Changes in Characteristics of Wood Fiber Insulation Board According to Density

Min Lee,* Sang-Min Lee, and Eun-Chang Kang

As the demand increases for low energy green buildings, such as passive housing, the development of new insulation systems based on natural materials is underway. In this study, 20-mm-thick wood fiber insulation board (WIB) samples of different densities were prepared using melamine-formaldehyde-urea (MFU) resin adhesives. The resin contents were fixed at 35% and the target densities were 0.10 g/cm^3, 0.15 g/cm^3, 0.20 g/cm^3, and 0.25 g/cm^3. The thermal conductivities of the WIBs gradually increased as the density increased. The formaldehyde (HCHO) emissions of all the WIBs indicated that they were of “Super E_0” (SE_0) grade, but the quantity of the HCHO emissions slightly increased as the density increased. The thickness swelling of all the WIBs was stable at less than 3%, and the bending strength linearly increased as the WIB density increased. A notable decrease in the water absorption rate was observed between the lower and higher density WIB samples. Based on the results of the cone calorimeter tests, the carbonization depth ratio and the weight loss rate remarkably decreased as the density increased. Therefore, the optimum WIB density was in the range of 0.15 g/cm^3 to 0.20 g/cm^3 to provide adequate insulation performance as well as human and structural safety.

Keywords: Wood fiber; Insulation; Thermal conductivity; Cone calorimeter; Density

*Contact information: Department of Forest Products, National Institute of Forest Science, Seoul 02455, Republic of Korea; *Corresponding author: mlee81@korea.kr*

INTRODUCTION

Concerns over global fossil fuel depletion and global climate change have highlighted the importance of global greenhouse gas reductions. Accordingly, worldwide efforts to reduce carbon dioxide (CO_2) emissions are underway (Hasan 1999; Reilly and Kinnane 2017). These efforts typically consist of energy conservation measures. Energy conservation is an important issue in Korea, where 97% of the nation’s energy is imported due to Korea’s lack of domestic energy resources (Song *et al*. 2013). In Korea, 90% of the population lives in cities, so most of the greenhouse gas emissions related to the lives of citizens are generated by factories and buildings. In particular, the building sector accounts for more than 40% of the national greenhouse gas emissions, so the implementation of energy efficient buildings has the potential to create a large reduction in the greenhouse gas emissions (Jelle 2011; Kaynakli 2012). In the United States, buildings consume 36% of the total energy and 65% of the power while generating 30% of the CO_2 emissions. Therefore, energy conservation in buildings is important in achieving national greenhouse gas reduction targets (DOE/CE-0180 2002; Al-Homoud 2005).

Since the early 1990s, passive houses have been built in Germany that have an energy heating demand of less than 10% that of normal buildings (Schiavoni *et al*. 2016). In Central Europe, passive houses are defined as those that have a heating energy consumption of less than 15 kWh per square meter, and whose primary energy consumption is 120 kWh or less (EPEU 2010). The core technology of such passive houses consists of high-efficiency equipment applied with extensive insulation, airtightness, high-efficiency windows, and high-efficiency heat exchange for building load reduction (Kaklauskas *et al*. 2012). To provide such extensive insulation, it is common to use the same 30 cm to 40 cm thickness as existing insulation materials, such as mineral wool, glass wool, cellulose, and Styrofoam, and to provide basement and balcony insulation to prevent thermal bridging (Kaynakli 2012; Aditya *et al*. 2017). High-performance vacuum insulation panels have been partially applied for this purpose. Low-energy buildings are indeed on the rise: the European Union will be obligated to build zero-energy buildings starting in 2019; the UK required that all new housing units be zero-energy starting in 2016; France will supply one million units of zero-energy housing by 2020; Germany has required passive-level houses since 2015; and the United States has announced the intention to supply zero-energy housing starting in 2025 (Kwon 2012). In Korea, a goal has been set to reduce the greenhouse gas emissions 31% in the construction sector by 2020. Furthermore, newly constructed houses are to be retrofit to the passive house level starting in 2017, with the goal of transitioning all newly constructed houses to the zero-energy house level in 2025. Currently, low-energy residential buildings are not optional but instead a mandatory requirement according to Korean national policy (Kwon 2012).

Various building materials for low-energy buildings have been developed. In recent years, many synthetic insulation materials have been introduced to the building materials market that are inexpensive, provide an excellent insulation effect, and can be quickly produced (Kwon *et al*. 2018). While the performance of synthetic insulation is quite good, the mechanical strength is weak, and thus such materials are generally used in auxiliary structures such as in sound-proofing walls of a building. Notably, insulation provides a basic and reliable way to save energy without requiring additional special equipment from the heating or air conditioning industries. However, it is consistently necessary to study and understand the basic heat transfer mechanism of insulation systems based on the insulation type, characteristics, design, and installation method (Kim *et al*. 2013; Yu *et al*. 2013).

In Korea, petrochemical-based insulation materials, such as foamed polystyrene, expanded polyurethane, extruded expanded polystyrene, and polyethylene, account for 72% of the insulation market, while inorganic glass wool and mineral wool materials account for the remaining 28% (Kwon 2012). The choice of insulation should consider low thermal conductivity, robustness against puncture, construction site workability, ease of installation, mechanical strength, fire resistance, smoke release, weather tolerance, resistance to ambient temperature changes, water resistance, cost, and environmental impact. However, there is no existing insulation that completely satisfies all these requirements, so it remains necessary to utilize both traditional and innovative insulation materials to continue to develop new insulation technologies to provide effective thermal protection and improved energy efficiency.

