characteristics were investigated. Furthermore, the optimal manufacturing conditions were established, and the acoustic and physical properties of the fiberboards were assessed. These findings can expand the use of low-density fiberboards in the current sound absorbing material market, which is currently dominated by petrochemical derivatives.

EXPERIMENTAL

Materials

Wood fibers (*Pinus radiata*, 5% MC) were provided from Dongwha Enterprise (Incheon, Korea). A 37% formaldehyde solution and a 60% wax emulsion were provided by Sunchang Corporation (Incheon, Korea). Melamine and urea were purchased from OCI N.V. (Amsterdam, Netherlands) and Hu-chems (Seoul, Korea), respectively. The rest of the chemical reagents used in this study were American Chemical Society (ACS) reagent grade and were purchased from Daejung Chemicals & Metals (Siheung-si, Korea). An extruded polystyrene (XPS, #2, 25-mm thickness) was purchased from Byucksan (Seoul, Korea)

Methods

Fiberboard and MFU resin preparation

According to a procedure reported by Lee *et al.* (2019), the MFU resin was prepared with a 0.80 formaldehyde/melamine-urea (F/MU) molar ratio, and a 30 wt% melamine content. The pH was adjusted by adding a 20% NaOH (aq) solution until achieving a pH of 8. The end point of MFU resin synthesis was set between reference tubes F and G using a bubble viscometer (Gardner-Holdt VG-9100; Gardco, Pompano Beach, FL, USA). The viscosity was measured with a viscometer (DV-II+; AMETEK Brookfield, Middleboro, MA, USA), with a spindle of 4.7 cm in diameter and a rotation of 60 rpm. The final viscosity of the MFU resin was 115 mPa·s, and the gel time at 100 °C was 137 s.

The fiberboards were prepared by mixing the MFU resin and the wood fiber in variable proportions and shaping them into 350 mm (length) × 350 mm (width) × 20 mm (thickness) blocks. The manufacturing conditions were tuned to obtain boards with different densities or different resin contents. First, Condition 1 was aimed at obtaining a set of different density boards with a fixed MFU resin content (35 wt% with respect to the oven-dried wood fibers), and boards were prepared at 150 kg/cm^3, 200 kg/cm^3, and 250 kg/cm^3. For Condition 2, the density was fixed at 150 kg/cm^3 and boards were prepared with different resin contents: 20 wt%, 25 wt%, and 35 wt% (Table 2). A 20% NH_4Cl (aq) solution was added as a curing agent (3 wt%) and the wax emulsion was used at 1% of the oven-dried weight of the wood fibers.

Table 1. Resin Properties

Solid Content	pH	Viscosity	Specific Gravity	Gel Time at 100 °C
67.3 %	8.0	115 mPa·s	1.29 mg/mL	137 s

The prepared resin adhesive was sprayed on the wood fibers with a drum-type applicator (So Jung Measuring Instrument; Anyang-Si, South Korea). After spraying the resin adhesive and forming a uniform layer (one side at a time), the fiberboard was hot pressed at 150 °C and 5 kgf/cm^2 for 7 min (hence pressing at a rate of 21 s/mm). The manufactured low-density fiberboard (LDF) is shown in Fig. 1.

Table 2. Information of Samples according to Density and Resin Content

Experiment	Condition 1			Condition 2		
Sample Name	D-1	D-2	D-3	R-1	R-2	R-3
Density (kg/m^3)	150	200	250	150		
Resin Content (%)	35			20	25	30

Fig. 1. Photo of the LDF prepared in this study

Acoustical properties

The sound absorption characteristics of the as-prepared boards were measured according to a procedure reported in the standard KS F 2814-1 (2016). The absorption rate was measured in the practical frequency range by the transfer matrix method using an impedance tube, a pulse analyzer, and a spectrum analyzer (Type 4206-T; Bruel & Kjaer, Nærum, Denmark). To measure the sound absorption variation according to the frequency change, it was divided into low frequency (100 to 1600 Hz) and high frequency (500 to 6400 Hz). During the test, the temperature, relative humidity, and air pressure were set to 23 °C, 56%, and 100.1 kPa, respectively. The diameter of the circular specimens were 99 mm and 29 mm for low and high frequency tests, respectively; each measurement was repeated three times, and the results were reported as the average of three measurements. Noise reduction coefficients (NRC) were calculated from the sound absorption rates measured at the major frequencies of 250, 500, 1000, and 2000 Hz. Moreover, as porosity plays an important role in the acoustic properties of a material, the porosity of the samples was estimated according to Eq. 1 (Smardzewski *et al*. 2015),

