Combustibility and Characteristics of Wood-Fiber Insulation Boards Prepared with Four Different Adhesives

Min Lee,* Sang-Min Lee, Eun-Chang Kang, and Dong-Won Son

Wood-fiber insulation boards can be utilized as a core construction material. They provide a comfortable and safe residential space and reduce energy consumption because of the ecofriendly nature and high heat insulation. In this study, wood-fiber insulation boards were prepared with different types of adhesive (melamine-urea-formaldehyde (MUF), phenol-formaldehyde (PF), emulsifiable 4,4’ methylene diisocyanate (eMDI), and latex resins), and the physical and heat insulation properties, toxic chemical emissions, and combustion characteristics were analyzed. The different adhesive types had no major effects on the insulation. With regard to the toxic emissions, all wood-fiber insulation boards showed the best rating possible except for the PF resin. In the cone-calorimeter test, the wood-fiber insulation board prepared with MUF showed a lower total heat release, mean heat release rate, smoke release, and CO and CO_2 yields than the other samples because of the early formation of the carbonized layer. Based on the comprehensive evaluation, the MUF adhesive is the best choice for wood-fiber insulation boards.

Keywords: Wood fiber; Insulation board; Thermal conductivity; Cone calorimeter; Combustion

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INTRODUCTION

Because of the recent demand for ecofriendly and low-energy buildings such as passive houses, the development of new high-performance insulation has been a priority for the building industry (Mihai *et al.* 2017). Insulation should have an air space, where no convection current occurs, and it fundamentally requires the properties of heat insulation, sound absorption, and fire resistance. Most insulation materials used in construction sites are petrochemical synthetic products such as Styrofoam, phenol foam, and urethane foam. These products have a negative environmental load and risk toxic chemical emissions when burned. Moreover, massive fires in high-rise buildings are probably due to insulation, so securing fire resistance is a top priority. Many studies have focused on replacing previous synthetic products with natural materials for insulation (Asdrubali *et al.* 2015). Wood is an ecofriendly and natural renewable resource. It fixes carbon dioxide (CO_2) and provides good humidity control, sound absorption, and heat insulation properties (Lewis 1968; Sikkema and Nabuurs 1995).

Wood insulation products are mostly manufactured from wood fiber with various additives. Wood fiber is generally applied for insulation in two ways: as a filling or as an insert. Filling-type wood fiber is blown with some additives between walls, and the insert-type wood fiber is made into boards with adhesive and then put into walls. In

America, filling-type wood insulation is more common, but European countries used the insert type more often. Panel-type wood-fiber insulation is mostly manufactured in European countries such as Germany, Switzerland, Poland, and France, to a lesser extent in Austria, and the product is also distributed around the world. Wood-fiber insulation boards are very popular in Europe and have already been applied to many buildings. This type of wood-fiber insulation has a density of around 0.20 g/cm^3, so it is classified as low-density fiberboard (Euring *et al.* 2015). The density and thermal conductivity have a proportional relationship, and a lower fiberboard density has positive effects on the workability and economic feasibility (Kawasaki *et al.* 1998). Current wood-fiber insulation boards (WIBs) have a thermal conductivity of 0.037 to 0.058 W/m-K and thickness of 18 to 200 mm. These WIBs are usually made from soft- and hardwood fiber with adhesive (pMDI, polyvinyl acetate, polyolefin, or polyurethane), ammonium sulfate, and paraffin wax (Gutex 2017; Pavatex 2017; Siempelkamp 2017; Steico 2017). Kirsch *et al*. (2018) applied polymeric methylene diphenyl diisocyanate (pMDI), urea-formaldehyde (UF) resin, and an enzymatic binder as bonding agents to fabricate WIB. In Europe, WIB are produced exclusively by WIB manufacturers, including the Gutex, Steico, and Pavatex companies. WIBs are applied mainly for insulation purposes in roofs, walls (inside/outside) and floor construction, *etc*. and less together with wood-based panels.

For the production of wood-based panel products including low-density fiberboard, various binders and adhesives are essential. They affect the physical properties of the final product and the pollution and fire resistance performance, such as the indoor air quality. Although amino-based adhesives are mainly used in wood-based panel products, phenol-based and isocyanate-based adhesives have been used recently to reduce formaldehyde emissions and increase water resistance (Pizzi 2015). A few studies have investigated the properties of low-density WIBs with different types of adhesive. Jang *et al*. (2017a,b) reported the thermal conductivity and the formaldehyde and total volatile organic compounds emissions of low-density WIBs.