Wood is a renewable natural material that not only provides a CO_2 fixing effect, but also has superior humidity control and insulation properties compared to many other building materials (Kang *et al*. 2016; Lee *et al*. 2018). Therefore, interest in eco-friendly wood fiber insulation materials is gradually increasing. The development of an environmentally friendly insulation using wood can be based on unused wood resources or non-woody biomass. Jang *et al*. (2017a,b) produced low-density wood fiberboard for use as an insulation material using various adhesives and reported their physical properties and thermal conductivity. According to the results of comprehensive evaluations by Jang *et al*. (2017a,b) and Lee *et al*. (2019), the melamine-urea-formaldehyde (MUF) adhesive was recommended for use as the binder of wood fiber insulation board (WIB). However, to date, little research has been conducted to quantify the relationship between the WIB characteristics and their performance. Therefore, to improve the understanding of WIB performance, this study used melamine-formaldehyde-urea (MFU) adhesives to produce a series of WIB specimens to investigate the changes in the physical properties, thermal conductivity, formaldehyde (HCHO) emission, and fire resistance according to their density.

EXPERIMENTAL

Materials

Wood fibers (*Pinus radiata*) and a 60% wax emulsion were provided from Donghwa Enterprise (Incheon, Korea). On average, the wood fibers were 1.65 mm long and 37.2 μm in diameter. The distribution of the wood fiber lengths is shown in Table 1. All the chemical reagents that were used to prepare the MFU were American Chemical Society (ACS) grade and were purchased from Sigma-Aldrich (St. Louis, MO, USA).

Table 1. Distribution of the Wood Fiber Lengths

Fiber Length (mm)	0.001 to 0.1	0.1 to 0.2	0.2 to 0.3	0.3 to 0.4	0.4 to 0.5	0.5 to 1.0	1.0 to 1.5	1.5 to 2.0	2.0 to 3.0	3.0 to 7.5
Percentage (%)	5	1	4	30	20	13	7	7	13	0

Methods

Preparation of the MFU resin

The MFU resin was prepared under laboratory conditions according to established methods (Lee *et al*. 2012; Pizzi 2014; Lee *et al*. 2016). The target viscosity was confirmed to be between reference tubes F and G using a bubble viscometer (Gardner-Holdt VG-9100; Gardco, Pompano Beach, FL, USA). The characteristics of the synthesized resin were determined in accordance with the Korean Standard (KS) M 3705 (2015).

Table 2 shows general information for synthesized MFU. The F/MU molar ratio was 0.80 with 30 % melamine content (wt% of MFU resin). The pH was adjusted to 8.0 with 20% NaOH and borax. The final viscosity of MFU resin was 106 mPa·s. Gel time at 100 ^{o}C was 120 seconds.

Table 2. General Resin Information

Resin	F/MU Molar Ratio	Melamine Content (wt% of MFU Resin)	pH	Viscosity (mPa·s)	Solids Content (%)	Gel Time at 100 °C (s)
MFU	0.80	30	8.0	106	60	120

Preparation of the wood fiber insulation board

The WIBs were prepared according to Lee *et al.* (2019) as 350 mm (length) × 350 mm (width) × 20 mm (thickness) specimens. The density of the WIBs was set to 0.10 g/cm^3, 0.15 g/cm^3, 0.20 g/cm^3, and 0.25 g/cm^3 with 35 wt% fixed MFU resin contents with respect to wood fiber. The amount of curing agent (20% NH_4Cl) used was set to 3% according to the solids content of the resin adhesive. The wax emulsion was dosed at 1% of the air-dried weight of the wood fibers (Table 3). The resin was sprayed on the wood fibers on the forming mat using a drum-type applicator (So Jung Measuring Instrument Co., Ltd., Anyang-Si, South Korea). After the forming mat, a hot press (Anjeon Hydraulic Machinery Co., Ltd., Seoul, South Korea) was applied to the WIBs at a temperature of 150 °C and pressure of 71.12 psi (5 kgf/cm^2) for 7 min. All the fabricated WIBs were then stored at a constant 23 °C and 50% relative humidity for three weeks.

Table 3. Manufacturing Conditions of the WIBs

Density (g/cm^3)		Additives			Hot-press Conditions		
Target	End Products	Resin Content (%)	Hardener (%)	Wax Emulsion (%)	Temp. (°C)	Pressure (kgf/cm^2)	Time (s/mm)
0.10	0.11	35	3	1	150	5	21
0.15	0.15						
0.20	0.21						
0.25	0.24						

Physical, emission, and thermal properties of the WIBs

The physical properties (density, water content, thickness/length absorption expansion rate, and bending strength) of the WIBs were investigated to confirm that they satisfied the specifications of the KS F 3200 (2006) standard. The emissions characteristics with respect to the HCHO and the total volatile organic compounds (TVOCs) in the WIBs were analyzed using the desiccator method and the 20-L chamber method according to the KS M 1998 (2009) standard. A thermal conductivity analyzer (λ-Meter EP500e; ATP Messtechnik GmbH, Ettenheim, Germany) was used to evaluate the thermal conductivity of the WIBs and provide a comparison to the thermal performance of the commercial medium-density fiberboard (MDF, 0.64 g/cm^3), extruded polystyrene (XPS), and expanded polystyrene (EPS) insulations. The λ-Meter EP500e (the guarded hot plate apparatus) was operated according to ISO 8302:1991(1991). Test sample size was 200 mm (width) x 200 mm (length). In this study, the measuring temperature was 25 °C. Moreover, the temperature difference between the hot plate and the cold plate was set at 40 °C.

Combustion properties of the WIBs

To determine the combustion properties of the WIBs, each WIB sample was cut into a 100 mm × 100 mm × 20 mm specimen and stored at 23 °C and 50% relative humidity until it reached a constant weight. A cone calorimeter (Fire Testing Technology, East Grinstead, UK) with a heat flux of 50 kW/m^2 was then used to investigate the time to ignition (TTI), flaming time (FT), total heat release (THR), peak heat release rate (PHRR), total smoke release (TSR), smoke release rate (SRR), carbon monoxide yield (COY), CO_2

yield (CO_2Y), and specific extinction area (SEA) of the WIBs. The combustion properties of the WIBs were compared to the combustion properties of the conventional XPS and EPS insulations, in accordance with the KS F ISO 5660-1 (2008) standard.

