Effect of Resin Content on the Physiochemical and Combustion Properties of Wood Fiber Insulation Board

Se-Hwi Park, Min Lee,* Pureun-Narae Seo, and Eun-Chang Kang

As petrochemical products (including plastics) contribute to the destruction of the natural environment, the use of such products must be reduced. Plastics account for 90% of the insulation materials used in Korea, including extruded polystyrene (EPS), expanded polystyrene (XPS), and urethane foam. Wood-fiber insulation board (WIB) is a promising natural alternative to petrochemical insulation. This study aimed to determine the optimal amount of adhesive resin required for manufacturing WIB. Fire-resistant WIB was prepared with a melamine-urea-formaldehyde (MUF) resin (ranging from 20% to 35%), and the physicochemical and fire-resistant properties were determined. Higher resin content led to improved physical properties, while the thermal conductivity was unaffected. With the exception of 35% resin content in the WIB, the formaldehyde emissions of the WIB samples complied with the Korean Industrial Standards requirements for Super E0 grade (less than 0.3 mg per L). The physicochemical properties of the WIB samples were sufficient for use as an insulating material, even at 20% resin content. A perpendicular flame test revealed that all samples formed a carbonized layer to prevent flame penetration, except for the specimen with 20% of the resin content. The cone calorimeter testing indicated that the MUF adhesives acted as an effective fire retardant at resin contents above 25%.

Keywords: Wood-fiber insulation; Resin contents; Melamine-urea-formaldehyde; Fire resistant

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INTRODUCTION

Residential development involves the design and construction of a home, as well as maintenance to ensure that the residential environment is comfortable (Dell'Isola 1997). Temperature is the most sensitive factor involved in maintaining a comfortable living environment, where control is usually achieved through insulation design or energy injection (Kelly and Male 1993). Radiators, ondols (under-floor heating), and air conditioners are commonly used in homes, but most of the consumed energy originates from fossil fuels that have negative economic and environmental repercussions (Pulseli *et al.* 2007). The International Energy Agency predicts an increase in global energy demand of over 50% by 2030 (Violeta and Ferhat 2012), where one-third of existing buildings will be rebuilt to save energy (Tu 2004). Therefore, improved energy efficiency is a major consideration during construction, because it has a great influence on the development of sustainable housing. A reduction in total energy consumption has been considered more frequently in building permits, where Europe has implemented various institutional or public solutions including passive house design (Feist *et al.* 2005). The social awareness surrounding sustainable housing has grown, and the global green building market is expected to reach $7 trillion by 2030.

The reinforcement of a building's insulation properties is vital for improving energy efficiency. It may be improved by reducing the number or size of windows, particularly windows that are vulnerable to heat exchange. Synthetic insulation materials are applied to insulate areas such as walls and roofs including polystyrene, polyurethane, and polyethylene (Guo *et al.* 2012). While these synthetic materials offer excellent heat insulation, easy construction, and a low price, they are petrochemical products that are difficult to dispose of and emit toxic gases when burned. These materials should be phased out to address these environmental issues. Therefore, natural alternatives have been recently developed, using materials such as mineral wool, silica, vermiculite, and wood fibers (Zhou *et al.* 2010; Zach *et al.* 2013). Fiberboard based on wood fibers is growing in popularity in the European building market due to its environmental friendliness and good product performance. For examples, in Europe, ContiTherm (Siempelkamp, Krefeld, Germany), Thermowall (Gutex, Gutenburg, Germany) and Pavaflex (Pavatex, Fribourg, Swiss) are selling in the market. These wood-fiber insulations are produced using isocyanate glues (pMDI) in different raw densities (100 to 250 kg per m^3) and thicknesses (6 to 240 mm) for different purposes. In general, the pMDI is used around 4 to 5% and cured with a steam-air-mixture around 100 °C. In Korea, medium and high-density fiberboards for furniture or floorboards have been manufactured so far, while all low-density fiberboards must be imported. A previous study produced low-density fiberboard based on wood fiber. The characteristics have been investigated to produce low-density fiberboard in Korea (Jang *et al.* 2017; Lee *et al.* 2019).

While fiberboard is an environmentally friendly alternative to ready-made insulation, a large amount of resin is used during manufacturing. Large amounts of formaldehyde are released from the resin into the air, similar to many other industrial processes and products, including paint, printing, pharmaceuticals, footwear, and upholstery. Formaldehyde is toxic and has been classified as a primary carcinogen by several national agencies including the U.S. Environmental Protection Agency (EPA) and the International Cancer Institute (IARA) (Yang *et al.* 2005). Efforts in research and in industry have focused on the reduction of formaldehyde emissions, while stricter regulations have been introduced with the addition of a new grade (Super E0). Formaldehyde emission reduction during fiberboard manufacturing is closely related to the type and amount of resin used (Pizzi 2015). Amino, phenolic, and isocyanate-based adhesives are commonly used, and a recent study (Lee *et al.* 2019b; Kirsch *et al.* 2018) has proposed the use of a melamine-urea-formaldehyde (MUF) or polymeric methylene diphenyl diisocyanate (pMDI) adhesive resin. Reducing the amount of resin has a direct impact on the properties and costs of a medium density fiberboard (MDF), but the use of optimal resin conditions also plays a vital role (Xing *et al.* 2004).