$$D_w = 1 - (P_w/P_s) \tag{1}$$

where P_w is the density of the oven dried wood (kg/m^3), and P_s is the density of a wood cell wall (in this case, P_s = 1500 kg/m^3).

Sound insulation refers to the action of preventing or reducing the transition of sound *via* reflection or absorption. For the performance measurements, instead of the universal reverberation chamber method, the impedance tube method was used, which comparatively requires less space and fewer pieces of equipment (Jung *et al.* 2008). The factor of interest was the acoustic transmission loss (*TL*), which is proportional to the ratio of the intensities of the incident wave before passing through the material and the transmitted wave after passing through the material (Eq. 2). The *TL* can be expressed by the impedance ratio and the wave number of the acoustic material and is expressed in Eq. 2 by the definition of plane wave diffusion (Humphrey *et al*. 2008),

$$TL = 10 \log(I_i/I_o) \tag{2}$$

where I_o is the incident sound intensity (dB) and I_i is the transmitted sound intensity (dB).

The *TL* was measured in the low- and high-frequency ranges at a temperature of 28 °C and a pressure (in air) of 1017.5 hPa.

Physical properties of fiberboards

The fiberboards fabricated in this study were evaluated for their basic physical and mechanical properties, such as density, moisture content, water absorption, thickness swelling, and bending strength, according to the Korean standard KS F 3200 (2016). All the test specimens were stored under constant temperature (20 °C) and humidity (65% relative humidity) conditions for 2 weeks after production. To investigate the density distribution of the fiberboards, the samples were scanned with an X-ray densitometer (GreCon DAX 6000; Fagus GreCon, Charlotte, NC, USA). The average density profile was calculated, which accurately reflected the density changes throughout the fiberboards' thickness.

Morphological properties

The fiberboard specimens were observed with a stereo microscope (Axiocam 506 color; ZEISS, Jena, Germany) to evaluate their morphology and porosity. All the fiberboards were sectioned using a sliding microtome. Because the boards had a relatively low density, they were brittle and easy to be torn out due to the elasticity of the wood fibers. Hence, a layer of polyethylene glycol (PEG 2000) was applied to make it easier to cut thin sections: this is known as the PEG embedding technique, which exploits the ability of PEG to hold wood in an inflated state (Bleicher 2008). The cubic specimens (5 x 5 x 5 mm^3) were impregnated with a 1:3 mixture of PEG and distilled water and then stored in an oven at 60 °C for 48 h. After coagulation at room temperature (25 °C) in a special mold, a 50-µm-thick cross-section of fiberboard was cut using a sliding microtome (Lab-Microtome; Swiss Federal Research Institute WSL, Birmensdorf, Switzerland).

RESULTS AND DISCUSSION

Acoustical Properties

Sound absorption performance

The sound absorption coefficients of samples D-1, D-2, and D-3; and R-1, R2, and R-3 are shown in Figs. 2 and 3, respectively, while the NRCs and porosities are shown in

Table 3. The sound absorption coefficients of all the specimens increased as the frequency increased, in line with the results obtained for typical porous sound-absorbing materials such as glass wool and rock wool (Or *et al.* 2017). The sound absorbing ability of a material depends on the amount of air trapped in its pores because of the friction that generates between the incident sound energy and the air layer inside the material (Nandanwar *et al.* 2017). When comparing fiberboards D-1 through D-3, higher sound absorption ability was observed for the least dense sample, due to its higher porosity (D-1: 89.7%, D-2: 86.2%, D-3: 83.0%). In the linear regression analysis of NRC and porosity, the sound absorption coefficient of determination between specific frequencies was $R^2 = 0.99$. Each fiberboard specimen showed an NRC value between 0.40 to 0.49, meeting the Korean standard requirements (0.3 to 0.5) for sound-absorbing fiberboards (KS F 3503 2012). In contrast, the sound absorption coefficients of the fiberboards prepared in this study far exceeded that of a commercially available extruded polystyrene (XPS) insulation board (Fig. 2).