RESULTS AND DISCUSSION

Physical Properties of the WIBs

The 20-mm thick WIBs that were prepared met their target densities of 0.10 g/cm^3 to 0.25 g/cm^3. After preparing the WIBs under the same manufacturing conditions, the moisture content (MC) of the WIBs increased as the density increased. The WIB sample with a density of 0.10 g/cm^3 had a MC of 2%, while the WIB sample with a density of 0.25 g/cm^3 had the highest MC of 6.7% (Fig. 1). According to the standard KS F 3200 (2006) for low-density fiberboard (LDF) used as insulation, the MC of LDF must be between 5% and 13%. Therefore, all the WIB samples in this study satisfied this standard except for the 0.10 g/cm^3 density specimen, in which there was more moisture evaporation during the hot-pressing process than there was for the higher density specimens. A WIB with low MC exhibits high water absorption, thickness swelling, and linear expansion, so the MC of wood-based panels should generally be controlled to be within 5% to 8% to minimize these negative effects (Hong *et al*. 2017).

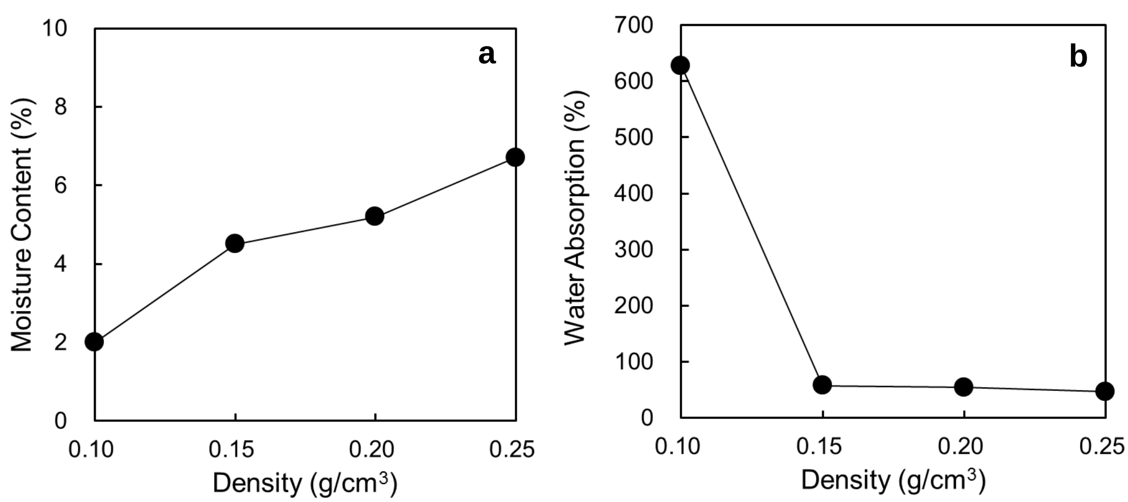

Fig. 1. The a) moisture content and b) water absorption rate of the WIBs according to their density

The water absorption results of the WIBs indicated that the 0.10 g/cm^3 density WIB sample absorbed 627% of its weight in water, while the other WIB densities (0.15 g/cm^3, 0.20 g/cm^3, and 0.25 g/cm^3) each absorbed approximately 50% of their weight in water (Fig. 1). No appreciable difference in the water absorption was found between the 0.15 g/cm^3, 0.20 g/cm^3, and 0.25 g/cm^3 density WIBs. The higher water absorption of the 0.10 g/cm^3 density WIB could result in damage from fungi and hydrolysis of the MFU resin, causing poor durability and short lifetime of the insulation. Therefore, the WIB density to be used as insulation is recommended to be greater than 0.15 g/cm^3.

The thickness swelling and linear expansion of the WIBs are shown in Fig. 2. All of the prepared WIBs exhibited a thickness swelling of less than 2.57%, which satisfied the water resistance requirements of less than 5% for LDF according to the KS F 3200 (2016) standard. For the linear expansion, all the WIBs except for the 0.10 g/cm^3 density specimen also met the KS F 3200 (2006) standard requirements for linear expansion (< 0.5%). Therefore, the WIBs with a density greater than 0.15 g/cm^3 can be considered water resistant. Figure 2 also shows the bending strength of the WIBs. The 0.10 g/cm^3 density WIB sample exhibited a bending strength of 0.06 MPa, which did not meet the KS F 3200 (2006) requirement of a bending strength greater than 1.0 MPa, though the other WIB density samples did meet the requirement.

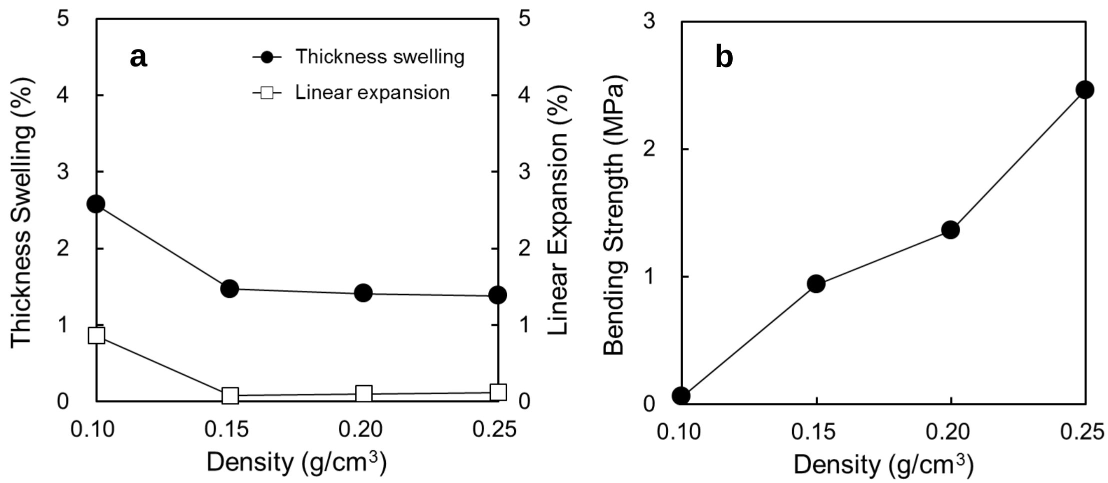

Fig. 2. The a) thickness swelling and linear expansion and b) the bending strength of the WIBs according to their density

Thermal Properties of the WIBs

When the WIBs are used as insulation, the thermal conductivity and heat resistance are important factors for preparing construction specifications. A lower thermal conductivity leads to a higher heat resistance, which affects the thermal transmittance coefficient. In the Korean construction standards for energy-saving green building or houses, the required outer wall thermal transmittance coefficient was reduced to 0.21 W/m^2·K or less in 2018. The thermal conductivity of the WIBs investigated in this study was shown in Fig. 3.