For low-density WIBs to be used for thermal insulation in an actual building site, the fire resistance, heat insulation, and toxic emissions need to be evaluated. In addition, WIB products are not the main objective of wood-based panel product manufacturers; rather, they want to exploit existing equipment and adhesives to produce new products and open up the market for ecofriendly architecture based on wood. Therefore, this study focused on comparing the fire resistance of WIBs made with different types of adhesives using the cone calorimeter method.

EXPERIMENTAL

Materials

Wood fiber (*Pinus radiata*) with a water content of about 5% was received from Donghwa Enterprise (Incheon Plant, Incheon, Korea) and used as the raw material of the WIBs. Amino-based (MUF), phenol-based (PF), isocyanate-based, and latex-based resins were selected. The MUF and PF resins were prepared directly in the laboratory according to known methods (Lee *et al.* 2012, 2016; Pizzi 2014). More details are given in Table 1. Emulsifiable methylene diphenyl diisocyanate (eMDI, Huntsman International LCC, Houston, TX, USA) and latex resins (Myungkwang Chemical Ind. Co., Ltd., Busan, Korea) were purchased.

Methods

Preparation of the insulation board

The target insulation board properties were a width and length of 350 mm, thickness of 20 mm, and density of 0.15 g/cm^3. All resin adhesives were fixed at 35% of the total weight of the used wood fiber; the amount of the curing agent was adjusted according to the characteristics of each resin adhesive. Before spraying, eMDI was mixed with water in a ratio of 1:1. During the manufacturing process, the wood fiber was placed in a cylindrical rotary applicator, mixed with an adhesive from a spray nozzle, and mixed in a 35 cm^3 mold to form a mat. After the mat molding, a hot press was applied at a temperature of 150 °C and pressure of 5 kgf/cm^2 for 21 s/mm. A small amount of a release agent was used to facilitate separation of the WIB from the caul after the hot pressing. Table 2 presents the characteristics of each fabricated insulation board. All specimens used for analysis were stored at a constant 23 °C and 50% RH for 2 weeks or more.

Table 1. General Information of Resins

Codes	Resins	pH	Viscosity (mPa-s)	Solid content (%)
MUF	Melamine-urea-formaldehyde	8	106	61
PF	Phenol-formaldehyde	12	240	53
eMDI	Emulsifiable methylene diphenyl diisocyanate	10	275	100
Latex	Latex	10–11	80	53

Table 2. Manufacturing Conditions of WIBs

Codes	Additives			Hot-press conditions		
	Resin content (%)	Hardener (%)	Wax emulsion (%)	Temp. (°C)	Pressure (kgf/cm^2)	Time (s/mm)
MUF	35	3	1	150	5	21
PF		3				
eMDI		-				
Latex		5				

Physical, emission, and thermal properties of the wood-fiber insulation board

The thermal conductivity was measured with a thermal conductivity analyzer (λ-Meter EP500e, ATP Messtechnik GmbH, Ettenheim, Germany) to evaluate the insulation performance of the WIBs. In order to investigate the physical properties, the density, water content, absorption thickness/length expansion rate, and bending strength of WIBs as listed in the specifications of the Korean Standard (KS F 3200 2016) were measured. All specimens used in the performance tests were stored for 2 weeks under constant temperature and humidity conditions after production. The emission characteristics of formaldehyde (HCHO) and total volatile organic compounds (TVOCs) were analyzed according to the Korea Standard test methods (KS M 1998:2009, 2009). The Korea

Standard test methods contained desiccator method for HCHO emission and 20 L chamber method for TVOCs emission.

Meckel burner test (45° angle method)

The Meckel test method was performed three times on each specimen to confirm the flame retardancy. The flame length of the burner was adjusted to 65 mm with liquefied petroleum gas (LPG) fuel. The WIBs were cut into dimensions of 30 cm × 20 cm, and the longer side of each sample was placed at an angle of 45°. The flame was spotted on the sample for 2 min. The residual burning times with and without the flame were measured. The carbonized area and length of the tested samples were calculated through image analysis.

Perpendicular burning test

A perpendicular burning test was carried out to investigate the burning behavior with direct flame exposure. Figure 1 shows the flame-induced combustion process and the carbonized depth and weight reduction rate in the cross-section. The test samples were cut into dimensions of 50 mm × 50 mm × 20 mm and then dried for 24 h in a constant-temperature dryer with a temperature of 40 ± 2 °C. They were then placed in a desiccator containing silica gel for 2 h to remove moisture. The specimens were fixed in a specimen holder in the test equipment so that they would not move. The flame length of the burner was set to 60 mm, and the end of the flame was brought into contact with the bottom of the specimen. The distance between the flame launcher of the torch and the specimen was fixed to 6 cm, and the angle was 90°. The torch was used to heat the specimen for 2 min at a maximum temperature of about 1350 °C. Immediately after the flame exposure, the surface temperature of the test specimen was measured with an infrared thermometer (SK-8900, Sato Keiryoki MFG, Co. Ltd., Tokyo, Japan). The burning shape was evaluated from photographs of the test pieces taken before and after the flame exposure, the carbonized depth inside the cross-section, and the rate of weight reduction.

