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ORIGINAL ARTICLE

Fire performance of carbonized medium density fiberboard manufactured at different temperatures

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Abstract Authors established a new manufacturing technology for crack-free carbonized boards by pressing and carbonizing the medium-density fiberboard. Industrialization of new functional carbon materials was performed by investigating the fundamental properties of the carbonized boards. To be used as a construction material, the carbonized board needs to satisfy the fire performance regulation. In this study, the carbonized boards were manufactured from medium-density fiberboard (c-MDF) at different temperatures and then fire performance including flame retardancy and smoke toxicity was analyzed using a cone calorimeter and noxious gas analyzer. The results show that as the carbonization temperature increases, weight loss ratio decreases and flame retardancy increases. In the c-MDF at 800 and 1000 °C, no external damage was observed after combustion. These c-MDFs satisfy the total heat release (standard below 8 MJ/m^2) and heat release rate (standard below 200 kW/m^2) regulations according to the Building Standard Law of Korea and Japan. In addition, the c-MDFs showed the lower total smoke release (TSR, 0.213 m^2/m^2) than that of virgin MDF (94.281 m^2/m^2). The c-MDF at 800 and 1000 °C were, therefore, classified as a class III flame retardancy material and can be used as indoor finishing material.

Keywords Carbonized boards · Medium-density fiberboard · Flame retardancy · Smoke toxicity

Introduction

Wood has been widely used as construction material mainly in the building industry because it is a natural material, has esthetic aspects, is a renewable raw material, and has excellent natural flame resistance due to low thermal conductivity [1–3]. Even though wood is flame-resistant, it is still prone to catch fire. The limitation of wood as building material is its flammability and smoke; therefore, fire-retardant materials have been developed and used in building materials [3]. The materials, which are not affected by fire, do not exist in the world although many researchers are studying about fire-retardant agent for indoor material.

Flammability and smoke can be the key points and essential parameters to evaluate the application of a wood material to a given area [4]. Browne [5] reviewed the various theories of flame retardancy for wood for reducing the flow of heat to prevent further combustion, extinguishing the flame, or modifying the thermal degradation process. Improving flame performance of wood products is relatively easily achieved by adding flame-retardant chemicals to wood materials [3, 6]. Chemical flame-

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retardants are still widely used in wood materials although there are environmental concerns regarding the use of these chemicals [7].

Heat and/or smoke are main sources of mortality and morbidity of flame victims [5]. According to Salthammer et al. [7], flame-retardants also can be potential sources for other halogenated volatile organic compounds (VOCs). The formation of char and emission of non-combustible gases such as H_2O and CO_2 are preferred during the pyrolysis of wood at low temperatures, while tars and combustible gases are produced at high temperatures [2, 8, 9]. The toxicity of the smoke resulting from the burning materials has been recognized as the greatest cause of flame deaths [8–10]. In general, more people are injured and died from flame smoke than from direct heat/flame exposure [2, 10–15]. Therefore, construction materials for indoor use require flame retardation to provide additional protection from ignition and open flames [6, 16–18].

Recently, authors are developing new carbonized board from medium-density fiberboard (MDF) which will has same functionality as white charcoal. New carbonized board from MDF has significant characteristics which are non-VOCs and formaldehyde emission, emitting far-infrared radiation, and electromagnetic shielding [19]. Therefore, it can be used as deodorization, dehumidification, filtration, and adsorption material. According to Kercher and Nagle [20], carbonized board can be possibly transformed to other shape due to its machinability and be used in industry. We recognized carbonized MDF (c-MDF) for use in indoor construction material as an environment controller due to its ability to absorb formaldehyde, benzene, and toxic VOCs and as replacement of inflammable materials.

However, to look at the possibility of the use of c-MDF for replacement of inflammable construction materials such as sponge, painted wall, and Styrofoam, c-MDF should satisfy the ability of flame retardancy and smoke toxicity before using in construction site. The objective of this study was to evaluate the flame retardancy and smoke toxicity of c-MDFs at different temperatures.