A low thermal conductivity (0.035 W/m·K) was observed in the WIB samples with densities of 0.10 g/cm^3 and 0.15 g/cm^3. The WIB samples with densities of 0.20 g/cm^3 and 0.25 g/cm^3 possessed thermal conductivities of 0.043 W/m·K and 0.046 W/m·K, respectively. Lee *et al*. (2019) reported that commercial insulation board made from wood fiber and additives exhibited a thermal conductivity of 0.037 W/m·K to 0.058 W/m·K. Therefore, the WIBs prepared in this study provided a better thermal conductivity performance than such commercial WIBs. In general, it is well known that moisture contents influence thermal conductivity of insulation. Higher moisture contents adversely affect thermal conductivity. However, density between 0.10 g/cm^3 and 0.15 g/cm^3 showed no difference on thermal conductivity. In this case, thermal conductivity was influenced not only by water contents but also by other factors.

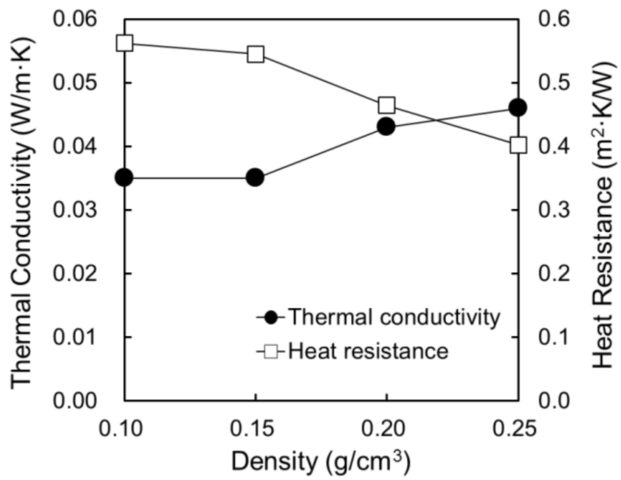

Fig. 3. The thermal conductivity and heat resistance of the WIBs according to their density

Density is a key parameter to determine the thermal conductivity of WIB. Lower density on fiberboard could provide airspace between wood fibers, and then these spaces contribute to the heat barrier. Therefore, decreasing density of WIB led to decreasing thermal conductivity, but density less than 0.15 g/m^3 did not carry further improvement of thermal conductivity. Moreover, wood fiber consisted of open cell and closed cell structure, so wood fiber itself has a thermal resistance function. Both of these mechanisms influenced the thermal conductivity of WIB. Notably, the WIB samples with densities of 0.10 g/cm^3 and 0.15 g/cm^3 exhibited thermal conductivities equal to that of XPS (0.035 W/m·K), and a lower thermal conductivity than that of EPS (0.047 W/m·K) (Fig. 4).

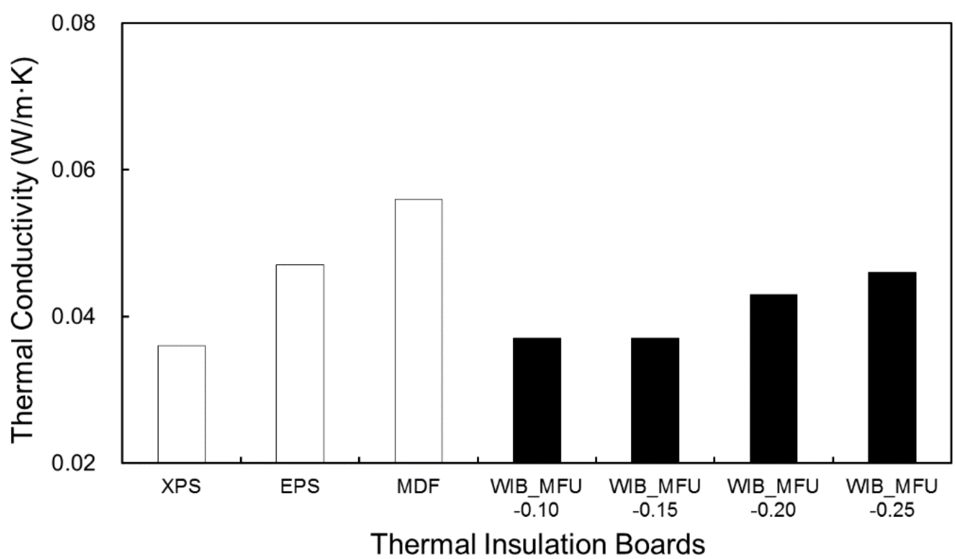

Fig. 4. Comparison of the thermal conductivities according to the thermal insulation board type

A low-density WIB allows for a large volume of air to exist inside the board, thereby achieving the smaller observed thermal conductivity. This lower thermal conductivity leads to greater heat resistance. Notably, the heat resistance of the WIBs evaluated in this study all exceeded the KS F 3200 (2006) requirement of greater than 0.361 m^2·K/W for a 20-mm-thick board. Such a high heat resistance performance enables thin wall thicknesses in architectural designs, which allows for a larger internal area of the subject house or building. Based on the thermal conductivity and heat resistance results, WIBs have the potential to replace petrochemical insulation materials currently on the market such as XPS and EPS.