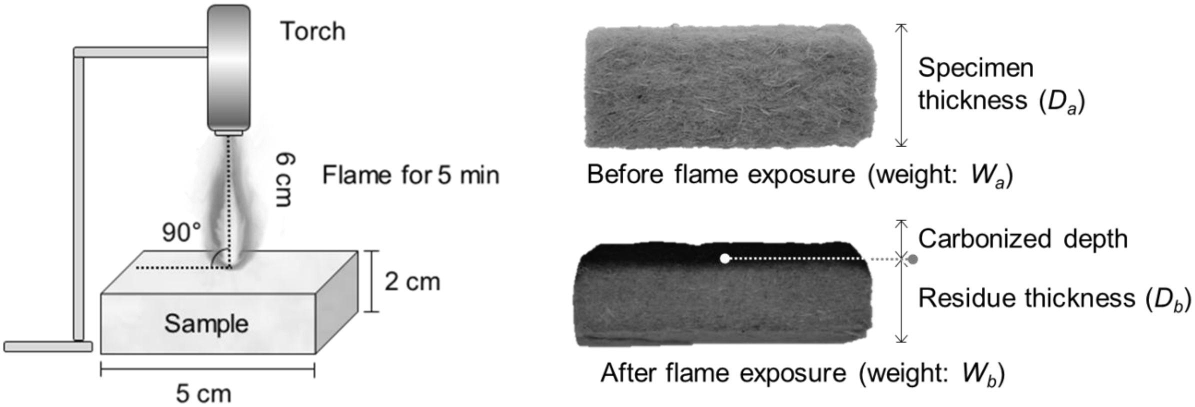

Fig. 1. Diagram of the flame test and example test specimen

The carbonized depth after flame exposure is given by,

$$Carbonized\ depth\ (\%) = \frac{(D_a - D_b)}{D_a} \times 100 \tag{1}$$

where D_a is the sample thickness before the test and D_b is the residue thickness after the test. The weight loss after flame exposure is given by,

$$Weight\ loss\ (\%) = \frac{(W_a - W_b)}{W_a} \times 100 \tag{2}$$

where W_a is the sample weight before the test and W_b is the sample weight after the test.

Cone calorimeter analysis

Test specimens with dimensions of 100 mm × 100 mm × 20 mm were stored at 23 °C and 50% RH until they reached a constant weight. Then, based on the combustion performance test method of the Korean Standard (KS F ISO 5660-1, 2008), the cone calorimeter (Fire Testing Technology Ltd, East Grinstead, UK) method was used with a heat flux of 50 kW/m^2 to determine 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), and specific extinction area (SEA).

RESULTS AND DISCUSSION

Preparation Conditions of the Wood-Fiber Insulation Board

In general, the amount of resin used for wood-based panels manufacture is less than 15%. Moreover, resin contents could be reduced to 4 to 5% when pMDI resin is used. In the preparation of WIBs, however, a relatively high amount of resin (35%) is used for making a hard form of WIB and securing physical property. Also, fire resistance properties might be affected by a high content of resin. The hot-press time was set to 21 sec/mm (7 min) to secure sufficient curing time of adhesive due to the high content ratio and thickness, while temperature of the hot-press was set to 150 °C to avoid losing too much moisture of WIBs after finishing hot-press. Extremely lower moisture contents of WIB soon after hot-press can result in bending and can adversely affect water absorption and thickness swelling.

Physical and Thermal Properties of the Wood-Fiber Insulation Board

The combustion characteristics of building materials are influenced not only by the raw materials but also by physical properties such as the thickness and density of the final product. All WIBs prepared in this study did not deviate significantly from the target thickness and density of 20 mm and 0.15 g/cm^3, respectively. The water content of each sample kept for 2 weeks under constant temperature and humidity conditions was 3% or less. The WIBs satisfied the Korean Standard for thickness swelling (< 20%). The WIBs prepared with MUF, PF eMDI, and latex resins showed a thickness swelling of less than 5% and length expansion rate of less than 2%. The physical properties of the WIBs ensured good dimensional stability under wet conditions. The flexural strength of the WIBs was less than 0.1 MPa with the MUF and PF resins and 0.5 MPa with eMDI. With the latex resin, the flexural strength could not be measured because of the softness and high flexibility. The thickness swelling and flexural strength properties of the WIB were similar to the results of previous studies (Jang *et al.* 2017a).