The focus on eco-friendly living environments has led to the use of exterior insulation finishing systems (EIFS) for building insulation. This is where building structures are designed to avoid direct interaction with the outside air by applying an insulation layer to the outside of the structure. This fundamentally avoids the thermal bridges generated using traditional heat-resistant insulation, thereby increasing the cooling and heating energy saving effect (Min *et al*. 2012). EIFS has grown in popularity due to internal space saving, applicability to high-rise buildings, construction cost reduction, constructability improvement, and compliance with energy saving policies (Çomakali and Yüksel 2003; Cho *et al.* 2019). External insulation is vulnerable to fire spreading, particularly in the case of a vertical fire spreading up a tall building. Common organic insulation materials can also cause asphyxiation by toxic gases generated when burned.

Domestic organic insulation occupies 90% of the total market, and fire performance is an important topic in the research of insulation materials.

This study aimed to develop an insulation material made from wood fiber and MUF resin to satisfy the demands of sustainable construction. Formaldehyde emissions were reduced to provide an insulation material suitable for eco-friendly housing. Density was investigated in a previous study and was set as a control variable to measure the other physical properties, thermal conductivity, formaldehyde emission, and fire performance according to the changes in resin content.

EXPERIMENTAL

Synthesis of Wood Adhesive

MUF resin adhesives were prepared directly using commercially available melamine (OCI N.V., Amsterdam, Neterlands), urea (Hu-chems, Seoul, Korea), and 37% formaldehyde (Sunchang corporation, Incheon, Korea). The properties of the MUF resin adhesives were evaluated according to the general test method of adhesives (KS M 3705), where the detailed information is provided in Table 1.

Table 1. Components Used to Formulate the MUF Resin

Content	Condition	Content	Condition
F / MU	0.80	pH	8.0
Melamine	30 %	Viscosity	115 mPa
Synthesis method	Alkali-Acid-Alkali	Specific gravity	1.29 mg / mL
Solid content	67.3 %	Gel time	137 s

Preparation of Wood-fiber Insulation Board

Wood fiber insulation board (WIB) was prepared according to a manufacturing method and by using *Pinus densiflora* wood fibers under air conditions reported previously by the current authors (Lee *et al.* 2019b). The WIB manufacturing procedure is illustrated in Fig. 1. Adhesive, wax emulsion (Dongwha Enterprise, Incheon, Korea), and curing agent (NH_4Cl) were mixed and sprayed onto wood fibers in a drum mixer. Ball-like agglomerates of wood fibers formed and were dissociated by passing in high-speed wind blowing. The coated wood fibers were formed into mats (350 by 350 by 20 mm) according to the target density of 150 kg per m^3. This was accomplished by using a mold that was compressed under 5 kgf per cm^2 at a rate of 21 s per mm and a temperature of 150 °C. The resin content varied (20, 25, 30, and 35%) at a fixed density, and the samples were named WIB-20, WIB-25, WIB-30, and WIB-35, respectively.

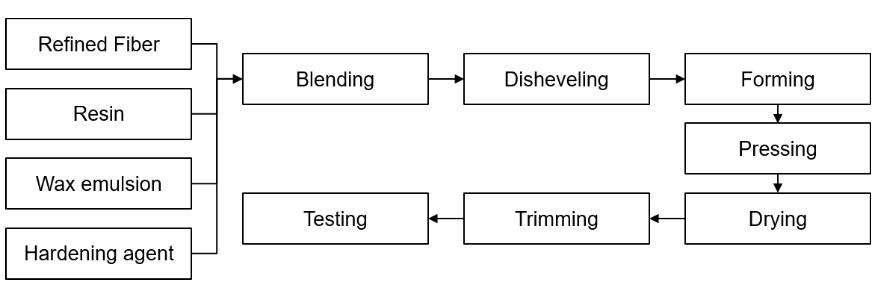

Fig. 1. The wood-fiber insulation board manufacturing process

Morphological and Physical Properties

The surface of the WIB samples was observed using a stereomicroscope (Axiocam 506 color, ZEISS, Germany). Differences between the samples were observed, including differences in the coating of the wood fibers by the resin. Water content, density, water absorption, thickness swelling, and bending strength were evaluated according to the Korean low-density fiberboard quality evaluation criteria (KS F 3200). The thermal conductivity and thermal resistance were measured using a thermal conductivity analyzer (λ-Meter EP500e, Messtechnik GmbH, Germany). The formaldehyde emission was measured using the desiccator method (KS M 1998).

Perpendicular Burning Test

A perpendicular burning test is a simple test that allows intuitive observation of the combustion process when the fiberboard was directly exposed to a flame, which was based on a procedure described in Lee *et al.* (2019a). A test piece (50 by 50 by 20 mm^3) was dried for 24 h in an oven-dryer at 40 ± 2 °C and dehumidified for 2 h in a desiccator. The samples were held in a mold while a 1,350 °C flame was applied vertically using a torch 60 mm away for 5 min. The surface temperature of the samples during flame exposure was measured using an infrared thermometer (SK-8900, Sato Keiryoki MFG, CO. Ltd., Tokyo, Japan). The weight change rate of the burnt sample was measured. The burnt sample was cut open, and the combustion depth was calculated using Eq. 1,

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

where D_a is the thickness of the specimen and D_b is the unburned residual thickness.

