Effects of Different Flame-Retardant Treatments on the Sound Absorption Properties of Low-Density Fiberboard

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Internal finishing materials for large auditoriums or public facilities are regulated in South Korea to ensure their flame-retardant performance. Flame-retardant treatment of low-density fiberboard (LDF), an eco-friendly material, was performed to expand its use as a sound absorber by improving its fire safety. In this study, an LDF with a target density of 0.15 g/cm^3 was prepared from radiata pine wood fibers and melamine–urea–formaldehyde resin, and recommended amounts of commercially available flame retardants (liquid type) were applied immediately after hot pressing. A powder-type flame retardant was blended with the resin used in LDF manufacture. The surface color and material changed partially depending on the flame-retardant type. The external application method slightly increased the moisture content and density, but it did not affect the physical properties of the LDF. The flame-retardant treatment reduced the emission of formaldehyde, as a scavenger. After treatment, the char area and char length of the LDFs decreased significantly to 9.42–23.64%, and 6.11–11.91%, respectively. The sound absorption performance of the flame-retardant-treated LDFs improved 4.08–9.11%, while their thermal-insulation performance remained unaffected. The flame-retardant-treated LDFs satisfy the regulation of flame retardancy, while maintaining sound absorption and thermal insulation functions.

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INTRODUCTION

Sound-absorbing materials are mainly used in special buildings, such as churches and auditoriums, ever since the concept of sound-absorbing materials was established in the 20th century. However, they are currently being used in most buildings and facilities that require noise control (Grimwood 1997). With the accelerated development of transportation and production facilities, the sources and levels of noise are gradually increasing; therefore, noise control is garnering appreciable attention in the Republic of Korea (South Korea). The noise problem between floors remains the most significant challenge in residential buildings. Because the installation of a separate sound system in a general residential environment is a burden to consumers, the integration of sound absorbers into the existing building structure is preferred. In this regard, a method for inserting a sound-absorbing material between the finishing material and main wall or installing a finishing material with sound-absorbing ability, such as wood fibers, textile fibers, glass wool, or polyester fibers, is favorable. In particular, lightweight fiberboards based on wood fibers, which are classified as porous sound-absorbing materials, have been applied as economical and eco-friendly sound-absorbing materials for a long time.

Wood-fiber-based materials have favorable features such as porous sound-absorbing materials, and their performance is largely influenced by the degree of porosity, thickness of the material, and airflow resistance of the material. In addition, because lightweight fiberboards have low heat conductivity and many voids, thermal insulation performance can also be expected (Zach *et al*. 2013).

Although wood materials have many advantages as sound absorbers, their poor fire resistance impedes their widespread application. Wood is a cellulosic material, and hemicellulose begins to decompose at 200 °C or higher; further, when the temperature reaches 500 °C, most of its components, including lignin, decompose. Therefore, many studies have attempted to improve their resistance to heat and flame by treating them with a flame retardant. Wood and wood fiberboard that can be used as an insulating material exhibited flame-retardant properties after being coated with a flame retardant through spraying, coating, or dipping, and the spraying method effectively imparted flame retardancy without impairing the thermal-insulation performance (Harada *et al*. 2007; Osvaldová 2017; Park *et al*. 2020). Chen *et al*. (2016) demonstrated that the flame-retardant performance of an ultralight fiberboard could be improved through flame-retardant treatment with various materials, such as phosphorus, boron, silicon, and halogen-based compounds, and that the boron-based compound had the greatest effect. Cai *et al*. (2016) produced ultra-low-density fiberboard (ULDF) using a fire-resistant adhesive composed of polyvinyl alcohol, urea, phosphoric acid, and starch, and reported that a chemical bond was formed between the fire-resistant adhesive and ULDF through Fourier transform infrared analysis. Hashim *et al*. (2009) analyzed the physical properties and flame-retardant performance of a rubberwood fiberboard fabricated using a flame-retardant urea-formaldehyde (UF) resin and reported that the physical properties of the treated fiberboard changed to some extent due to the flame-retardant resin. To date, various flame-retardant treatment methods have been developed, and prototypes such as WOODWORKS Walls (Armstrong, USA) that satisfy the non-combustibility requirement, according to international standards, are commercially available. Wood-based lightweight fiberboards are excellent sound-absorbing materials with high potential as an acoustic material. Moreover, unlike asbestos, they are eco-friendly products that cause no harm to the human body, and they have strengths in terms of energy usage and carbon storage (Wilson 2010). In this study, to expand the use of wood-based materials, a low-density fiberboard (LDF) manufactured as a sound-absorbing material was treated with different flame-retardant materials, and the physical, acoustic, flame-retardant, and insulation properties of the resulting samples were analyzed and compared.