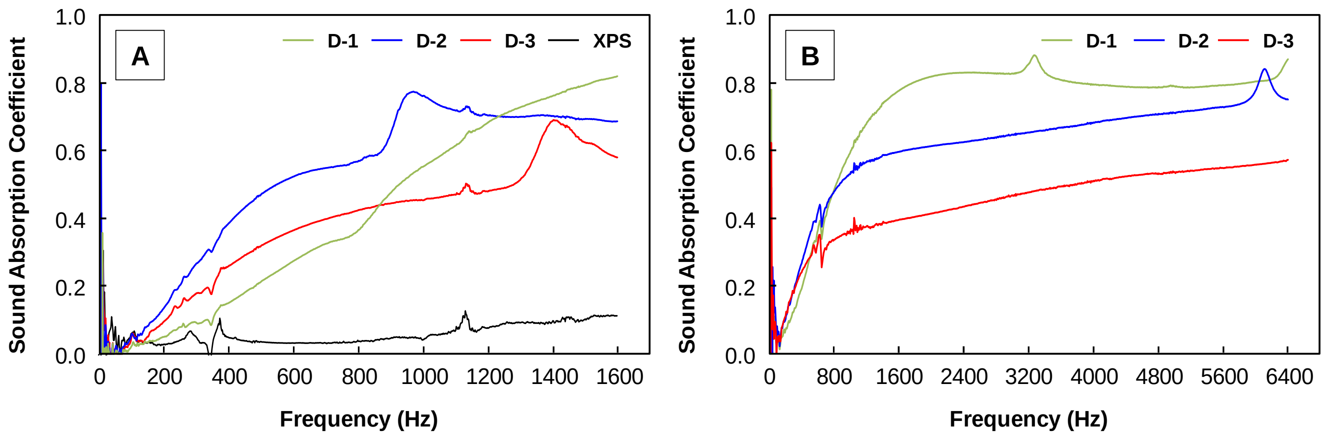

Fig. 2. Sound absorption coefficients of fiberboards with different densities (A: Low frequency, B: High frequency)

Conversely, specimens R-1, R2, and R-3 all displayed similar porosities and NRC values. The sound absorption coefficient of R-1 was higher than those of the other specimens in the low-frequency range, indicating its higher sound-absorption ability. This seems to be related to the characteristics of the wood fibers that make up the fiberboard: at lower resin contents, the individual wood fibers appear short and unconstrained, due to a low degree of aggregation of the fibers (Fig. 8). This creates a more tortuous pathway for sound energy and generates high airflow, which results in an increase in viscous friction. Moreover, the length of the fibers has been reported as an important physical and geometric factor in the improvement of the sound absorption ability of a material at low frequencies (Mamtaz *et al.* 2016). Because their sound absorption rate in the low frequency region was not elevated; this is the noise that occurs the most in residential facilities, such as that generated by blowers, dust collectors, and vacuums. However, low-frequency noise can be compensated by increasing the thickness of the material or ensuring that the air layer is permanently locked inside the material (Kawasaki *et al.* 1998). Acoustic properties of various sound panels are shown in Table 4. Even if the materials are same, sound absorption performance varies depending on thickness, density or presence of binder (Berardi and Iannace 2015).

Table 3. Sound Absorption Coefficients, NRC, and Porosity of Fiberboards

Samples	Absorption Coefficient				NRC* (%)	Porosity (%)
	250 Hz	500 Hz	1000 Hz	2000 Hz		
D-1	0.15	0.30	0.65	0.85	0.49	89.70
D-2	0.15	0.30	0.70	0.65	0.45	86.23
D-3	0.20	0.40	0.55	0.45	0.40	83.02
R-1	0.15	0.35	0.60	0.70	0.45	88.83
R-2	0.10	0.25	0.55	0.80	0.43	88.24
R-3	0.15	0.35	0.65	0.80	0.49	88.79