Table 2. Combustion and Smoke Release Properties Measured Using a Cone-Calorimeter

Content	Abbreviation	Unit	Signification
Combustion properties	TTI	(s)	time to ignition
	HRR_{mean}	(kW / m^2)	mean heat release rate
	HRR_{peak}	(kW / m^2)	peak heat release rate
	THR	(MJ / m^2)	total heat release
	EHC_{mean}	(MJ / kg)	mean effective heat of combustion
	SMLR	(g / s × m^2)	specific mass loss rate
	MLR	(g / s)	mass loss rate
Smoke release properties	TOC	(g)	total oxygen consumed
	TSR	(m^2 / m^2)	total smoke release
	SEA	(m^2 / kg)	specific extinction area
	COY	(kg / kg)	carbon monoxide yield
	CO_2Y	(kg / kg)	carbon dioxide yield
	CO / CO_2	-	CO / CO_2 ratio

Cone Calorimeter Analysis

The combustion characteristics of the WIB samples were measured using the cone calorimeter method (KS F ISO 5660-1; Fire Testing Technology Ltd, East Grinstead, UK). Samples (100 by 100 by 20 mm) were air-dried until a constant weight was reached. The unexposed surface of the specimen was wrapped in aluminum foil to prevent exposure to radiant heat. The heat capacity of the cone heater was within ± 2% of the set value, the discharge flow rate was 0.024 ± 0.002 m^3 per s, and the oxygen concentration of the oxygen analyzer was calibrated to 20.95 ± 0.01%. The parameters measured by exposing the specimen to 50 kW per m^2 radiant heat are given in Table 2.

RESULTS AND DISCUSSION

Morphological and Physical Properties

The surface of the WIBs was imaged using a stereomicroscope, which revealed that the glossiness of the wood fiber surface increased at higher resin contents due to the increased adhesion of the wood fibers (Fig. 1). Proportionally, a higher resin content reduced the amount of wood fibers in the WIB (Tang *et al.* 2017), thus increasing the voids between the wood fibers. This was noted in the comparison of the WIB-20 and WIB-35 samples.

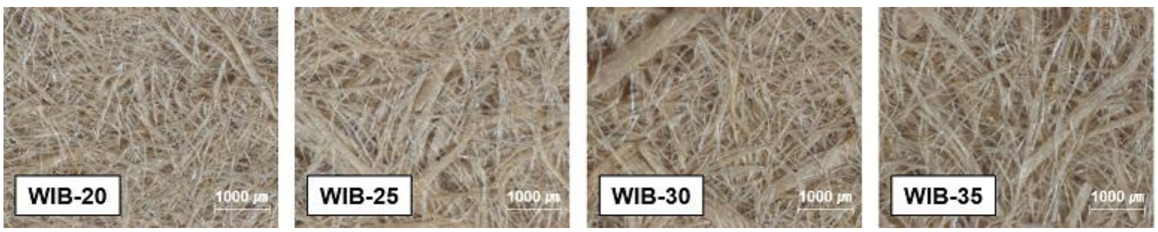

Fig. 2. Stereo microscope images (25x) of the WIB samples with varying resin content (20, 25, 30, and 35%).

The physical properties of WIB samples manufactured under various conditions are shown in Table 3. The WIBs were 20 mm thick and had a density of *ca.* 150 kg per m^3. The water content varied slightly between 6.23 and 7.22% but was not related to resin content. According to the KS F 3200 (2006) guideline, the water content of a low-density fiberboard used for insulation should range between 5 and 13%. However, the water absorption rate tended to gradually decrease with an increasing resin content due to the strengthening of the bonds between the wood fibers by the resin. The lower water absorption rate of WIB-35 was attributed to the coating of the wood fibers in adhesive and the lower content wood fibers in comparison with the other WIBs (20%, 25%, and 30%). Increased resin content in fiberboard has been found to lower the water absorption rate and prevent weight loss due to fungal damage (Chow *et al.* 1999). The water absorption of WIB-30 and WIB-35 differed by *ca*. 15%, and this boundary was determined as the conversion point of water absorption.

The thickness swelling was 0.90% for WIB-20, 0.92% for WIB-25, 1.12% for WIB-30, and 1.52% for WIB-35. Halvarsson *et al.* (2008) reported a decrease in water absorption rate and an increase in thickness swelling as the MUF resin content of wood fiberboards increased. This was attributed to internal bond enhancement, which is often observed in common fiberboards (Hague *et al.* 1999). Furthermore, the melamine in the resin is naturally hydrophobic and does not absorb moisture (Çavdar 2020). The bending strength between the wood fibers in the WIB-20 and WIB-25 samples was very similar (0.61 and 0.62 MPa, respectively), while the bonding in WIB-30 was much higher (0.94 MPa). A resin content of 30% was observed to be the turning point in the changing physical and mechanical properties according to result of moisture content, water absorption, and bending strength.