EXPERIMENTAL

Materials

The wood fiber used in the manufacture of the LDF was supplied by Donghwa Enterprise (Incheon, South Korea). The wood fiber was derived by refining radiata pine (*Pinus radiata*) chips after applying steam (200 °C) under pressure (8 to 9 bar), and its moisture content was approximately 3.9%.

For synthesizing the resin, 37% formalin, 99% melamine (industrial use), and urea (industrial use) purchased from Donghwa Enterprise (Incheon, South Korea) were used. The wax emulsion used to manufacture the board had a solid content of 60%. Ammonium chloride purchased from Daejung Chemicals and Metals Co. Ltd. (Siheung-si, South Korea) was used as the curing agent, and its concentration was adjusted to 20%. Four different types of flame-retardant materials were purchased from manufacturing companies and used in this study, and the related details are provided in Table 1.

Table 1. Properties of the Liquid and Solid Flame Retardants Used in the Study

Retardants	Type	Component	Concentration (%)	Viscosity (cp)	pH
A	Liquid	Phosphorus, Boron	13	27	5.87
B	Liquid	Phosphorus	24	102	4.52
C	Liquid	Phosphorus	28	30	6.50
D	Powder	Hybrid ceramic	100	-	-

Methods

Adhesive synthesis

Because the LDF was developed as a sound-absorbing material with flame-retardant performance and was intended to be applied as an interior finishing material, a suitable adhesive was synthesized considering the anticipated adhesive performance and formaldehyde emission. A melamine–urea–formaldehyde (MUF) resin adhesive with a final F/MU molar ratio of 0.80 and a melamine content of 30% was synthesized through an alkaline-alkaline reaction using a 37% formalin solution, melamine, and urea. The general physical properties, *viz.*, the solid content, pH, and specific gravity, of the resin were evaluated according to KS M 3705 (2020).

Table 2. Targeted Properties and Ingredients Used for the Fabrication of Low-Density Fiberboard

Contents		Conditions
LDF		
	Size (L × W × T)	350 mm × 350 mm × 20 mm
	Target density	0.15 g/cm^3
	Moisture content of wood fiber	3.9%
Resin		
	Type	Melamine–urea–formaldehyde resin
	Solid content	66.2%
	Content	25% with respect to the oven dry weight of wood fibers
Wax emulsion		
	Type	Paraffin wax
	Solid content	60%
	Content	1% to oven dry weight of wood fiber
Hardener		
	Type	Ammonium chloride
	Concentration	20% in water
	Content	3% with respect to the solid content of the resin

Preparation of the LDF

The targeted properties and raw materials used in the fabrication of the LDF are listed in Table 2. The target dimensions of the LDF were 350 mm × 350 mm × 20 mm, and the target density was 0.15 g/cm^3. A resin content of 25% was used based on the weight of the dry wood fibers. The amount of the wax emulsion was 1% with respect to the weight of the dry wood fibers, and 3% curing agent was used based on the solid content of the adhesive, in accordance with the conditions for manufacturing medium-density fiberboards. First, the adhesive, wax emulsion, and hardener were weighed separately and mixed, and the resulting mixture was spray-coated onto wood fibers in a drum-type mixer.

Table 3. Preparation Conditions of the Low-Density Fiberboard

Contents		**Conditions**
Blending		
	Atomizing pressure	6.5 kgf/cm^2
	Spray method	Drum mixer
	Spray time	30 min
Pressing		
	Press type	Oil-pressure, Auto-controlled press
	Temperature	150 °C
	Pressure	5 kgf/cm^2
	Time	21 s/mm

The liquid and solid flame retardants were applied in two different ways: the liquids were sprayed on the surface of the LDF after hot-pressing and the solid was mixed with the resin. The powder-type solid flame retardant was mixed with the resin at 35% content with respect to the total solid content of the resin and then used in LDF preparation. The wood fibers treated with the adhesive were weighed based on the target density to prepare a mat using a mold. The prepared mat was hot-pressed for 7 min at a target pressure of 5 kgf/cm^2 at 150 °C in a thermopress (see Tables 3 and 4).