*NRC: noise reduction coefficient

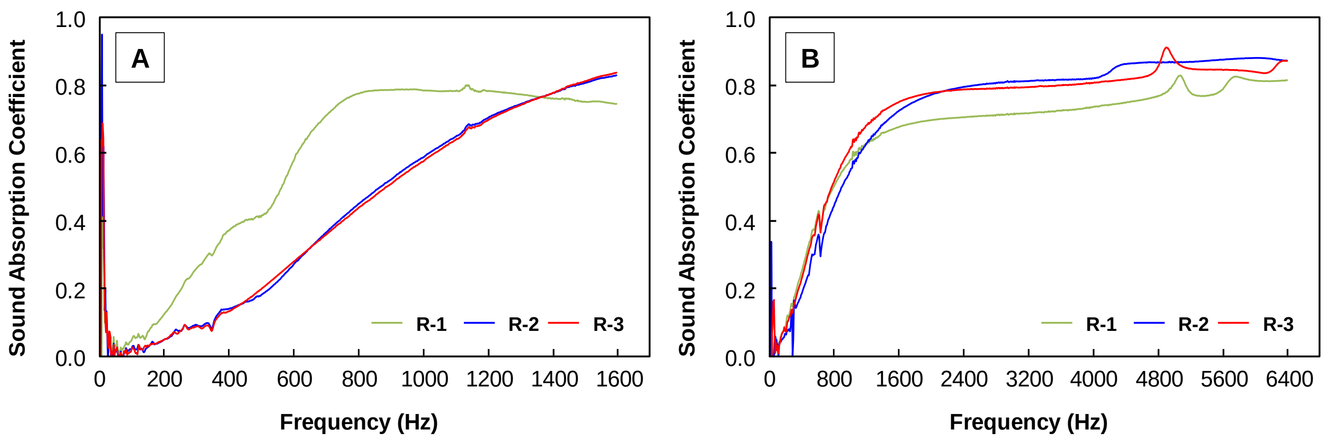

Fig. 3. Sound absorption coefficients of fiberboards with different resin contents (A: Low frequency, B: High frequency)

Table 4. Sound Absorption Performance of Various Sound Panels

Materials	Density (kg/m^3)	Thickness (mm)	NRC* (%)	References
Corrugated cardboard	-	150	0.39	Kang and Seo 2018
Coir fiberboard	100	10	0.15	Or *et al.* 2017
	200	50	0.53	Mamtaz *et al.* 2016
Wood fiberboard	550	16	0.20	Smardzewski *et al.* 2015
	450	16	0.28	Smardzewski *et al.* 2015
	200	20	0.46	Peng *et al.* 2015
	250	24	0.49	Kawasaki *et al.* 1998
	400	25	0.36	Wassilieff *et al.*1996
Wood-wool board	250	25	0.20	Wassilieff *et al.* 1996
Heat treated wood	220	-	0.13	Byeon *et al.* 2010

*NRC was calculated by specific data of sound absorption coefficient curves in each reference.

Sound transmission loss

The *TL* values of the fiberboards prepared with different densities and resin contents are shown in Figs. 4 and 5, respectively. Comparing specimens D-1, D-2, and D-3, the latter had the highest density and showed the highest *TL*. In general, the *TL*, which measures sound insulation, is proportional to the mass of the species, and because the specimens in this study were prepared with a fixed thickness, the *TL* was closely related to the density (Kang and Seo 2018). The average *TL* of the fiberboards prepared with different resin contents was 8.97 dB, 8.14 dB, and 7.64 dB between 0 and 1,600 Hz, and 15.98 dB, 15.13 dB, and 16.49 dB between 0 and 6,400 Hz for R-1, R-2, and R-3, respectively. There was no noticeable tendency relative to the resin content; hence, the resin content was considered as a factor that does not remarkably affect sound insulation. The *TL* tends to be higher in the high-frequency range in both the D and R series. The average *TL* values of gypsum, rock wool, and glass wool boards, which are all widely used as general sound insulation materials, are all above 40 dB (Asdrubali 2006). Hence, the fiberboard used in this study may not be suitable to use as sound-blocking materials, because of the lower *TL*. As a result, coincidence effect or air gap effect, which can bring dramatic decrease on sound transmission loss, were not detected in this study (Kang and Seo 2018).