Table 3. Physical Properties of the WIB Samples with Varying Resin Content (20, 25, 30, and 35%)

Experiment	WIB-20	WIB-25	WIB-30	WIB-35
Density (kg / m^3)	157.58 ± 2.55	156.46 ± 7.66	158.21 ± 0.64	154.57 ± 4.92
Moisture content (%)	6.23 ± 0.13	6.30 ± 0.71	6.14 ± 0.28	7.22 ± 0.49
Water absorption (%)	78.21 ± 6.51	74.14 ± 9.18	73.81 ± 3.11	58.36 ± 6.06
Thickness swelling (%)	1.40 ± 0.76	0.92 ± 0.35	1.12 ± 0.66	1.52 ± 1.00
Bending strength (MPa)	0.61 ± 0.06	0.62 ± 0.08	0.94 ± 0.10	0.95 ± 0.10

Moisture content was measured immediately after manufacture.

Thermal Conductivity and HCHO Emission

Thermal conductivity analysis is used to determine the thermal insulation performance of exterior walls. It is important because insulation has the largest impact on energy reduction in buildings. The main factor affecting thermal conductivity was density, (Uysal *et al.* 2009) and the related previous study obtained optimal insulation performance at a density of 150 kg per m^3 (Lee *et al.* 2019b). The difference in thermal conductivity and thermal resistance of the fiberboards produced in this study was 0.002 W per m × k and 0.030 m^2 × KW, respectively (Fig. 3).

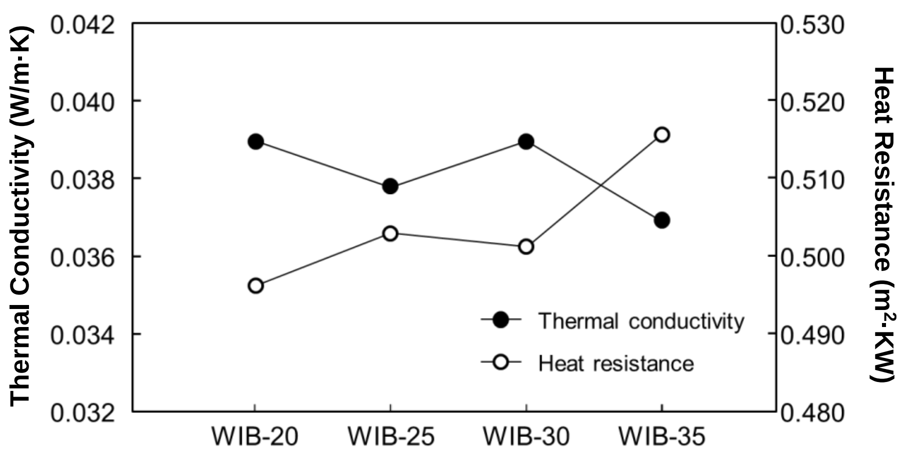

Fig. 3. The thermal conductivity and heat resistance of the WIB samples with varying resin content (20, 25, 30, and 35%)

Therefore, the difference in resin content did not affect the thermal performance. Insulation material can be produced using various natural organic materials in addition to wood, as described in Table 4. With the exception of hemp fiberboard, the thermal conductivity of the other materials was 0.040 W per m × k or higher. This demonstrated the excellent thermal insulation of the wood fiberboard in this study. The thermal conductivity of commercially available petrochemical insulation, namely extruded polystyrene (XPS) and expanded polystyrene (EPS), ranged from 0.037 to 0.049 W per m × k (Lakatos 2014). This indicated that the thermal insulation performance of the wood fiberboards was similar or superior to these materials.

Table 4. Thermal Conductivity of Various Organic Insulation Materials

Materials	Density (kg / m^3)	Thermal conductivity (W / m × K)	Reference
Cork	100 - 390	0.047 - 0.083	Barreca and Fichera 2015
Hemp	290 - 400	0.031 - 0.051	Zach *et al.* 2013
Cotton stalk	150 - 350	0.055 - 0.083	Zhou *et al.* 2010
Kenaf	150 - 200	0.051 - 0.058	Xu *et al.* 2004
Wheat straw	150 - 250	0.048 - 0.052	Zhou *et al.* 2004
Wood fiber	50 - 500	0.026 - 0.137	Kawasaki *et al.* 1998

Formaldehyde emissions have gained increasing attention regarding residential health in numerous contemporary housing processes. The formaldehyde emission of the WIB samples was directly proportional to resin content and ranged from 0.23 to 0.52 mg. Jang *et al.* (2017) found that the formaldehyde emissions of low-density fiberboard prepared using phenol (phenol formaldehyde), eMDI (emulsified methylene diphenyl diisocyanate), and latex were 0.43 mg per L, 0.14 mg per L, and 0.18 mg per L, respectively. Melamine was the main component in the MUF resin adhesive and enhanced the stabilization of the C-N bonds, which resulted in emissions similar to other low-emission resins such as eMDI and latex (Salem and Böhm 2013). Formaldehyde emissions are stipulated in the Korean Industrial Standards (KS F 3200 2016) and classified as Super E0 (0.3 mg per L or less), E0 (0.5 mg per L or less), and E1 (1.5 mg per L or less). The WIBs with resin contents below 30% fall under the highest-grade classification (Super E0), while WIB-35 was classified as the E0 grade.