Materials and methods

Carbonization of MDF

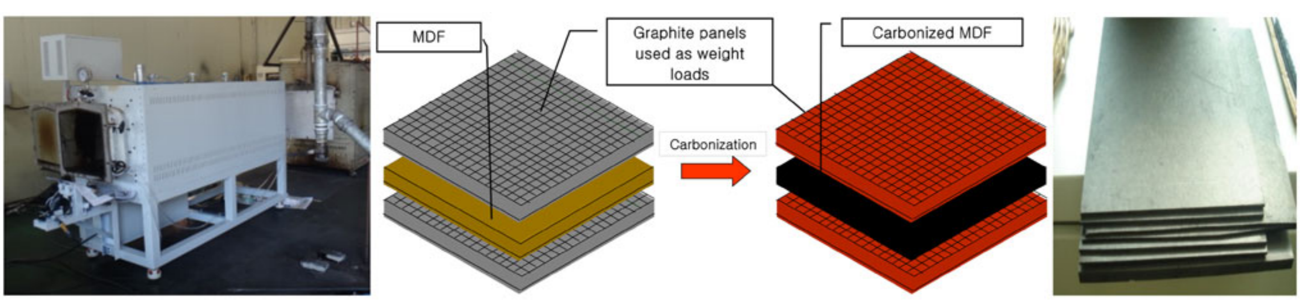
The MDF used in this experiment was commercially manufactured by Sunchang Corp. (Inchon, South Korea) and cut into 40 cm (W) × 40 cm (L) × 1.2 cm (T). Each MDF specimen was placed between two graphite sheets (2.87 kg, 1 cm thickness) without extra pressure to prevent distortion and crack during carbonization (Fig. 1). Carbonization was performed in a vacuum furnace with different maximum temperatures (400, 600, 800, and 1000 °C). The thermal schedule was used as follows: the rate of temperature rise: 50–100 °C/h; hold for 2 h at maximum target temperature.

Fire performance

Fire performance of c-MDF includes ignition time, heat release, and smoke production. Each c-MDF specimens made at 400, 600, 800, and 1000 °C were cut again into 10 cm (W) × 10 cm (L). The flammability of sample was determined by cone calorimeter (Fire Testing Technology Ltd., UK) according to ISO 5660-1 [21]. Carbon monoxide (CO), carbon dioxide (CO_2), and total amount of smoke release were determined according to ISO 5660-2 [22] and ASTM E 1678 [23]. Fire performances of c-MDFs were evaluated and ranked by heat release according to the Building Standard Law of Japan [24]. After cone calorimeter test, each sample was evaluated by changes in physical properties such as surface appearance, dimensions, and weight.

Smoke toxicity

Smoke toxicity was carried out by bioassay test method according to Korean Standard Association method (KS F 2271) [25]. Smoke, which generated from combustion of test samples, was directly flowed to noxious gas analysis (Festec International Co., LTD.). Eight mice were directly



(a) Vacuum furnace (b) Carbonization process (c) c-MDF

Fig. 1 The carbonization method by loading graphite sheets (2.87 kg, 1 cm thickness) and final product of carbonized MDFs exposed to the smoke and the time of mice's end motion was monitored. Based on KS F 2271 [25], the regulation of smoke toxicity for internal finishing material requires at least 9 min motion of mouse during the smoke exposure.

Results and discussion

Fire performance

Ignition time

The ignition time of c-MDFs was recorded and summarized in Table 1. Figure 2 indicates two different behaviors of sample during combustion process. Ignition was observed on virgin MDF and c-MDF-400 °C at 33 and 32 s, respectively. These ignition times were close to averaged ignition time of virgin wood-based panels including particle board (PB), high-density fiberboard (HDF), plywood, and laminated flooring [26]. In addition, ignition time of flame retardant-treated wood-based panels is around 65–85 s [27, 28]. We assume that carbonization below 600 °C causes remaining some elements could possibly be combusted in c-MDF, which means MDF was carbonized incompletely. However, on carbonized MDF above 600 °C, ignition and flame were not detected. This result indicated c-MDF at 600, 800, and 1000 °C did not have enough combustible gas-forming elements for ignition. Therefore, c-MDF made above 600 °C may be used as indoor finishing material because of no further combustion.