The thermal conductivities of WIBs prepared with MDF, PF, eMDI, and latex resins were around 0.035 to 0.037 W/mK, while a medium-density fiberboard (MDF, thickness: 20 mm, density: 0.61 g/cm^3) showed a thermal conductivity of above 0.091

W/mK. All of the WIBs showed three times higher thermal property than MDF. Moreover, the WIBs showed a thermal conductivity equivalent to that of extruded expanded polystyrene (XPS, density: 0.03 g/cm^3), which is the most typical synthetic material-based insulation actually used in current buildings. Sonderegger and Niemz (2012) analyzed the thermal conductivity of fiberboards made from adhesives such as polyolefins, polyurethanes, and latexes and found that the density ranged from 0.036 to 0.039 W/mK.

The thermal resistance, which is obtained by dividing the thermal conductivity by the thickness of the material, is an important index for evaluating the heat insulation performance. According to the Korean Standard, the heat resistance of WIBs with a thickness of 20 mm should be 0.361 m^{2}K/W or more. As presented in Table 3, the WIBs in this study showed high thermal resistances of 0.535 to 0.551 m^{2}K/W, which exceed the Korean Standard.

The HCHO emissions of the WIBs were in the order of PF (0.48 mg/L), MUF (0.21 mg/L), latex (0.12 mg/L), and eMDI (0.10 mg/L). The higher HCHO emissions from PF may be because of uncured PF resin due to the low curing temperature (150 °C) and short time for the press. Among the WIBs prepared in this study, those with the PF resin adhesive belonged to grade E_0 (<0.5 mg/L), while the others where in grade Super E_0 (<0.3 mg/L). Super E_0 grade is equal to Japanese emission class F****. These two HCHO emission grades correlated 0.03 ppm boards by 1 m^3 chamber method. In Korean regulation for indoor materials, wood-based panel should not emit HCHO more than 1.5 mg/L (E_1 grade). The TVOC emissions from the WIBs were in the order of latex (211 µg/m^{2}h), PF (83 µg/m^{2}h), MUF (31 µg/m^{2}h), and eMDI (15 µg/m^{2}h). All WIBs satisfied TVOC emission regulation (4000 µg/m^{2}h) according to Indoor Air Quality Act of South Korea (No. 799, Ministry of Environment). The WIB prepared with eMDI resin released the least HCHO and TVOC emissions.

Table 3. Thermal, Emission, and Physical Properties of WIBs

WIBs	Thermal Properties		Emission Properties		Physical Properties			
	Thermal conductivity (W/mK)	Thermal resistance (m^{2}K/W)	HCHO (mg/L)	TVOC (µg/m^{2}h)	Density (g/cm^3)	Moisture content (%)	Thickness swelling (%)	Bending strength (MPa)
MUF	0.035	0.551	0.21	31	0.15	2.0	2.21	0.10
PF	0.036	0.535	0.48	83	0.14	2.8	5.25	0.08
eMDI	0.035	0.537	0.10	15	0.15	2.7	1.89	0.49
Latex	0.037	0.538	0.13	211	0.15	1.8	4.21	-

Burning Features of the Wood-Fiber Insulation Board

The WIBs used in this study had a porous structure because of a low density of about 0.15 g/cm^3, which increased the heat and oxygen transfer paths. Therefore, the Meckel burner test (45°) and perpendicular burning test (90°) were performed to investigate the burning features of the WIBs. According to the Meckel burner test results, all WIBs satisfied the Korean Standard for the carbonized area (< 30 cm^2) and carbonization length (< 20 cm) except for the burning time after flame and glowing time after flame.

Figure 2 and Table 4 present the changes in the shape of the WIBs after the flame test (90°), carbonized depth, and weight loss. Almost all of the WIBs prepared with PF, eMDI, and latex resins were burned and turned into ash with 5 min of flame exposure. With the MUF resin, only the surface of the test specimen was carbonized, and the flame did not penetrate deep inside. When the carbonized depth was measured from the cross-section of the test specimen after the flame exposure test, only 19.8% of the total thickness of the WIB with the MUF resin was carbonized, while the WIBs with PF, eMDI, and latex resins were almost destroyed by the flames. It was expected that PF resin, unlike MUF resin, also could be formed a carbonized layer, but it did not work as fire retardant. In the case of MUF, a large amount of adhesive was applied and cover to the wood fiber and melamine of the adhesive was initially carbonized to form a char, thereby forming a carbonized layer on the surface, which would make it difficult for the flame to penetrate into the inside. Therefore, 35% of MUF resin contents could provide fire resistance ability to WIB.