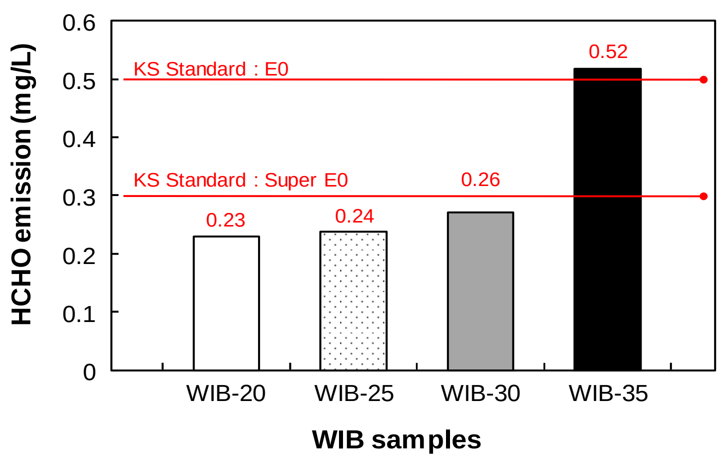

Fig. 4. The HCHO emission of the WIB samples with varying resin content (20, 25, 30, and 35%)

Fire Performance

Perpendicular burning test

Organic insulation materials composed of carbon are vulnerable to open flames and easily generate toxic fumes when ignited. Insulation has been identified as the main contributor to the spread of fire. Therefore, the study of combustion characteristics is required. While a flame-resistant melamine resin was used for this study, the combustion process must be analyzed because the raw wood fiber is very flammable. The shape, carbonization depth, and weight loss rate of the WIB samples was evaluated after the perpendicular burning test. The 5 min flame exposure led to the complete burning of the entire WIB-20 sample. Higher resin content decreased the carbonized depth, and a gray ash bubble was observed on the surface. The carbonized depth decreased from 90 to 29% as resin content increased from 20 to 35%, while the weight loss rate decreased from 71 to 35%. Melamine in the resin gradually condensed due to ammonia release during heating, producing more thermally stable melam ($C_6H_9N_{11}$), melem ($C_6H_6N_{10}$), and melon ($C_6H_3N_9$) that formed a barrage (Liu *et al.* 2016). Although the total amount of melamine in the WIBs was small, it had a noticeable effect.

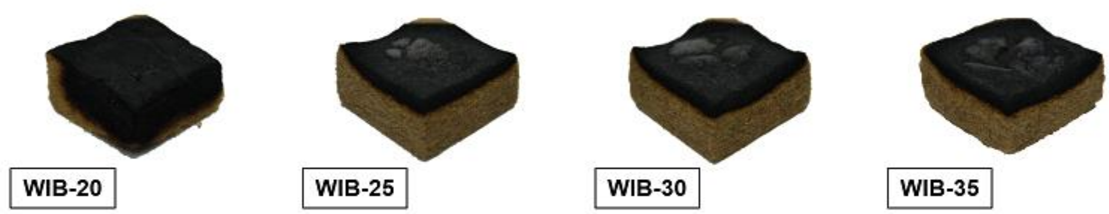

Fig. 5. Specimen shapes of the WIB samples with varying resin content (20, 25, 30, and 35%) after the perpendicular flame test

Table 5. Carbonized Depth and Weight Loss of the WIB Samples with Varying Resin Content (20, 25, 30, and 35%) Determined Using a Perpendicular Flame Test

Samples	WIB-20	WIB-25	WIB-30	WIB-35
Carbonized depth (%)	90	38	36	29
Weight loss (%)	71	44	42	35

Combustion properties

Quantitative analysis was conducted using a cone-calorimeter test, which was compared to the results of the simple perpendicular burning test. Combustion modeling was conducted using the cone-calorimeter results, which provided important information for fire prevention via in-depth analysis of the heat and smoke released during combustion of the WIB samples. Combustion characteristics were evaluated in WIBs exposed to 50 kW per m^2 radiant heat (Table 6), which were compared to commercially available XPS and EPS used in the previous study (Lee *et al.* 2019a). Heat release rate (HRR) is a very important factor that provides an indication of the fire risk and is measured using oxygen consumption calorimetry (Babrauskas and Peacock 1992). A higher HRR indicates that heat is collected at the surface of the sample more easily, thus contributing to higher fire risk (Babrauskas 1984). The HRR_{mean} and HRR_{peak} values decreased from 85.2 to 74.4 kW per m^2 and 115.9 to 99.0 kW per m^2, respectively with an increasing resin content. The HRR_{mean} and HRR_{peak} values of the WIB samples (except WIB-20) were lower than XPS and EPS indicating a lower fire risk.