Table 4. Flame Retardant Treatment of the Low-Density Fiberboard

Retardant	**A**	**B**	**C**	**D**	**E = (C + D)**	
Pre-treatment						
Type	-	-	Powder	-	Powder	-
Solid content	-	-	100%	-	100%	-
Used amount	-	-	35% to resin solids	-	35% to resin solids	-
Application	-	-	Mixed with resin	-	Mixed with resin	-
Post-treatment						
Type	Liquid	Liquid	-	Liquid	-	Liquid
Solid content	13%	24%	-	28%	-	28%
Used amount	300 g/m^2	150 g/m^2	-	50 g/m^2	-	50 g/m^2
Application	Spray onto the surface	Spray onto the surface	-	Spray onto the surface	-	Spray onto the surface

After hot pressing the fiberboard, each liquid-type flame retardant was sprayed on either side of the LDF. Because the liquid-type flame retardant has a high moisture content, it was applied on the LDF surface at temperatures ranging from 80 to 100 °C to enable the evaporation of water from it, dimensional stability, and cooling effect. The applied amount of each flame retardant is as follows: 300 g/m^2 for flame retardant A, 150 g/m^2 for flame retardant B, and 50 g/m^2 for flame retardant D, as recommended by the manufacturer. In addition, sample E was treated with both flame retardants C and D. Each prepared LDF sample was then cooled to room temperature.

Mechanical Properties of the LDF

The surface of the prepared LDF was observed using a stereomicroscope (Axiocam 506 color, ZEISS, Oberkochen, Germany), and visually observable differences, such as the color and coating state, of the flame retardant were noted. The density, moisture content, thickness swelling, and bending strength were measured according to the KS F 3200 (2021) standard. The swelling along the thickness was measured after immersion in water at 20 °C for 2 h. The bending strength was measured at a loading rate of 10 mm/min. The formaldehyde emission test of the prepared LDF was performed according to ISO 12460-4:2016 (2021). The number of LDF samples was adjusted to have a total surface area of 1800 cm^2, and they were stored for 7 d at 20 ± 2 °C and 65 ± 5% relative humidity (RH). The prepared LDF samples were placed in an 11-L desiccator in which a collecting glass dish containing 300 mL of distilled water was placed. After 24 h, 25 mL of the formaldehyde-absorbed distilled water was mixed with 25 mL of acetylacetone-ammonium acetate solution and the absorbance of the resulting solution at the wavelength of 412 nm was measured using a UV–visible spectrophotometer (Lambda 465, PerkinElmer, Waltham, MA, USA).

Flame-Retardant Performance

The flame-retardant performance of the LDF was evaluated through a 45° Meckel burner test, according to KS F 2819 (2016). A sample measuring 300 × 200 mm^2 was fixed at 45° and exposed to a flame with a length of 65 mm for 2 min. The flame persistence time and glow time of the LDF sample after flame exposure were measured, and then the carbonized area and carbonized length were calculated through image analysis.

Sound Absorption Performance

The sound absorption characteristics of the LDF were measured according to the test procedure of KS F 2814-1 (2016). The absorption rate was measured by the transfer matrix method using an impedance tube, pulse analyzer, and spectrum analyzer (Type 4206-T; Bruel & Kjaer, Nærum, Denmark) in the real frequency range. To measure the change in sound absorption according to the change in frequency, the frequency range was divided into low-frequency (100 to 1600 Hz) and high-frequency (500 to 6400 Hz) ranges. The experimental environment was set at 23 °C, 56% RH, and air pressure of 100.1 kPa. The diameters of the circular specimens after the low- and high-frequency tests were 99 and 29 mm, respectively. Each measured value was obtained as the average of three repeated tests. The noise reduction coefficient (NRC) was calculated from the sound absorption measured at major frequencies of 250, 500, 1000, and 2000 Hz.