Table 4. Carbonized Depth and Weight Loss of Low-Density Fiberboards Prepared with Different Adhesives by the Flame Test

Adhesives	MUF	PF	eMDI	Latex
Carbonized depth (%)	19.8	100	100	100
Weight loss (%)	39.7	95.3	93.1	96.3

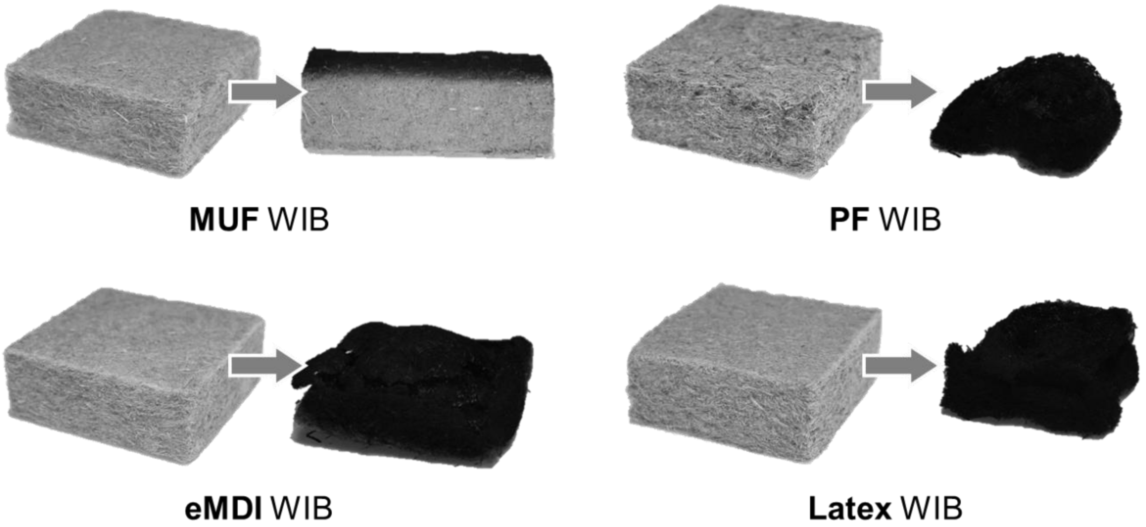

Fig. 2. Specimen shapes of WIBs with different adhesives before and after the flame test (90 °C)

Combustion Characteristics of the Wood-Fiber Insulation Board

Tables 5 and 6 summarize the combustion characteristics of the WIBs from the cone-calorimeter analysis. The ignition time is when the combustion started, and the combustion time is when the maximum heat release rate was reached. The total heat release (THR) is the total amount of heat generated from a specimen during combustion; this is the most important index for evaluating the flammability rating of a building material. The maximum heat release rate (PHRR) is the instantaneous calorific value

(Son and Kang 2015). Therefore, the above factors are very important to determining the flame retardancy of a heat insulating material.

Table 5 summarizes the ignition times of WIBs manufactured with four different adhesives. Ignition was observed for all WIBs at 1 s. Thus, the ignition time was not noticeably affected by the adhesive. These ignition times were shorter than the average ignition time of wood and wood-based panels (9 to 50 s), including particle board (PB), high-density fiberboard (HDF), plywood, and laminated flooring (Lee *et al.* 2011). In addition, fire-retardant treated wood-based panels have shown an ignition time of around 65 to 85 s (Seo *et al.* 2015). For wood and wood-based panels, when heat is applied to the object, thermal decomposition progresses step by step as the temperature increases due to the applied heat. At the beginning of pyrolysis, the dehydration reaction and release of volatile gas start, and tar forms below 200 °C. Above 225 °C, the three main components (cellulose, hemicellulose, and lignin) of the wood begin to degrade, and the ignition proceeds with the ignition source. If pyrolysis occurs rapidly at 280 to 500 °C, the physical structure of the wood quickly turns into combustible gases such as methane. This is also the temperature range at which the carbonized layer starts to form. Above 500 °C, combustion progresses to an explosion, and CO, CO_2, and H_2O are released because of oxidation of the material (Harada 2001; Son and Kang 2015). Although the WIBs were made with 35% MUF and PF resins, which are known flame retardants, they did not affect the initial ignition. During the combustion of the WIBs, the initial dehydration reaction and release of volatile gases may have been lower than those of wood and wood-based panels, and heat and air (O_2 supply) may have found it easier to penetrate and migrate inside the WIBs. This may be why the ignition time was faster than those for other wood products.