The specific mass loss rate (SMLR) and effective heat of combustion (EHC) exhibited similar trends to the HRR. EHC is constant during the combustion of uniform specimens that decompose, and SMLR reflects the decrease in mass. Both measures provide further indication of the material's fire behavior. HRR is calculated by multiplying the SMLR by the EHC. Thus, HRR and SMLR are directly proportional (Pearce *et al.* 1992). The total heat release (THR) of the WIB samples was 12 to 15 MJ per m^2 higher than XPS and EPS, which is based on the proportional relationship between the total amount of heat and specific gravity (Tran and White 1992). The specific gravity of XPS and EPS ranged between 0.03 and 0.05 g per cm^3 (Lee *et al.* 2019a), which is approximately 5 times lower than the WIBs samples. The Korean Standards (KS F ISO 5660-1) requires a Class 3 fire retardant to have a THR below 8 MJ per m^2 during 5 min of combustion. Therefore, further fire-retardant treatment is needed to satisfy these requirements. Most of the combustion characteristics did not differ noticeably in WIB-20 and WIB-25. Increased resin content was expected to suppress combustion where a 25% resin content was the most effective.

Table 6. Combustion Properties of the WIB Samples with Varying Resin Content (20, 25, 30, and 35%)

Lists	WIB-20	WIB-25	WIB-30	WIB-35	XPS	EPS
TTI (s)	9	5	5	6	18	7
HRR_{mean} (kW / m^2)	85.22	74.42	75.74	74.43	84.86	83.13
HRR_{peak} (kW / m^2)	115.86	101.36	103.38	99.03	222.0	157.13
THR (MJ / m^2)	26.3	22.7	23.2	22.8	9.1	5.8
EHC_{mean} (MJ / kg)	11.40	11.09	10.52	9.75	18.07	16.35
SMLR (g / s × m^2)	8.17	7.34	7.35	7.60	9.97	4.26
MLR (g / s)	0.074	0.067	0.068	0.069	0.092	0.040
*Note: XPS is extruded polystyrene and EPS is expanded polystyrene (Lee *et al.* 2019a).						

The HRR curves illustrate the pyrolysis mechanism during combustion of the WIB samples (Fig. 6). Exposure to radiant heat caused a rapid increase in heat release until the HRR_{peak} value was reached. After peaking around 40 s, the HRR gradually dropped and plateaued between 130 and 200 s. The HRR then increased again and reached the second peak at 290 s (WIB-20), 300 s (WIB-25), 270 s (WIB-30), and 240 s (WIB-35). None of the WIBs exceeded the maximum HRR_{peak} stipulated in the Korean regulations (greater than 200 kW per m^2 for 10 s). Woody composites including MDF, plywood, and particle board (PB), are classified as char-forming polymers (Liu *et al.* 2007). Depending on the combustion mechanism, volatiles are released upon initial ignition which causes a strong heat release.

The first peak was attributed to this phenomenon. A carbonized layer formed on the intensively burned surface, which led to gradual stabilization of combustion, reduced heat release, and a plateau in the HRR values. The after-glow effect is where the carbonized layer turns to ash and is followed by decomposition of the carbonized layer. This causes reburning of the WIB interior, which gives rise to the second peak. The heat release during this carbonization process depended on the resin content. The HRR_{peak} value and overall HRR curve of the WIB-20 sample was higher than the others. The HRR decreased with an increasing resin content because of the melamine. Melamine and its derivatives (melamine oxalate, melamine phosphate, melamine phthalate, and melamine cyanurate) are organic nitrogen compounds used as flame-retardant additives. Melamine undergoes gradual endothermic condensation during heating to form melam, melem, and melon, which are more thermally stable than melamine (Xiong *et al.* 2018). These materials are retained in the carbonized layer for a long time to slow the development of the secondary heat peak and reduce the overall heat release.

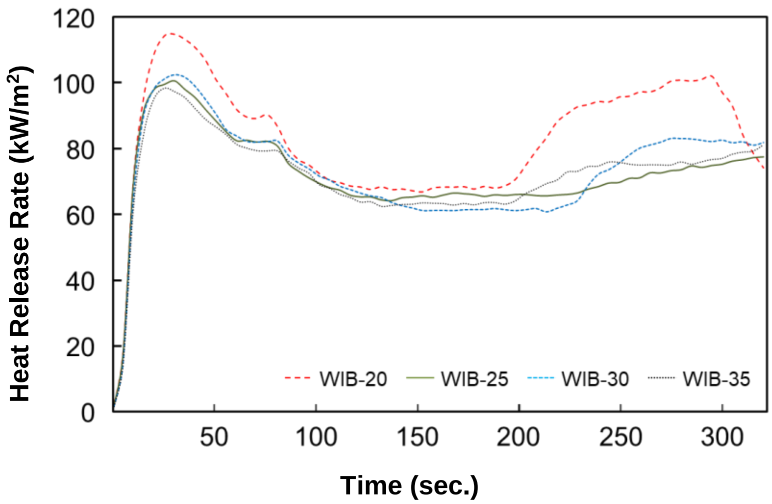

Fig. 6. The HHR curves of the WIB samples with varying resin content (20, 25, 30, and 35%).