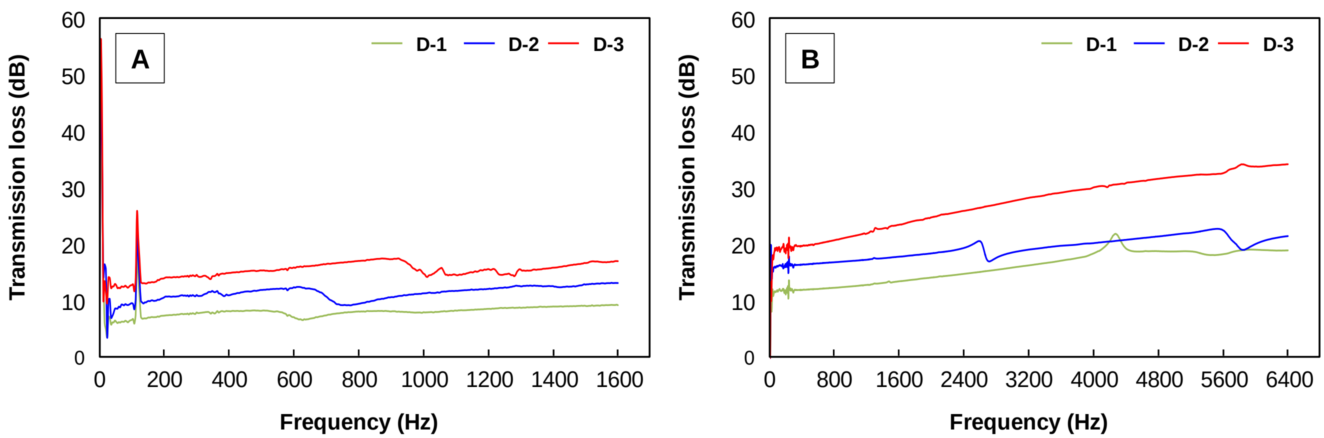

Fig. 4. Transmission loss of fiberboard with different densities (A: Low frequency, B: High frequency)

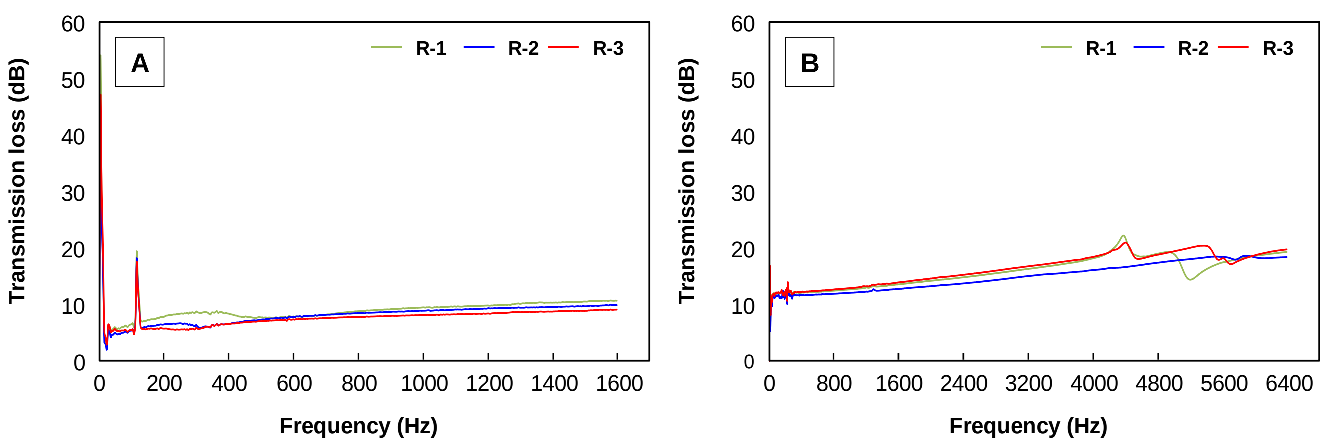

Fig. 5. Transmission loss of fiberboard with different resin contents (A: Low frequency, B: High frequency)