The flameout time was between 270 and 318 s for all WIBs, which was less than that of polystyrene-based nanocomposites (471 to 611 s; Ahmed *et al.* 2018). The WIBs with the MUF and PF resins performed better than those with the eMDI and latex resins. The eMDF and latex resins contained polyol and isocyanate, which may have acted as a fuel source for the continuous burning of the flame. With the MUF and PF resins, melamine and phenol blocked oxygen from contacting the wood fiber by forming a carbonized layer.

All WIBs showed a mean heat release rate (HRR_{mean}) of 31.29 to 55.97 kW/m^2. These values are generally lower than those of wood products. Sweet (1993) reported that wood species had HRR_{mean} values of 73 to 131 kW/m^2. A lower HRR_{mean} was measured for Douglas fir (*Pseudotsuga menziesii*, density: 0.53 g/cm^3) and yellow poplar (*Liriodendron tulipifera*, density: 0.51 g/cm^3), while a higher HRR_{mean} value was observed for red oak (*Quercus rubra*, density: 0.77 g/cm^3). HRR_{mean} may be related to the density of the woody material, so a lower density may indicate a lower HRR_{mean}. However, the density is not always correlated with HRR_{mean}. The WIBs showed a lower PHRR (134.59 to 302.11 kW/m^2) than wood products (250 to 300 kW/m^2, Lee *et al.* 2011; Son and Kang 2014). According to the building standards of Korea and Japan, the PHRR should not exceed 200 kW/m^2 for 10 s consecutively during the test period. Therefore, the WIBs prepared with the MUF, PF, and eMDI resins satisfied regulation, but those prepared with the latex resin did not.

Table 5. Combustion Properties of WIBs with Different Adhesives

Adhesive type	Time to ignition (s)	Time to flameout (s)	HRR_{mean} (kW/m^2)	HRR_{peak} (kW/m^2)
MUF	1	270	31.29	134.59
PF	1	273	50.59	161.77
eMDI	1	295	55.97	184.63
Latex	1	318	43.87	302.11

HRR_{mean}, mean heat release rate; HRR_{peak}, peak heat release rate

The THR of the WIBs was 37.8 to 80.5 MJ/m^2. The MUF resin showed a lower value, while the latex resin had the highest value. None of the WIBs satisfied the flame retardant grade III in the Korean Standard (KS F 3200 2016) (*i.e.*, < 8 MJ/m^2 for 5 min). Therefore, the fire resistance of WIBs should be improved by treatment with a retardant reagent for future applications. In general, wood and wood-based materials have shown THR values of 49.8 to 180.9 MJ/m^2 (Son and Kang 2014; Seo *et al.* 2016). The THR of fiberboard with a density of about 0.25 g/cm^3 is about 33 MJ/m^2, which is around the midrange of the values for petroleum-based synthetic material insulation (Östman and Tsantaridis 1995). For petroleum-based synthetic materials, for which 50 kW was applied for 5 min, the extruded expanded polystyrene had a THR of 26 to 63 MJ/m^2; rigid polyurethane foam had a THR of 19 to 44 MJ/m^2; and polyethylene foam had a THR of 6 to 23 MJ/m^2 (Park *et al.* 2001). Although the WIBs did not meet the Korean Standard, their low THR is meaningful because this indicates that they may not be a fire growth source compared to other materials. This is important because woody material can be a source of energy and chemicals and may contribute to fire growth (Grexa and Lubke 2001).

The WIB prepared with the MUF resin had a lower specific mass loss rate (MLR), mean effective heat of combustion (EHC), and total oxygen consumption (TOC) than the other resins. During the cone-calorimeter test, the wood fiber of the WIB cured with MUF resin was burned, which turned into a carbonized layer on the surface (Fig. 2). The quick formation of the carbonized layer meant that the flame and oxygen did not penetrate the middle of the WIB, which reduced the MLR, EHC, and TOC. Consequently, the WIB with MUF had a lower THR than the other samples. While the MUF and PF resins both were expected to provide similar reactions and results, the latter did not work, while the former did. The unreacted PF resin may have remained in the WIB because of the lower curing temperature (150 °C), so it may have turned into a gaseous material rather than form a carbonized layer.