The CO and CO_2 yield and concentration curves of the WIB samples are shown in Figs. 7 (CO) and 8 (CO_2). CO was produced in all samples from 40 s. WIB-20 and WIB-25 produced CO until *ca*. 100 s, while WIB-30 and WIB-35 continued to yield CO until 170 and 230 s, respectively. The CO yield increased noticeably above a 30% resin content, where WIB-30 and WIB-35 exhibited similar results. The CO concentration reflected the CO yield, where the CO concentration increased after *ca.* 40 s. Higher resin content samples (WIB-30 and WIB-35) exhibited a higher CO concentration.

Large amounts of nitrogen were released during pyrolysis of melamine in the resin, which promoted CO release by limiting the oxygen supply (Tai *et al.* 2012). CO production in woody composites is divided into three stages: pre-flaming pyrolysis, flaming, and glowing (Tsuchiya 1994). Pre-flaming pyrolysis mainly involves the release of water vapor until the ignition temperature is reached, after which flaming and non-flaming begins. Volatiles and carbon are fully decomposed during this stage.

An insufficient oxygen supply or temperature can cause incomplete thermal decomposition of carbon, which leads to the formation of CO or soot. Glowing entails the depletion of volatiles and stable combustion of the charcoal (carbonized layer). Only carbon can be decomposed without being affected by oxygen consumption, thereby reducing the amount of CO produced. The CO yield and CO concentration curves of the WIB samples only exhibited the first and second stages in the short measurement time of 300 s. CO_2 yield and CO_2 concentration were related to the combustion mechanism presented with the HRR results.

Complete combustion proceeds at temperatures sufficient for combustion, which contributes to CO_2 emissions (Chen *et al.* 2015). CO_2 is easily produced during the combustion of organic matter containing carbon in an atmosphere with abundant oxygen. The CO_2 emission and concentration increased remarkably at the points at which the two HRR peaks occurred. Therefore, HRR, CO_2 yield, and CO_2 concentration curves exhibited similar trends. As with the HRR values, WIB-20 exhibited the highest CO_2 yield and CO_2 concentration, while WIB-35 was the lowest.

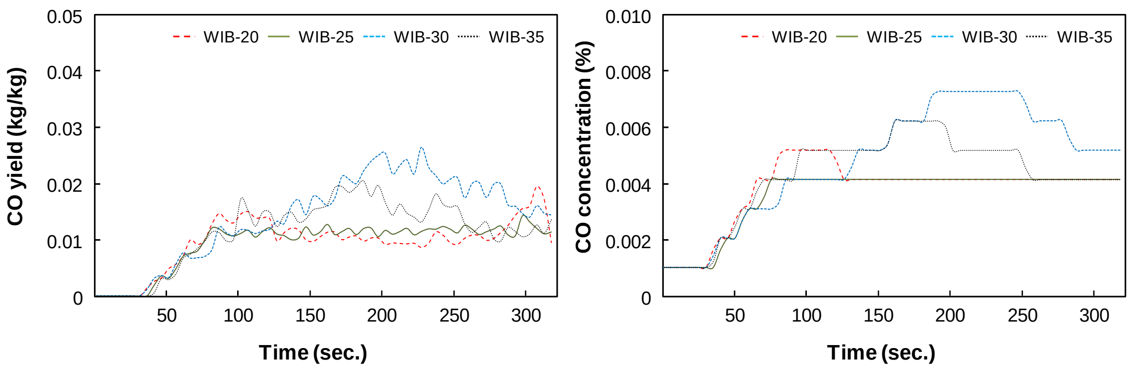

Fig. 7. CO yield (left) and concentration (right) of the WIB samples with varying resin content (20, 25, 30, and 35%)

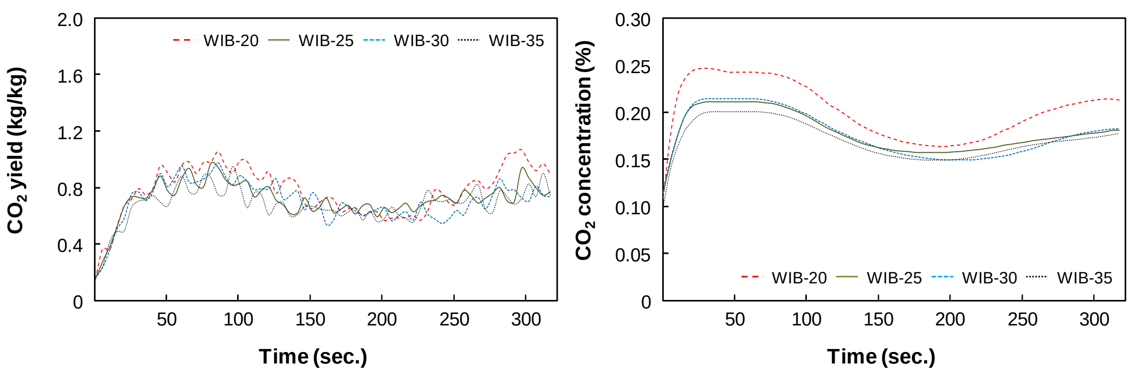

Fig. 8. CO_2 yield (left) and concentration (right) of the WIB samples with varying resin content (20, 25, 30, and 35%)