Emission Properties of the WIBs

The WIBs prepared in this study contained 35% MFU resin, so the HCHO and TVOCs emission characteristics were determined as shown in Fig. 5. The HCHO emissions from the WIBs increased with increasing density because the quantity of the MFU resin in the board increased in proportion to the density. Additionally, as the density increased, the TVOCs emissions increased due to the increased quantity of the wood fibers. The highest HCHO emissions were observed for a WIB density of 0.25 g/cm^3 (0.30 mg/L), which can be classified as "Super E_0" type (< 0.30 mg/L) according to the KS F 3200 (2006) standard. All the WIB samples could be classified as Super E_0-type wood products. The quantity of the TVOC emissions from all the WIBs was less than 40.3 μg/m^{2}h, which was far below the regulation requirements of 4000 μg/m^{2}h set by the Indoor Air Quality Management Law of South Korea (No. 799, Ministry of Environment 2019).

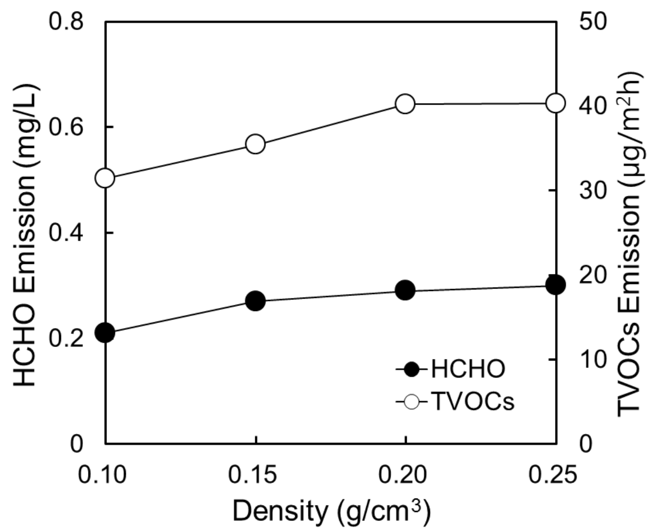

Fig. 5. The HCHO and TVOC emissions of the WIBs according to their density

Combustion Properties of the WIBs

Tables 4 and 5 summarize the combustion characteristics of the WIBs, as determined by the cone calorimeter tests. The ignition times of the WIBs became more delayed as the density increased. The ignition times were generally between those of EPS (7 s) and XPS (18 s). A lower density object will burn more quickly than a higher density object because of the larger oxygen supply volume inside the material and the larger fire contact surface (Lee *et al.* 2019). The mean heat release rate (HRR) of the WIBs decreased as the density increased. A lower mean HRR was observed for the 0.15 g/cm^3, 0.20 g/cm^3, and 0.25 g/cm^3 density WIB samples than for the XPS and the EPS. No appreciable difference in the mean effective heat of combustion (EHC) was observed between the different WIB densities. Thus, the mean HRR, peak HRR, and ignition time all increased as the WIB density increased, while the mean EHC was not influenced by the density.

Table 4. Combustion Properties of the Conventional Insulation and WIB Samples According to the Density

Specimen Code	TTI (s)	HRR_{mean} (kW/m^2)	HRR_{peak} (kW/m^2)	EHC_{mean} (MJ/kg)
WIB_MFU-0.10	2	86.32	135.2	10.01
WIB_MFU-0.15	7	72.35	122.4	9.75
WIB_MFU-0.20	9	73.21	115.9	10.88
WIB_MFU-0.25	10	71.36	101.4	11.27
XPS	18	84.86	222.0	18.07
EPS	7	83.13	157.3	16.35
HRR_{mean} is the mean heat release rate; HRR_{peak} is the peak heat release rate; EHC_{mean} is the mean effective heat of combustion; XPS is extruded polystyrene; EPS is expanded polystyrene				

According to the Building Standard Law of Korea No. 548 (2018), the peak HRR is required to be below 200 kW/m^2 and cannot be maintained for 10 or more consecutive seconds during the test period (under a heat flux 50 kW/m^2 for 5 min). Based on the HRR results, all the WIBs evaluated satisfied the requirements of Class III fire resistance. Even though the WIBs could constitute a fuel source on a fire site, they would not affect the growth of the fire due to their lower HRR. Notably, the XPS produced a peak HRR above 200 kW/m^2 for 15 s, so it did not meet any class of fire resistance.

Table 5. Cone Calorimeter Test Results of the Conventional Insulation and WIB Samples According to their Density

Specimen Code	THR (MJ/m^2)	TOC (g)	SMLR ($g/s{\cdot}m^2$)	MLR (g/s)
WIB_MFU-0.10	34.5	24.9	8.21	0.074
WIB_MFU-0.15	22.8	14.6	8.14	0.074
WIB_MFU-0.20	20.8	16.9	8.17	0.074
WIB_MFU-0.25	18.2	14.7	7.43	0.067
XPS	9.1	5.8	9.97	0.092
EPS	5.8	3.7	4.26	0.040
THR is the total heat release; TOC is the total oxygen consumed; SMLR is the specific mass loss rate; MLR is the mass loss rate; XPS is extruded polystyrene; EPS is expanded polystyrene				

The 0.10 g/cm^3 density WIB showed the highest total heat release (THR) value of 34.5 MJ/m^2, which decreased to 18.2 MJ/m^2 (0.25 g/cm^3) with the highest WIB density sample. However, all WIB densities exhibited THR values greater than 8 MJ/m^2 during the 5-min test period, so they did not satisfy the requirements of Class III fire resistance. The XPS also failed to meet the Class III fire resistance requirements, but the EPS (5.8 MJ/m^2) completely met these requirements. Therefore, to satisfy the THR regulations, WIBs should be treated with a fire retardant. The highest total oxygen consumption (TOC) of 24.9 g was detected in the 10 g/cm^3 density WIB sample. The TOC decreased to 14.7 g in the 0.25 g/cm^3 density WIB samples, while the XPS and EPS exhibited TOCs of less than 5.8 g. Due to the increased WIB density, a larger quantity of MFU resin content on the surface of the WIB might be expected. This would cause the melamine in the MFU to turn

into a carbonized layer, preventing fire from penetrating the WIB. The specific mass loss rate (SMLR) and mass loss rate (MLR) were not considerably different for the WIB samples with different densities. A higher SMLR and MLR of 9.97 g/sm^2 and 0.092 g/s, respectively, were observed for the XPS, indicating that it burned faster than the WIBs.