Table 6. Combustion Properties of WIBs with Different Adhesives

Adhesive type	SMLR (g/s·m^2)	EHC_{mean} (MJ/kg)	THR (MJ/m^2)	TOC (g)
MUF	2.88	14.76	37.8	24.9
PF	3.96	23.09	53.6	39.4
eMDI	3.19	21.66	52.4	37.4
Latex	3.96	30.39	80.5	50.0

SMLR, specific mass loss rate; EHC_{mean}, mean effective heat of combustion; THR, total heat release; TOC, total oxygen consumption

Figure 3 shows that the curves of the heat release rate changed over time with WIB combustion. The PHRR of all WIBs was observed in the very first burning stage (20 s). Secondary PHRR values were detected between 180 and 300 s. These combustion patterns are different from those of wood and wood-based materials. In general, wood combustion initiates with a lower HRR. Then, the PHRR occurs around 400 s or later. In contrast, the WIBs generated the most heat energy in the first 30 s and then had a second peak at 180 to 300 s. After the two peaks, the WIBs had a low HRR (< 40 kW/m^2). Therefore, a lower PHRR with a short time interval could be an advantage in the case of an actual fire.

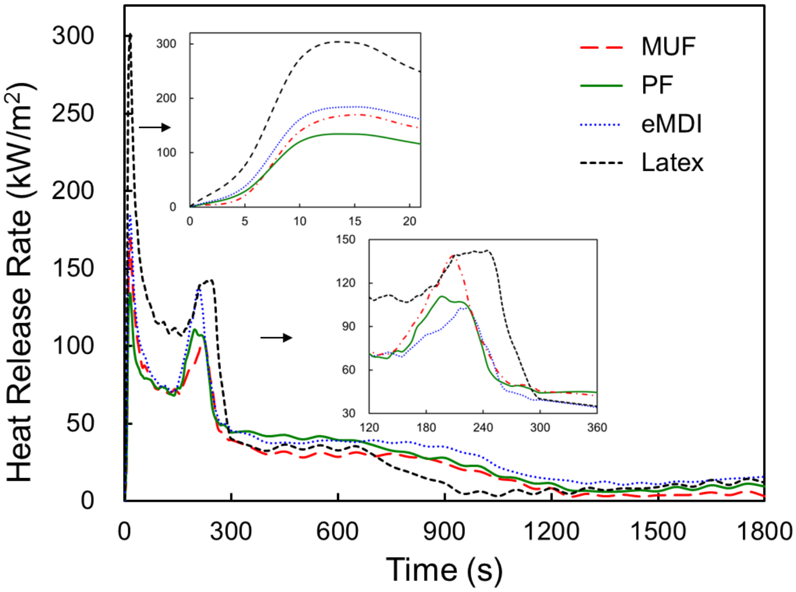

Fig. 3. Heat release rate curves of WIBs with different adhesives

Smoke and Gas Production

Table 7 presents the analysis results for the TSR, SEA, carbon monoxide yield (COY), and carbon dioxide yield (CO_2Y) from the WIBs during the combustion test. The amount of smoke was measured according to light absorption to determine the accumulation of liquid particles (tar), vapors, inorganic particles, and carbon-containing particles in the cone calorimeter.

Table 7. Smoke Release of WIBs with Different Adhesives during the Cone Calorimeter Test

Adhesive type	Total Smoke Release (m^2/m^2)	Specific Extinction Area (m^2/kg)	COY (kg/kg)	CO_2Y (kg/kg)
MUF	4.3	23.36	0.0569	1.07
PF	325.4	107.16	0.0963	1.33
eMDI	912.9	208.98	0.0673	1.29
Latex	1005.5	306.94	0.0796	1.51

COY, Carbon monoxide yield; CO_2Y, carbon dioxide yield

WIBs prepared with the MUF resin showed a markedly lower TSR (4.3 m^2/m^2) than the other samples (325.4 to 1005.5 m^2/m^2). Heat and/or smoke is a major source of mortality and morbidity for fire victims. The toxicity of smoke from burning substances is recognized as a major cause of fire-related deaths. In general, more people are injured and killed by smoke inhalation than direct heat/flame exposure (Park *et al.* 2014). Therefore, a low TSR is a great benefit for potential insulation materials. Smoke, which is formed by flame combustion and combustible gas generated from the pyrolysis of combustible objects, is composed of polycyclic aromatic hydrocarbons that generate char in the flame region. While tar and combustible gases are generated at high temperatures, char is formed and flammable gases such as H_2O and CO_2 are released during wood pyrolysis at low temperatures.

Figure 4 shows the smoke production rate of WIBs with different adhesives as a function of time. With the MUF resin, smoke was produced in the initial combustion period (> 20 s) and a later period (~240 s). Because of the quick formation of the carbonized layer by the reaction of melamine and combustible gas in the wood fiber at low temperatures in the first 20 s, this may have consumed essentially all of the oxygen that was present. This would have caused the burning process to no longer proceed. In the case of the latex and PF resins, most of the smoke was released within 300 s in the initial stage; thereafter, no smoke was generated. In contrast, the eMDI resin not only had a large amount of initial smoke but also continuously released smoke until the end of the test.