Thermal Insulation Properties

The thermal conductivity, thermal transmittance, and thermal resistance were measured according to ISO 8302:1991 (2019) using a λ-Meter EP500 (Messtechnik, Dresden, Germany). The thermal conductivity was measured by setting a temperature difference of 15 K between the upper and lower plates of the device at a measurement temperature of 25 °C.

RESULTS AND DISCUSSION

Properties of the Resin

The solid content, pH, and specific gravity of the synthesized resin were determined as 66.2%, 8.2, and 1.29, respectively. The viscosity was measured as 112 cP using a DV-II+ Viscometer (AMETEK Brookfield, Middleborough, MA, USA) with spindle #2. The gel time of the resin was 142 s, as measured after mixing at 100 °C following the addition of 3% curing agent (based on the solid content of the resin) to the resin using a gel time meter (Davis Inotek Instruments, Hayward, CA, USA).

Properties of the LDF

The density, moisture content, thickness swelling due to water absorption, and formaldehyde emission properties of the control and flame-retardant-treated LDFs are summarized in Table 5. The LDF surface was treated with 50, 150, and 300 g/m^2 of the flame retardants, and the density of treated LDFs increased with increasing weight of the solid content of the flame retardant, indicating that the flame retardant was well coated on the LDF without wastage.

Table 5. Physical and Chemical Properties of Control and Flame-Retardant-Treated LDFs

Contents	Control	A	B	C	D	E
Density (g/cm^3)	0.16	0.18	0.19	0.16	0.17	0.16
Moisture content (%)	6.45	6.90	11.71	6.00	8.80	8.37
MOR (MPa)	0.32	0.18	0.44	0.25	0.31	0.28
Thickness swelling (%)	2.78	2.89	1.40	1.93	2.53	1.43
HCHO emission (mg/L)	0.25	0.15	0.03	0.25	0.11	0.12

*All values are an average of 10 samples from each 4 replicates.

All LDF samples satisfied the moisture content standard of 5 to 13% (see Table 5). Although an increase in the moisture content due to the liquid-type flame retardant treatment was initially observed, as the treatment was performed at a high temperature, immediately after hot pressing, most of the water in the flame retardant was evaporated. Therefore, an additional drying process was not required. A lower moisture content was observed in the sample treated with the powder-type flame retardant. It is noteworthy that a relatively higher moisture content was observed in the liquid-type flame retardant-treated LDF compared with that of the control LDF. Among the flame retardants, B and D had greater propensity to absorb moisture than the others.

The bending strength of the control and flame retardant treated LDF ranged from 0.18 to 0.44 MPa, as expected based on the target density of 0.15 g/cm^3. These results of bending strength, however, did not satisfy standard (> 1.0 MPa). In general, the bending strength was highly dependent on the density of the LDF, and the effect of the flame retardant on the bending strength was noticeable. In terms of the physical properties, the bending strength of the LDF decreased after the spray-coating of flame retardant A with a low solid content or mixing of the powder-type flame retardant C with the adhesive used in the manufacture of the LDF.

For the treatment with flame retardant A, the LDF was exposed to excessive moisture because of a high dilution ratio and a large amount of the flame retardant being used, resulting in reduced adhesive performance and adversely impacted physical properties. In contrast, when flame retardant B was used, the bending strength of the LDF rather increased, which is presumably due to surface hardening induced by the flame retardant. This is considered to be due to the inclusion of the resin component, which has a relatively high bending strength, in the coating layer.

The thickness swelling of the LDF decreased after flame retardant treatment. This is attributed to the increased dimensional stability through the process of wetting by the moisture in the flame retardant followed by drying. Remarkably, all LDF test specimens satisfied the standard of less than 3% swelling in the thickness direction.

Formaldehyde emissions were less than 0.3 mg/L from all LDF samples, satisfying the KS F 3200 (2022) SE$_0$ standard. The low formaldehyde emission is essentially due to the effect of melamine and the F/MU molar ratio of the resin. In addition, He *et al.* (2012) reported that formaldehyde was released because of the hot-pressing temperature during the fiberboard manufacturing process, which contributed to the reduction in the emission value of the manufactured fiberboard. Therefore, the effect of flame-retardant treatment on the formaldehyde emission was investigated. The emitted amount of formaldehyde from the LDFs treated with the liquid-type flame retardants was 0.03 to 0.15 mg/L, which was remarkably lower than that emitted from the control LDF sample. Gao *et al*. (2015) reported that the phosphorus component of the flame retardant was partially decomposed during the high-temperature pressing, resulting in the generation of a gas that reacted with formaldehyde. A similar effect appeared in the current study because the flame retardant was applied in a state where the high temperature of the LDF was maintained after hot pressing. The resin, surfactant, and phosphorus components are considered to react with unreacted formaldehyde and fix it to the wood fiber.