Smoke release properties

Smoke generated during combustion causes suffocation in fire accidents. Understanding smoke release is essential because the WIB insulation was composed of a wood-based material (Park *et al.* 2015). The measured smoke release characteristics were total oxygen consumed (TOC), total smoke release (TSR), specific extinction area (SEA), carbon monoxide yield (COY), carbon dioxide yield (CO_2Y), and the CO to CO_2 ratio (Table 7). TOC is directly related to HRR (Lee *et al.* 2019a) and was thus the highest in the WIB-20 sample (16.9 g). It decreased with an increasing resin content. The TSR ranged between 1.3 and 3.4 m^2 per m^2, which is very little smoke when compared to the XPS and EPS. Small amounts of smoke release are associated with incomplete combustion of volatiles with low molecular weight (Chen *et al.* 2015). The difference in the amount of smoke generated at the various resin contents was very small, indicating that the resin had little effect on the smoke release rate. The SEA is calculated by dividing the smoke production rate (SPR) by the mass loss rate (MLR) and is widely used as a smoke-related index. SEA exhibited the same trend as TSR, where all the WIB samples were preserved without ignition and extinction after burning. There was no noticeable difference with varying resin content. Upon combustion, the WIB samples released a gaseous mixture containing low molecular weight off-gases including CO, CO_2, Cl_2, HCl, H_2S, and SO_2. CO and CO_2 must be released during combustion, while the others easily vary in type and quantity (Niu *et al.* 2014). CO is very important in combustion testing as it causes asphyxiation due to the strong bond to hemoglobin (Mouritz *et al.* 2006). COY represents the amount of CO produced. The COY values were 0.0094, 0.0092, 0.0136, and 0.0115 at resin contents of 20, 25, 30, and 35%. CO is generated during incomplete combustion suggesting that incomplete combustion increased with an increasing resin content. CO_2Y decreased with the increasing resin contents exhibiting the inverse trend of COY. Melamine consists of 67% nitrogen and is often used as a fire retardant because it releases nitrogen in fires (Tai *et al.* 2012). Therefore, the COY and CO_2Y trends were attributed to the disturbance of oxygen supply by nitrogen generated during the carbonization of melamine. The CO to CO_2 ratio increased remarkably with an increasing resin content, but the absolute number and risk of smoke produced was remarkably lower than for XPS or EPS.

Table 7. Smoke Release Properties of the WIB Samples with Varying Resin Content (20, 25, 30, and 35%)

Measurement	WIB-20	WIB-25	WIB-30	WIB-35	XPS	EPS
TOC (g)	16.9	14.7	14.9	14.6	5.8	3.7
TSR (m^2 / m^2)	1.3	1.7	1.3	3.4	518.3	265.1
SEA (m^2 / kg)	0.27	0.00	0.00	0.95	882.62	1087.90
COY (kg / kg)	0.0094	0.0092	0.0136	0.0115	0.0844	0.0484
CO_2Y (kg / kg)	0.82	0.72	0.71	0.68	1.41	1.22
CO / CO_2	0.0114	0.0127	0.0191	0.0169	0.0599	0.0396
*Note: XPS is extruded polystyrene and EPS is expanded polystyrene (Lee *et al.* 2019a).						

CONCLUSIONS

1. Wood-fiber insulation board (WIB) was manufactured with resin contents of 20%, 25%, 30%, and 35% and a density of *ca.*155 kg per m^3. The surface voids and glossiness of the WIB increased with an increasing resin content because the amount of wood fiber decreased proportionally.
2. The water content and water absorption decreased with the increasing resin contents, which improved durability. All of the criteria stipulated in the Korean Standards were satisfied. The bending strength increased with an increasing resin content particularly at 30%, which was considered a major turning point for the improvement of the WIB mechanical properties.
3. The thermal conductivity ranged from 0.037 to 0.039 w per m × K and was not affected by the difference in resin content. The insulation performance was like or better than the existing petrochemical insulation materials and other natural materials.
4. WIB-20, WIB-25, and WIB-30 satisfied the super-E0 grade formaldehyde emission standard (less than 0.3 mg per L), while WIB-35 was classed as E0 grade due to the formaldehyde emission of 0.5 mg per L.
5. The carbonized depth and weight loss ratio of WIB-20 during the perpendicular burning test were noticeably different to the other WIBs. Furthermore, unlike the other samples, WIB-20 did not form a gray carbonized layer. These findings indicate that a 20% resin content was insufficient for ensuring safe fire properties.

6. The overall combustion characteristics (HRR, THR, EHC, and SMLR) decreased with the increasing resin content due to the fire suppression force of melamine in the resin.
7. The smoke generation indicators (TSR and SEA) did not differ remarkably among the various resin contents. However, COY increased and CO_2Y decreased because increasing melamine levels disturbed the oxygen supply and caused incomplete combustion. While the amount of harmful CO gas increased slightly, the value was much lower than the XPS or EPS.
8. A resin content of 30% was found to be optimal and is recommended for producing fire resistant WIB that offers superior mechanical properties, formaldehyde emission compliance, and good fire resistance. However, further fire-retardant treatment would be needed to satisfy the requirement of standard (KS F ISO 5660-1).

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