Smoke and Gas Production of the WIBs

Figure 6 shows the SRR values of the XPS, EPS, and the evaluated WIBs according to their densities. The XPS exhibited a remarkably higher SRR than the other specimens. The SRR of the XPS continued to increase with burning time, and only dropped after 200 s, once the flammable XPS materials had completely burned. The SRR of the EPS also increased and then remained high until 100 s, at which time all its flammable material had been combusted, leaving no residue or ash. The SRR pattern of the WIBs showed that smoke was released for 100 s to 150 s, after which no more smoke was produced. The carbonized layer formed after approximately 100 s on the 0.25 g/cm^3 density WIB sample and after approximately 150 s on the 0.10 g/cm^3 density WIB sample.

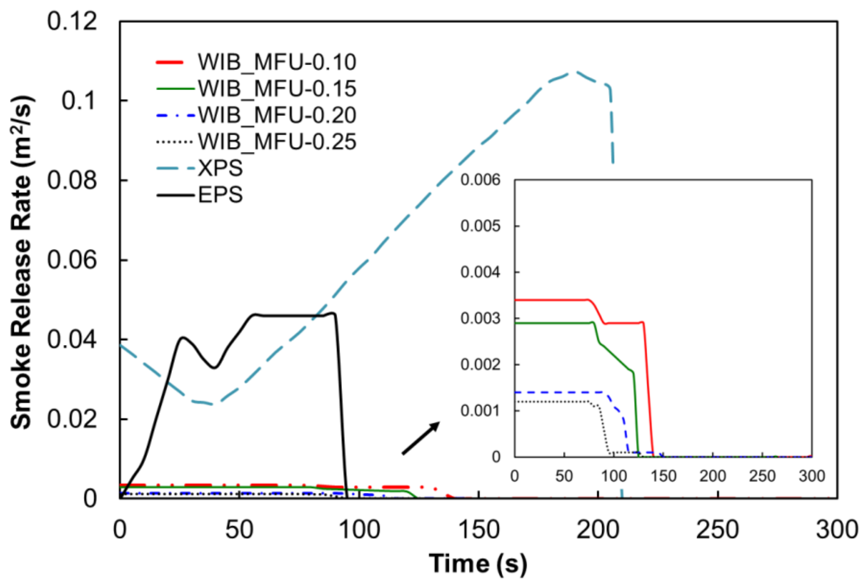

Fig. 6. The SRR values of the WIBs and conventional insulations with different densities as a function of time

Table 6 summarizes the cone calorimeter test results for the WIB and conventional insulation samples, including the TSR, the SEA, the COY, and the CO_2Y. The TSR of the WIBs decreased as the WIB density increased. Even though the XPS and EPS exhibited shorter smoke release times, their TSR was 300 to 400 times higher than that of the WIBs. The SEA also decreased as the WIB density increased. A lower SEA value indicated that the material was not on fire despite being a flammable object (Lee *et al*. 2019). This explanation also could have been valid for the TSR results. The lower TSR of the WIBs could constitute an important advantage of this insulation material, as it might help to reduce deaths due to smoke inhalation by providing adequate evacuation time (Park *et al.* 2014).

In addition to their lower total smoke release, the WIBs produced lower CO and CO_2 emissions during the cone calorimeter tests. These results can also be explained by the formation of a carbonized layer on the surface of the WIBs in the early stages of the combustion test. Under these circumstances, only the surfaces of the WIBs were burned, after which no further burning occurred. As seen in Fig. 7, for the 0.25 g/cm^3 density WIB sample, 14.2% of the thickness of the board was carbonized from the surface to the center, while 32.8% of the thickness was carbonized on the 0.10 g/cm^3 density WIB sample. Notable changes in both the weight loss and carbonized depth by flame were observed between the WIB samples with densities of 0.10 g/cm^3 and 0.15 g/cm^3. Furthermore, as the WIB density increased, the weight loss and carbonized depth by flame decreased.

Table 6. Smoke Release Parameters of Insulation and Different Densities of WIBs Determined by the Cone Calorimeter Test

Specimen Code	TSR (m^2/m^2)	SEA (m^2/kg)	COY (kg/kg)	CO_2Y (kg/kg)
WIB_MFU-0.10	4.2	43.55	0.0369	0.89
WIB_MFU-0.15	3.4	42.13	0.0115	0.68
WIB_MFU-0.20	1.5	16.56	0.0094	0.82
WIB_MFU-0.25	1.3	15.35	0.0092	0.64
XPS	518.3	882.62	0.0844	1.41
EPS	265.1	1087.90	0.0484	1.22

TSR is the total smoke release; SEA is the specific extinction area; COY is the carbon monoxide yield; CO_2Y is the carbon dioxide yield; XPS is extruded polystyrene; EPS is expanded polystyrene

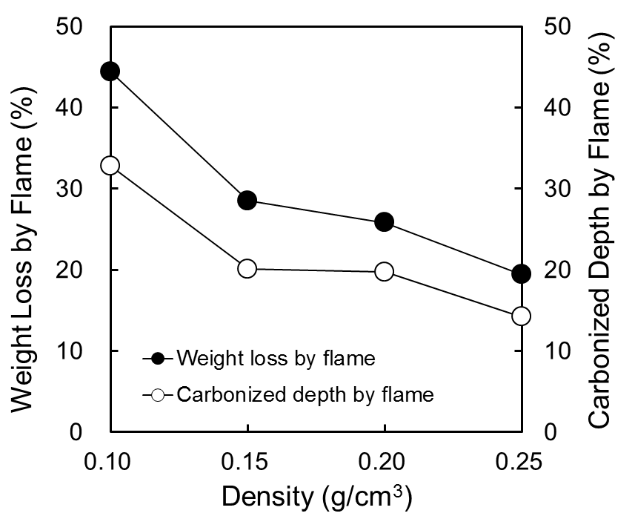

Fig. 7. Weight loss and carbonized depth by flame on the WIBs according to their density