Figure 1 displays the surface images of the LDFs with 25x magnification after the flame retardant treatment. The color of the wood fiber was slightly altered after the treatment. Flame retardant A caused a brighter color of the wood fibers; this is because of boron contained in flame retardant A, which can have a bleaching effect.

In contrast, flame retardant D changed the color to a more intense and darker tone. Flame retardant D contains components with antibacterial and antifungal properties, in addition to having flame-retardant components, and it was expected to change the color of wood fibers because of its relatively strong permeability because of its lower viscosity. The LDF treated with flame retardant B exhibited white grains attached to the surface of the wood fibers. These are crystals of the resin, surfactant, and phosphorus that did not penetrate the wood fibers but rather were present in the form of a coating around them.

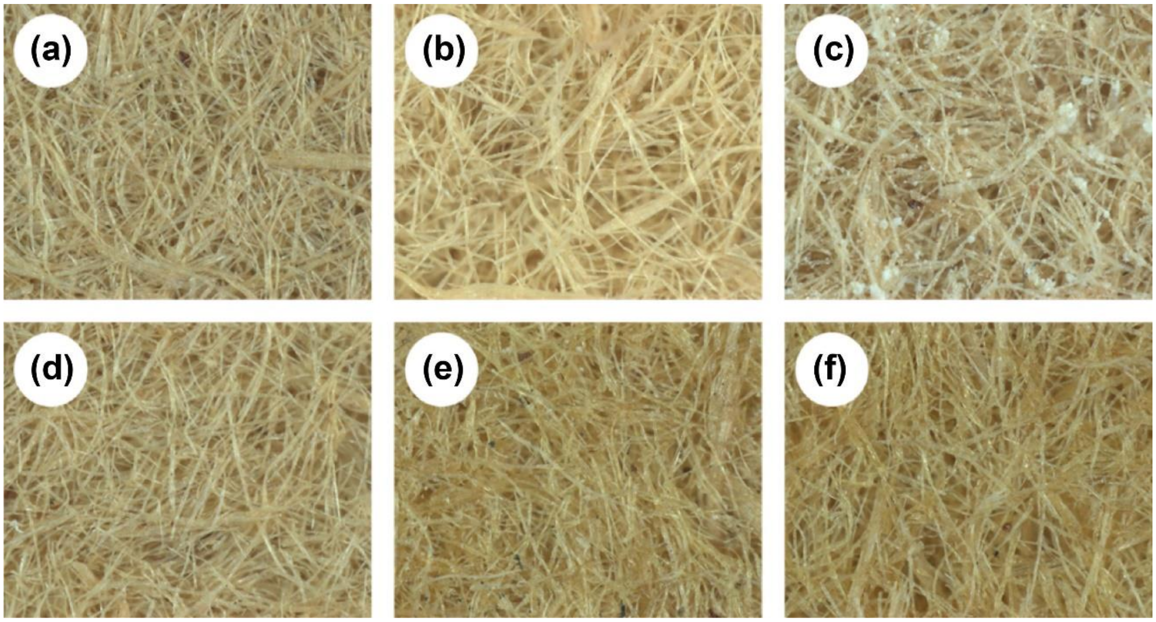

Fig. 1. Surface images of the control and flame-retardant-treated LDFs (25x magnification)

Flame-Retardant Performance

The flame-retardant properties of the prepared LDF samples are presented in Table 6. All flame retardant-treated LDF samples met the flame-retardant performance standards specified in the National Fire Agency Notice No. 2021-7 (National Fire Agency 2021) (char area: < 50 cm^2, char length: < 20 cm, after-flame time: < 10 s, and after-glow time: < 30 s), whereas the control LDF failed to meet the standards.