Physical Properties

The physical properties of the fiberboards prepared with different densities and resin contents are shown in Table 5. Samples D-1, D-2, and D-3 all had an actual density close to the target density. However, R-1, R-2, and R-3 all had a higher density than the target 150 kg·m^{-3}. The moisture content ranged between 6.14 and 7.22%, and there was no remarkable difference between the two groups, although water absorption tended to decrease as the density and resin content increased. This is in line with the concept that increasing the density or the resin content of a fiberboard increases its dimensional stability, because the bonds between the wood fibers get more robust. The thickness swelling rate decreased with increasing density: the thickness swelling was the lowest (0.99%) for R-2, although all specimens satisfied the standard's requirements (< 5%). According to the Korean Standard KS F 3200 (2016), when the thickness swelling of a fiberboard is 5% or less, the board is classified as water-resistant, and can be used as an outer wall finish material. The bending strength of the fiberboards was assessed as well. In general, density and bending strength are directly proportional, and results showed the same tendency (Gindl *et al.* 2001). In contrast, the bending strength decreased slightly with increasing resin content. Tang *et al.* (2017) reported that increasing the resin content of fiberboards, with density being equal, decreases the strength, and that this is due to a decrease in the amount of wood fibers.

Table 5. Physical Properties of Fiberboards

Samples	Density (kg/m^3)	Moisture Content (%)	Water Absorption (%)	Thickness Swelling (%)	Bending Strength (MPa)
D-1	154.57 ± 4.92	7.22 ± 0.49	72.99 ± 6.06	1.82 ± 1.00	0.57 ± 0.10
D-2	206.55 ± 6.83	6.64 ± 0.22	54.43 ± 5.25	1.41 ± 0.66	1.36 ± 0.06
D-3	254.72 ± 2.27	6.70 ± 0.19	46.25 ± 2.41	1.38 ± 0.14	2.46 ± 0.40
R-1	167.58 ± 2.55	6.23 ± 0.13	66.11 ± 6.51	1.37 ± 0.76	0.64 ± 0.06
R-2	176.46 ± 7.66	6.30 ± 0.71	63.19 ± 9.18	0.99 ± 0.35	0.59 ± 0.08
R-3	168.21 ± 0.64	6.14 ± 0.28	57.58 ± 3.11	1.12 ± 0.66	0.57 ± 0.10

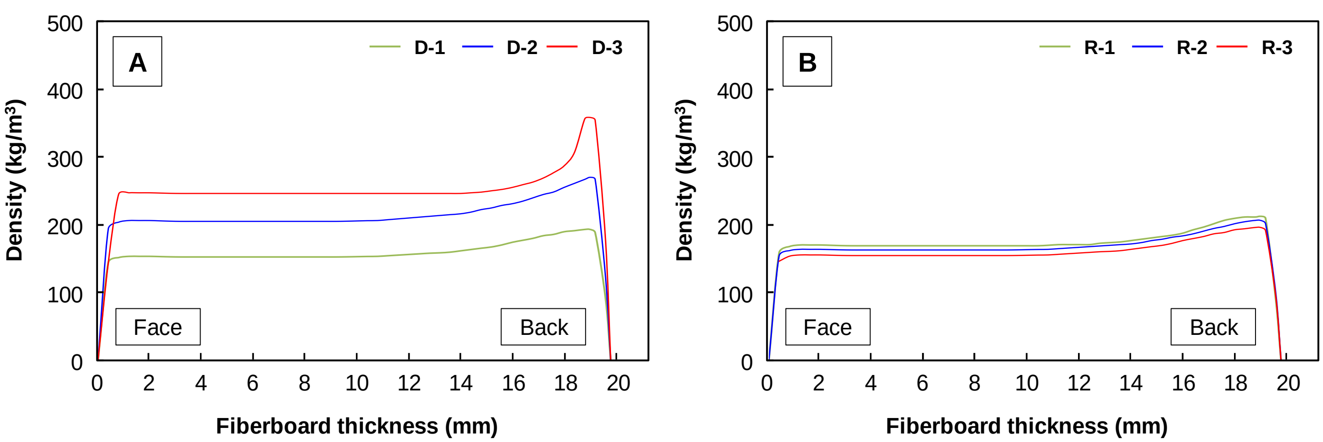

Fig. 6. Density profile of fiberboard samples manufactured by different conditions (A: Densities, B: Resin contents)