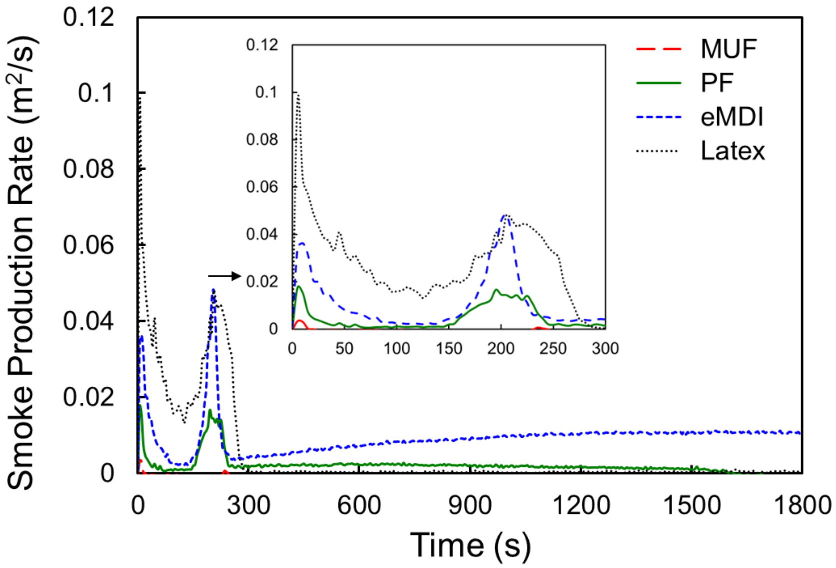

Fig. 4. Smoke production rate of WIBs with different adhesives as a function of time

The SEA was calculated by dividing the SRR by the mass reduction rate. The WIB prepared with MUF showed a significantly lower SEA (23.36 m^2/kg) than the other samples (107.16 to 306.94 m^2/kg). A low SEA value indicates that the WIB did not burn despite being a combustible object. This can be explained similarly to the results for the TSR.

During the combustion of wood products, gas components such as CO, CO_2, NOx, and CH_2CHCN (Acrylonitrile) are mainly produced. However, existing insulation materials based on synthetic raw materials such as polyurethane and polystyrene emit additional gases such as HCl, HCN, SO_2, HBr, and HF (Park *et al.* 2001; Park 2010). According to Seo and Son (2015), extruded expanded polystyrene, which is used in the construction field for insulation material, produces more than 1.5 times the COY allowed by standards. Meanwhile, the WIB with MUF resin demonstrated a lower COY and CO_2Y than the other samples. Park (2010) reported that phenolic and latex resins generate a relatively low CO_2Y.

CONCLUSIONS

1. Wood-fiber insulation boards (WIBs) were prepared under the same conditions (35% resin content, 1% wax emulsion, 150 °C for 7 min with 5 kgf/cm^2) with different adhesives (melamine-urea-formaldehyde (MUF), phenol-formaldehyde (PF), emulsifiable 4,4’ methylene diisocyanate (eMDI), and latex resins). The WIB density was about 0.15 g/cm^3, and they showed excellent thermal conductivity of about 0.035 to 0.037 W/mk.
2. The WIBs made with the MUF, eMDI, and latex resins exhibited excellent HCHO emission performance (grade super E_0), while the WIB with the PF resin was slightly worse (grade E_0). The TVOC emissions of all WIBs satisfied the Korean Standard for indoor air quality (<400 µg/m^{2}h).
3. In the Meckel burner test, all WIBs satisfied the requirements for the carbonized area (< 30 cm^2) and carbonization length (< 20 cm) but not the burning time after flame and glowing time after flame. After the 90° flame exposure test, the WIB prepared with the MUF resin had only 19.8% of the total thickness carbonized, while the WIBs with the PF, eMDI, and latex resins were almost destroyed by the flames.
4. The WIB prepared with the MUF resin showed a lower HRR_{mean} (31.29 kW/m^2), PHRR (134.59 kW/m^2), and THR (37.8 MJ/m^2) than the other samples during the cone-calorimeter test.
5. The WIB prepared with the MUF resin showed a remarkably low TSR (4.3 m^2/m^2) compared to the other samples (325.4 to 1005.5 m^2/m^2) and a lower COY and CO_2Y. The MUF resin and wood fiber quickly formed a carbonized layer from the reaction of the melamine and combustible gas within 20 s. This layer may have prevented an oxygen supply during combustion, so the burning process did not proceed.
6. For WIBs, the MUF resin is recommended as a binder because of its outstanding thermal, emission, and physical properties as well as fire safety.

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