Table 6. Flame-Retardant Performance of the Control and Flame-Retardant-Treated LDFs

Experiment	Control	A	B	C	D	E
Char area (cm^2)	54.36	40.63	35.27	41.50	37.54	41.84
Char length (cm)	10.55	9.13	8.65	9.09	9.10	9.22
After flame (s)	0	0	0	0	0	0
After glow (s)	Over 120	Less 30	0	Less 30	0	0
Standard satisfaction	Fail	Pass	Pass	Pass	Pass	Pass
Char area reduction rate (%)	-	25.30	35.15	23.70	30.98	23.07

Although the char area reduction rate of the LDF samples with different flame retardants was different, their char area and char length decreased compared with those of the control LDF sample. For all LDF samples, the flame disappeared immediately after the end of the flame exposure; therefore, the after-flame time was recorded as 0 s. However, the control LDF sample exhibited more than 120 s of afterglow, while the LDF samples treated with flame retardants A and C exhibited afterglow of less than 30 s. Remarkably, no after-glow was observed in the other flame retardant-treated LDF samples.

In particular, the LDF treated with flame retardant A presented the least remarkable flame-retardant effect because of the difference in the extinguishing mechanism. The boron compound in flame retardant A loses moisture during thermal decomposition and aromatizes the thermal decomposition product. Moreover, the generated boron oxide accelerates the dehydration of the carbonized material and thus reduces its activation energy (Wang *et al*. 2004). Therefore, the boron-based flame retardant (A) is inefficient in securing the flame retardancy of the LDF because of the low production rate of carbonized materials.

Flame retardant C mixed with the adhesive improved the flame-retardant performance of the LDF. Although this flame retardant was not concentrated on the surface of the LDF and was widely distributed in the LDF body, satisfactory flame retardancy was achieved. Flame retardant B, which exhibited the best performance, contained a resin component based on phosphorus. As can be seen in the surface image in Fig. 1C, the flame retardant appeared to attach to the wood fibers in the form of granules, interfering with their combustion. Phosphorus used in flame retardants generates phosphate during combustion, which mixes with soot to form a barrier that blocks access to oxygen (Pen *et al*. 2012). In addition, melamine contained in the MUF resin used to manufacture the LDF condenses during heating to produce melam or melem, which are thermally stable materials that help in the formation of a barrier (Liu *et al*. 2016). According to the results of this experiment, powder and liquid-type flame retardants could work effectively on LDFs when applied through surface spraying or by mixing with the adhesive.

Sound Absorption Performance

The sound absorption coefficients according to frequency of control and flame-retardant-treated LDF are shown in Figs. 2 and 3. When sound is incident on the surface of the LDF, pressure fluctuations occur in the voids between the wood fibers, resulting in air vibration, friction, and viscous resistance, which are typical characteristics of porous sound absorbers (Or *et al*. 2017).

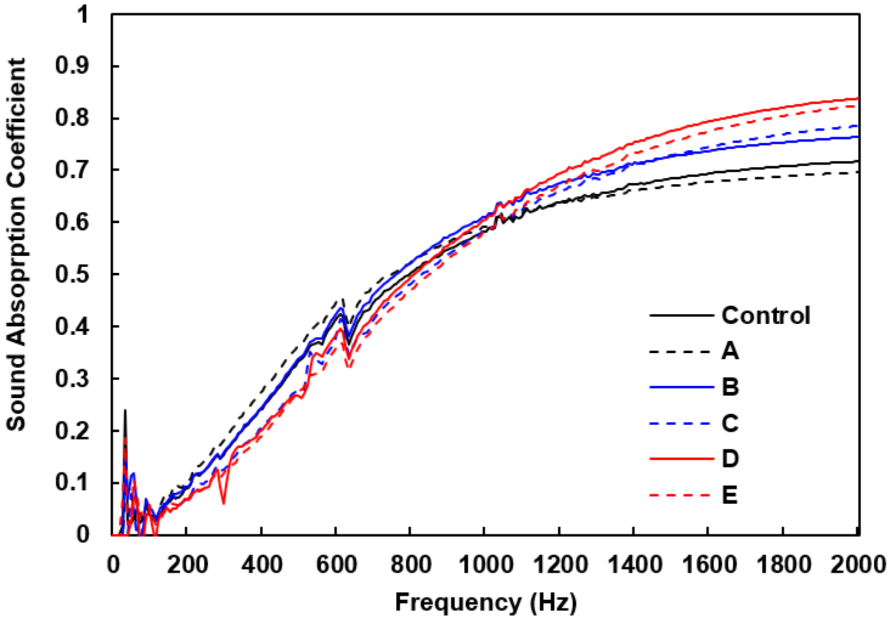

Fig. 2. Sound absorption coefficients of the control and flame-retardant-treated LDFs in the frequency range of 0 to 2000 Hz