CONCLUSIONS

1. A series of wood fiber insulation boards (WIBs) were prepared with different densities (0.10 g/cm^3, 0.15 g/cm^3, 0.20 g/cm^3, and 0.25 g/cm^3) with a 35% MFU resin content. All the prepared WIBs satisfied the KS F 3200 (2006) requirements for the moisture content, thickness swelling, and linear expansion, while only the WIBs with densities greater than 0.15 g/cm^3 met the requirements for the bending strength and the water

absorption. The mechanical performance of the WIBs improved as the density of the WIBs increased. Based on the moisture properties determined in this study, a density of 0.15 g/cm^3 is recommended for WIBs.

2. To be a suitable thermal insulation material, the thermal conductivity of a WIB should be equal to or better than conventional thermal insulation materials currently on the market. To this end, all the WIBs exhibited lower thermal conductivities than general medium density fiberboard (MDF) and expanded polystyrene (EPS). When the WIB density was less than 0.15 g/cm^3, its performance was similar to that of XPS. The thermal conductivity of the WIBs increased with their density, so their insulation performance accordingly decreased. Therefore, to meet thermal requirements, a density in the range of 0.15 g/cm^3 to 0.20 g/cm^3 is recommended for WIBs.
3. All the WIBs showed sufficiently low HCHO and TVOC emission characteristics. Based on the HCHO emissions, all the WIBs could be certified as "Super E_0" grade (< 0.3 mg/L), even though they possessed a 35% resin content. The TVOC emissions of the evaluated WIBs were all less than 40 μg/m^{2}h, which exceeded the requirements of the pertinent regulation (< 4000 μg/m^{2}h), and thus the WIBs could be certified as an eco-friendly product.
4. As the WIB density increased, the ignition time was delayed from 2 s (for a density of 0.1 g/cm^3) to 10 s (for a density of 0.25 g/cm^3) and the both mean heat release rate (HRR) and peak HRR decreased. When the WIB density was greater than 0.15 g/cm^3, the mean HRR and peak HRR were smaller than those of the XPS and EPS. However, the total heat release (THR) and the total oxygen consumed (TOC) of the WIBs were higher than those of the XPS and EPS because the WIBs consisted of wood fibers, which are combustible.
5. The smoke emissions of the subject WIBs were 300 to 400 times lower than those of conventional XPS and EPS materials. The smoke from the WIBs was continuously produced for approximately 100 s to 140 s with a low SRR, while the smoke from the EPS was eliminated after 90 s and the smoke from the XPS was only eliminated after 210 s with a high SRR. In general, the main cause of fire-related deaths is known to be smoke and gas inhalation. Therefore, the low smoke emission characteristics of the WIBs can help to reduce such fire-related deaths by providing more evacuation time for building occupants in the event of a fire.
6. The cone calorimeter test results indicated that the WIBs prevented the continued development of fire by forming a carbonized layer on their surfaces when they were exposed to flames. The weight reduction rate and carbonization depth of the specimens after the tests indicated that the carbonization depth was 15% and the weight reduction rate was less than 20% at the highest evaluated WIB density of 0.25 g/cm^3.
7. Based on comprehensive consideration of all the WIB experimental results, the optimum WIB density when used as insulation is recommended to be 0.15 g/cm^3.

ACKNOWLEDGMENTS

This study was supported by a Research Project (FP0600-2017-01) through the National Institute of Forest Science (NIFoS), Korea.

REFERENCES CITED

Aditya, L., Mahlia, T. M. I., Rismanchi, B., Ng, H. M., Hasan, M. H., Metselaar, H. S. C., Muraza, O., and Aditiya, H. B. (2017). "A review on insulation materials for energy conservation in buildings," *Renewable and Sustainable Energy Reviews* 73, 1352-1365. DOI: 10.1016/j.rser.2017.02.034

Al-Homoud, M. S. (2005). "Performance characteristics and practical applications of common building thermal insulation materials," *Building and Environment* 40(3), 353-366. DOI: 10.1016/j.buildenv.2004.05.013

DOE/CE-0180 (2002). "Insulation fact sheet with addendum on moisture control," US Department of Energy, Washington D.C., USA.

Hasan, A. (1999). "Optimizing insulation thickness for buildings using life cycle cost," *Applied Energy* 63(2), 115-124. DOI: 10.1016/S0306-2619(99)00023-9

Hong, M.-K., Lubis, M. A. R., and Park, B.-D. (2017). "Effect of panel density and resin content on properties of medium density fiberboard," *Journal of the Korean Wood Science and Technology* 45(4), 444-455. DOI: 10.5658/WOOD.2017.45.4.444

ISO 8302:1991 (1991). "Thermal insulation—Determination of steady-state thermal resistance and related properties—Guarded hot plate apparatus," International Organization for Standardization, Geneva, Switzerland.