The density profiles reported in Fig. 6 confirm the manufacturing characteristics. After hot pressing, higher density was observed at the back face (lower side) of the fiberboards, while the rest of the layers (upper and middle) showed the same density as the target density. This can be imputed to the fact that pressure was not applied equally on the upper and lower faces during hot pressing. Moreover, the back faces of the fiberboards were always the ones that were exposed to heat first, and it can be assumed that the fact that they were subject to slightly longer curing times than the other parts plays a role in this density gradient. Similar trends have been reported in previous studies for low-density fiberboards (Badel *et al*. 2008).

Morphological Properties

The prepared specimens were observed with a stereomicroscope, and the optical images are shown in Fig. 7. As the density of the fiberboard increased, the porosity decreased, and the wood fibers became tightly pressed together. This difference is clearly visible between D-1 and D-3.

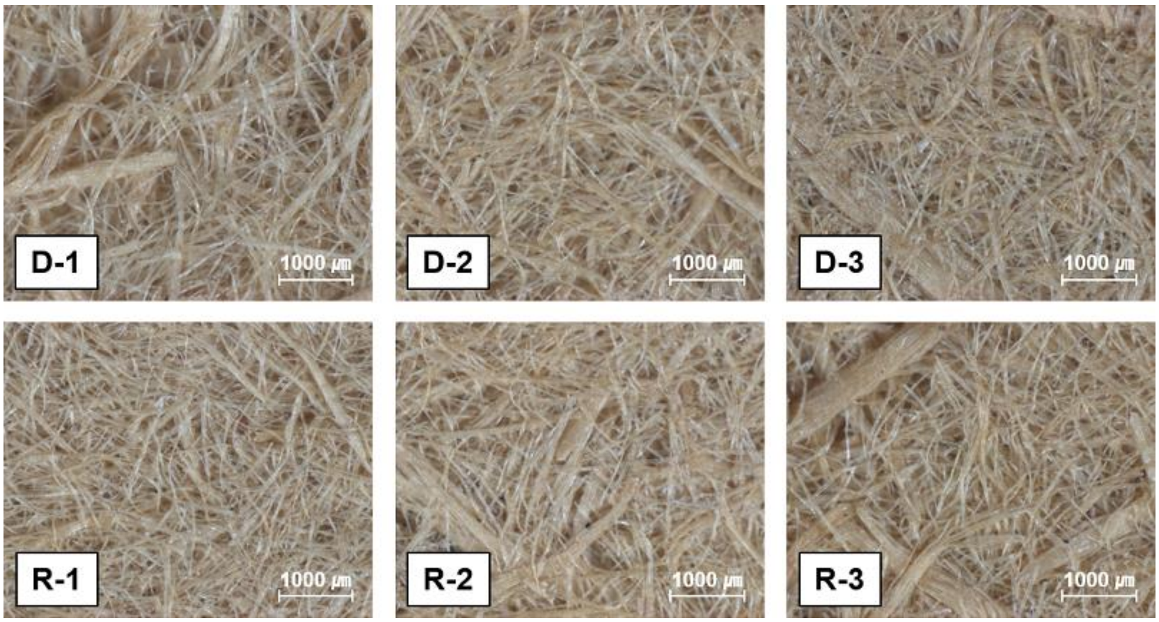

Fig. 7. Optical images displaying the morphology of the fiberboard samples (magnitude 25x)