The sound absorption coefficients of all LDF samples were low in the low-frequency region of 1000 Hz or less, and they decreased or increased according to the type of flame retardant or treatment. In the high-frequency region of 1000 Hz or higher, the sound absorption coefficient increased following the treatment of the LDF with a flame retardant.

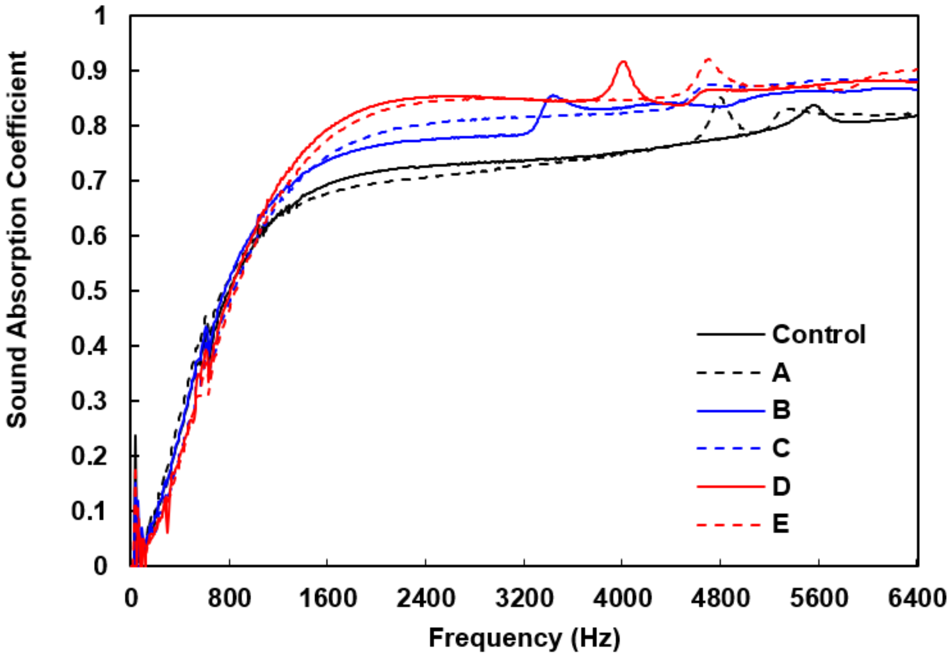

Fig. 3. Sound absorption coefficients of the control and flame-retardant-treated LDFs in the frequency range of 0 to 6400 Hz

The increase in the sound absorption coefficient in the high-frequency region of the flame-retardant-treated LDFs is because of non-uniform physical property changes of their surfaces, such as the destruction of the adhesive layer on the surface due to the application of the flame retardant with a high moisture content and surface swelling due to moisture absorption. After treatment, physical changes appeared in the form of agglomeration of the wood fibers and interconnection of the fibers. Moreover, Zhu *et al*. (2014) reported that the sound absorption performance of long-fiber-based composites improves as the frequency increases because of the increase in the propagation path of the sound waves inside the material.

Table 7. Sound Absorption and Noise Reduction Coefficients of Control and Flame-Retardant-Treated LDFs

Frequency (Hz)	Control	A	B	C	D	E
250	0.103	0.148	0.130	0.097	0.100	0.096
500	0.251	0.348	0.323	0.268	0.276	0.261
1000	0.547	0.586	0.606	0.603	0.580	0.580
2000	0.769	0.694	0.759	0.828	0.779	0.815
NRC	0.417	0.444	0.455	0.449	0.434	0.438

Among the treated samples, the LDF treated with flame retardant B exhibited the largest sound absorption coefficient of 0.455 (see Table 7), which is possibly related to the singularity of the material structure. As shown in Fig. 1C, the surface of the wood fibers in the LDF treated with flame retardant B was distributed with white grains, unlike in the cases of other specimens.