Jang, J.-H., Lee, M., Kang, E.-C., and Lee, S.-M. (2017a). "Characteristics of low density fiberboards for thermal insulation material with different adhesives (I) – Thermal insulation performance and physical properties," *Journal of the Korean Wood Science and Technology* 45(3), 360-367. DOI: 10.5658/WOOD.2017.45.3.360

Jang, J.-H., Lee, M., Kang, E.-C., and Lee, S.-M. (2017b). "Characteristics of low density fiberboards for thermal insulation material with different adhesives (II) – Formaldehyde, total volatile organic compounds emission properties and combustion shapes," *Journal of the Korean Wood Science and Technology* 45(5), 580-587. DOI: 10.5658/WOOD.2017.45.5.580

Jelle, B. P. (2011). "Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities," *Energy and Buildings* 43(10), 2549-2563. DOI: 10.1016/j.enbuild.2011.05.015

Kaklauskas, A., Rute, J., Zavadskas, E. K., Daniūnas, A., Pruskus, V., Bivainis, J., Gudauskas, R., and Plakys, V. (2012). "Passive house model for quantitative and qualitative analyses and its intelligent system," *Energy and Buildings* 50, 7-18. DOI: 10.1016/j.enbuild.2012.03.008

Kang, Y., Chang, S. J., and Kim, S. (2016). "Analysis of hygrothermal performance of wood frame walls according to position of insulation and climate conditions," *Journal of the Korean Wood Science and Technology* 44(2), 264-273. DOI: 10.5658/WOOD.2016.44.2.264

Kaynakli, O. (2012). "A review of the economical and optimum thermal insulation thickness for building applications," *Renewable and Sustainable Energy Reviews* 16(1), 415-425. DOI: 10.1016/j.rser.2011.08.006

Kim, S., Yu, S., Seo, J., and Kim, S. (2013). "Thermal performance of wooden building envelope by thermal conductivity of structural members," *Journal of the Korean Wood Science and Technology* 41(6), 515-527. DOI: 10.5658/WOOD.2013.41.6.515

KS F 3200 (2006). "Fiberboards," Korean Standards Association, Seoul, Republic of Korea.

KS F ISO 5660-1 (2008). "Reaction to fire test - Heat release, smoke production and mass loss rate - Part 1: Heat release rate (cone calorimeter method)," Korean Standards Association, Seoul, Republic of Korea.

KS M 1998 (2009). "Determination of the emission rate of formaldehyde and volatile organic compounds in building interior products," Korean Standards Association, Seoul, Republic of Korea.

KS M 3705 (2015). "General testing methods for adhesives," Korean Standards Association, Seoul, Republic of Korea.

Kwon, H.-S., Lee, S.-Y., Kim, J.-B., and Yoon, M.-O. (2018). "A study on the combustion characteristics of synthetic insulation for building," *Fire Science and Engineering* 32(2), 30-37. DOI: 10.7731/KIFSE.2018.32.2.030

Kwon, Y.-C. (2012). "High-efficiency insulations for passive houses," in: *Proceedings of the SAREK (The Society of Air-Conditioning and Refrigerating Engineers of Korea) 2012 Winter Annual Conference*, Jeju, Korea, pp. 326-333.

Lee, S. M., Park, S. B., and Park, J. Y. (2012). "Characteristics of urea resin modified by melamine or phenol," in: *2012 Proceedings of the Korean Society of Wood Science and Technology Annual Meeting*, Daegu, Republic of Korea, pp. 220-221.

Lee, S. M., Kang, E. C., Lee, M., and Park, S. B. (2016). *Phenolic Resin Adhesives for Wood* (Report No. 691), National Institute of Forest Science, Seoul, Republic of Korea.

Lee, H., Chang, S. J., Kang, Y., Lee, D. R., and Kim, S. (2018). "Analysis of heating energy reduction of wooden-based Korean Hanok using passive houses planning package (PHPP)," *BioResources* 13(2), 4145-4158. DOI: 10.15376/biores.13.2.4145-4158

Lee, M., Lee, S. M., Kang, E. C., and Son, D. W. (2019). "Combustibility and characteristics of wood-fiber insulation boards prepared with four different adhesives," *BioResources* 14(3), 6316-6330. DOI: 10.15376/biores.14.3.6316-6330

Ministry of Environment (ME) Law No. 799 (2019). "Indoor Air Quality Management Law for restrictions on the use of pollutant emission building materials," ME Law, Sejong-Si, South Korea.

Ministry of Land, Infrastructure and Transport (MLIT) Law No. 548 (2018). "The building standard law for regulations on standards for evacuation and fire protection of buildings," MLIT, Sejong-Si, South Korea.

Park, S.-B., Lee, M., Son, D.-W., Lee, S.-M., and Kim, J.-I. (2014). "Fire performance of carbonized medium density fiberboard manufactured at different temperatures," *Journal of Wood Science* 60(1), 74-79. DOI: 10.1007/s10086-013-1379-6

Pizzi, A. (2014). "Synthetic adhesives for wood panels," *Reviews of Adhesion and Adhesives* 1, 85-126. DOI: 10.7569/RAA.2013.097317

The European Parliament and the Council of the European Union (EPEU) Directive 2010/31/EU (2010). "Directive 2010/31/EU on the energy performance of buildings," Official Journal of the European Union, Aberdeen, UK.

Reilly, A., and Kinnane, O. (2017). "The impact of thermal mass on building energy consumption," *Applied Energy* 198, 108-121. DOI: 10.1016/j.apenergy.2017.04.024

Schiavoni, S., D'Alessandro, F., Bianchi, F., and Asdrubali, F. (2016). "Insulation materials for the building sector: A review and comparative analysis," *Renewable and Sustainable Energy Reviews* 62, 988-1011. DOI: 10.1016/j.rser.2016.05.045

Song, S., Park, S., Koo, B., Lim, J., and Ryu, S. (2013). "Performance evaluation of EIFS using vacuum insulation panels for passive and zero-energy apartment buildings," *Journal of the Architectural Institute of Korea* 29(9), 219-228. DOI: 10.5659/JAIK_PD.2013.29.9.219

Yu, S., Kim, S., Seo, J., and Kim, S. (2013). "Analysis of energy efficiency of light-weight wood frame house and wooden passive house using PHPP," *Journal of the Architectural Institute of Korea* 29(8), 199-207.

Article submitted: April 28, 2019; Peer review completed: June 16, 2019; Revised version received: June 20, 2019; Accepted: June 21, 2019; Published: June 26, 2019.
DOI: 10.15376/biores.14.3.6529-6543