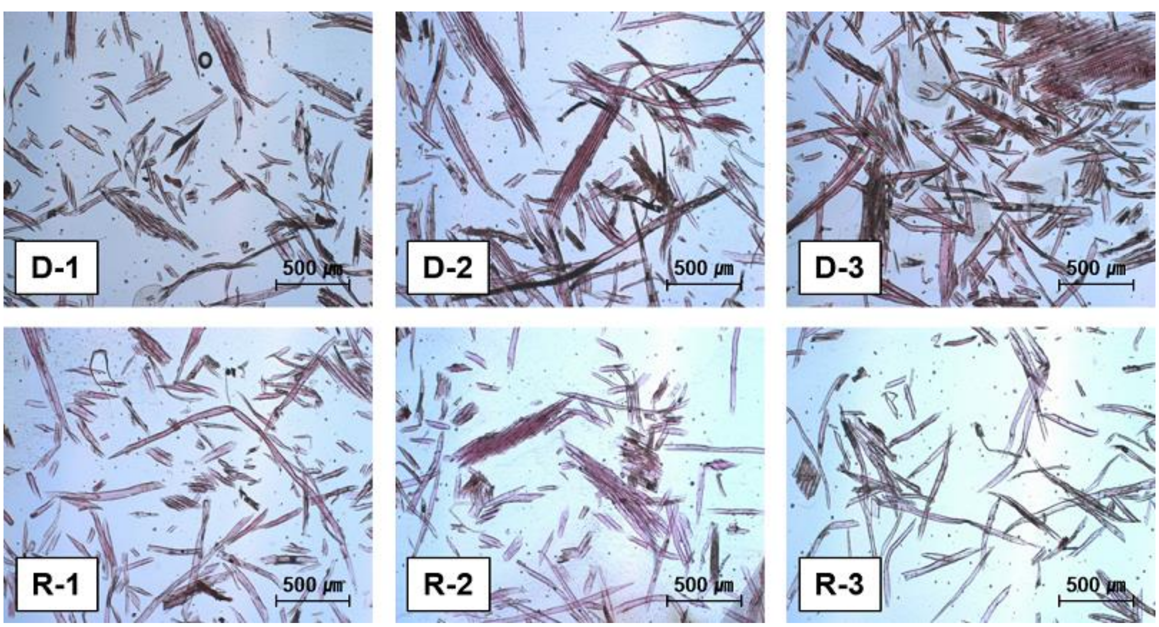

Fig. 8. Cross-section images of fiberboard samples prepared by PEG embedding

The voids in the fiberboards increased going from R-1 to R-3. Increasing the amount of resin in the raw mixture improves the binding strength between wood fibers in the final fiberboard. This contributes to enlarging the gaps between consecutive clogs of agglomerated fibers. Figure 8 shows the cross-section of the different fiberboard samples fixed and embedded in PEG. As the density increased, the quantity of embedded wood fibers increased. Therefore, more empty space in a fiberboard is related to a lower frictional resistance, which allows sound to pass through the fiberboard more easily. During transmission, sound waves are diffused and reflected in the voids inside a porous material like a fiberboard, and sound is eventually reduced. However, adding more resin to the raw mixture caused the formation of more gaps between wood fiber clogs in the final fiberboard; therefore, higher resin amounts positively affect the sound absorbing properties.

CONCLUSIONS

1. The sound absorption coefficients' trends of the prepared fiberboard samples were in agreement with the characteristics of typical porous sound-absorbing materials, in which the sound absorption coefficients are higher at high frequencies than at low frequencies. The sound absorption ability was greatly influenced by the density of the fiberboard, and the low-frequency absorption coefficient was higher for lower resin contents. The noise reduction coefficient values of all fiberboards satisfied the Korean standard requirements.
2. The transmission sound loss, which quantifies the sound insulation characteristics of a material, was positively correlated with the density. The average transmission loss values of the samples ranged between 10 and 30 dB, showing lower sound insulation abilities than those of commonly employed gypsum and glass wool boards.
3. Regardless of the difference in density and resin content, the physical properties of the fiberboards satisfied all the criteria set in the reference Korean Standard. The density profile analysis established that the implemented manufacturing process is highly reliable, and sound absorption was more likely to be improved when the bare side of the fiberboard was placed in the direction of the sound source.
4. An increase in the overall voids in the material was observed as the density of the fiberboards decreased. As the resin contents increased, the aggregation of wood fibers increased, enlarging the space between consecutive wood fiber agglomerates.
5. In summary, manufacturing conditions were developed for preparing fiberboards to be used as sound-absorbing panels. Compared to those of existing wood-based materials, the sound-absorbing properties of the prepared panels were highly superior. In addition, the use of inexpensive, eco-friendly materials in the field of sound absorption is expected to rise, being environmentally and economically advantageous compared to employing petrochemical derivatives.

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