After being sprayed, flame retardant B, which has a higher viscosity than the other flame retardants, quickly coagulated on the surface of the LDF at the high temperature, and it adhered in the form of solid particles to the fibers. Irregular amorphous particles were attached to the linear wood fibers, which changed the morphology of the wood fibers on the surface. This feature appears to help improve sound absorption by causing diffused reflection of the sound waves. Attenborough *et al*. (2014) reported that noise reduction was effectively improved upon increasing the surface roughness of the sound absorber. Liu and Hu (2010) improved sound absorption through shape diversification of the surface by stacking several layers of fabric.

Thermal Insulation Properties

Because the LDF can serve as an insulator, its thermal insulation characteristics were investigated by evaluating its thermal conductivity, thermal transmittance, and thermal resistance (Uysal *et al*. 2009). The experimental results are listed in Table 8. The thermal conductivities of the control and flame-retardant-treated samples were measured to be 0.041 to 0.044 W/m·k, and the thermal conductivity tended to decrease slightly because of the external flame-retardant treatment.

Table 8. Thermal Properties of the Control and Flame-Retardant-Treated LDFs

Type	Thermal Conductivity (W/m·k)	Thermal Transmittance ($W/m^2 \cdot K$)	Thermal Resistance ($m^2 \cdot K/W$)
Control	0.0434	2.205	0.454
A	0.0412	2.083	0.480
B	0.0410	2.045	0.489
C	0.0418	2.090	0.478
D	0.0426	2.130	0.469
E	0.0441	2.204	0.454

This phenomenon can be attributed to the thermal conduction anisotropy mechanism caused by structural separation between the surface and bulk parts of the sample. Although it has been reported that phosphorus-based flame retardants contain many hydrogen ions and form a typical polyol structure, thereby improving the bonding strength between the wood fibers and simplifying the directionality to improve conductivity (Chen *et al.* 2015), in the current case, the externally applied flame retardant complicated and hardened the surface layer. Consequently, the heat supplied was transmitted more easily in the horizontal direction of the surface layer than in the vertical direction through the board (Sulistyo *et al*. 2009; Pradha *et al*. 2012).

CONCLUSIONS

LDFs were applied as sound-absorbing or insulating materials in the past, but they are currently required to have flame-retardant performance, as stipulated by the Building Act and the Fire Protection Act. Therefore, this study aimed to impart flame retardancy to LDFs. The following conclusions were drawn based on the changes in the properties of the LDF according to the flame-retardant treatment:

1. Flame-retardant treatment can change the color and surface appearance of the LDF depending on the type of flame retardant. The application of the flame retardant as a surface coating slightly increased the moisture content and density, but did not remarkably affect the strength of the LDF.
2. The phosphorus component or resin components of the flame retardant noticeably decreased formaldehyde emission by acting as formaldehyde scavengers.
3. When the flame retardant was sprayed on the LDF surface or incorporated in the LDF body by mixing within the adhesive, the flame retardancy of the treated sample satisfied the government regulations. When the flame retardant was mixed in the resin, the flame-retardant performance was manifested without a separate external coating treatment. However, the external application method led to better flame-retardant performance of the LDF. A flame retardant containing a phosphorus-containing surfactant or resin component is suitable for LDFs, because the phosphorus component plays a flame-retardant role and sufficiently coats the surface of the wood fiber or penetrates the LDF body.
4. The flame-retardant treatment did not impair the sound absorption performance of the LDF, and the treatment method that increased the surface roughness rather increased the sound absorption performance.
5. The increase in the surface density of the LDF after the flame-retardant treatment increased the horizontal transmission of heat, resulting in a slight increase in the thermal insulation performance of the LDF.

Thus, the flame-retardant treatment improved the sound absorption and heat insulation performances of the LDF, without noticeably affecting its physical performance. In addition, the effect of reducing formaldehyde emission was excellent. The method of imparting flame-retardant performance by mixing a flame retardant with an adhesive is advantageous in the manufacturing process because no separate treatment is required.

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