Table 1 Ignition time of MDF and MDF-carbonized boards

Samples	Ignition time (s)
MDF-control	33
Carbonized MDF-400 °C	32
Carbonized MDF-600 °C	None
Carbonized MDF-800 °C	None
Carbonized MDF-1000 °C	None

Total heat release and heat release rate

According to Building Standard Law of Japan, three classes of flame retardancy rank for interior finishing material are specified (Table 2) [24]. Class I (non-combustible materials) requires testing condition at 20 min for 50 kW/m^2 combustion. For Class II (quasi non-combustible materials), testing condition is 10 min for 50 kW/m^2 combustion. Class III (flame-retardant materials) has 5 min condition for 50 kW/m^2 combustion. All classes of fire retardancy requires below 8 MJ/m^2 on total heat release (THR) and non-consecutively 200 kW/m^2 for 10 s on heat release rate (HRR). Materials not satisfying the upper limit of Class III are considered not accepted to use where the flammability of the material is regulated.

Table 2 A performance standard of flame retardancy rank test condition (KS F ISO 5660-1)

Rank test	Test condition		Performance standard
	Heating condition	Heating time	
Non-combustible material	50 kW/m^2	20 min	Total heat release(THR) is below 8 MJ/m^2
Semi-non combustible material	50 kW/m^2	10 min	Heat release rate(PHHR) is under 200 kW/m^2 for 10 consecutive seconds
Flame retardant material	50 kW/m^2	5 min	Tunnels, cracks, holes are not found after test

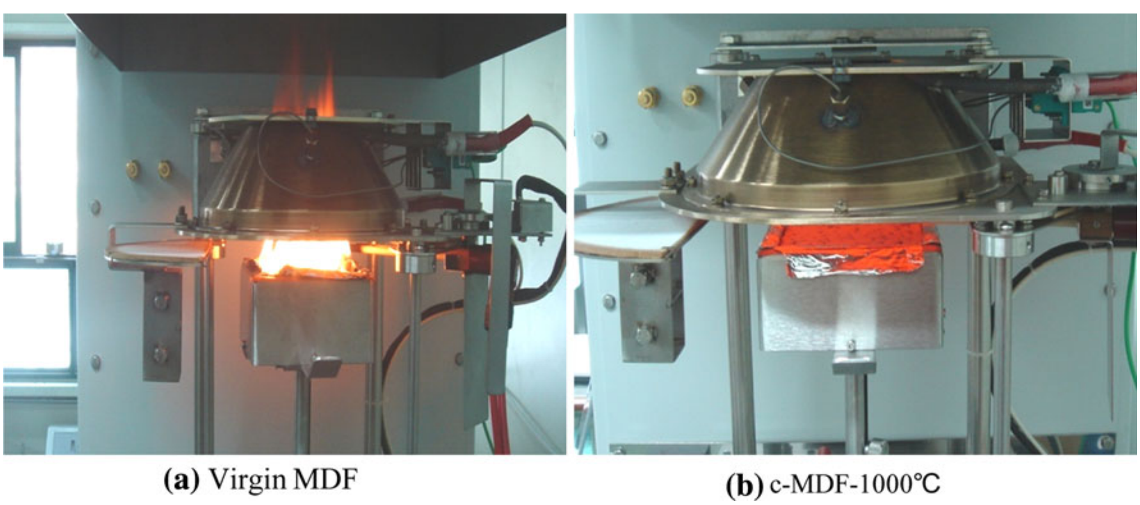


Fig. 2 Cone calorimeter analysis of virgin MDF and carbonized MDF-1000 °C

Figure 3 and 4 show total heat release (THR) and heat release rate (HRR) of samples by time, respectively. The THR of virgin MDF and c-MDFs exceeded Class I and II requirements, while only the c-MDF-600, 800, and 1000 °C (8, 7, and 6 MJ/m^2, respectively) were accepted in Class III of the Building Standard Law. The HRR results show all c-MDFs satisfied the regulation, which is no 200 kW/m^2 consecutive HRR for 10 s, except the virgin MDF. In general, c-MDFs' HRR were under 50 kW/m^2 during the test period. This lower HRR characteristic of c-MDF can be compared with other flame retardant-treated wood. Virgin HDF, plywood, and laminated flooring did not meet the regulation [26]. Based on Grexa et al. study [1], the HRR of flame retardant-treated plywood was more than 50 kW/m^2 during the test period at 25–50 and 230–410 s approximately, and then HRR became lower than 50 kW/m^2. Unfortunately, flame-retardant treatment only can delay the fire on wood-based panels, and eventually that panels will be burnt.

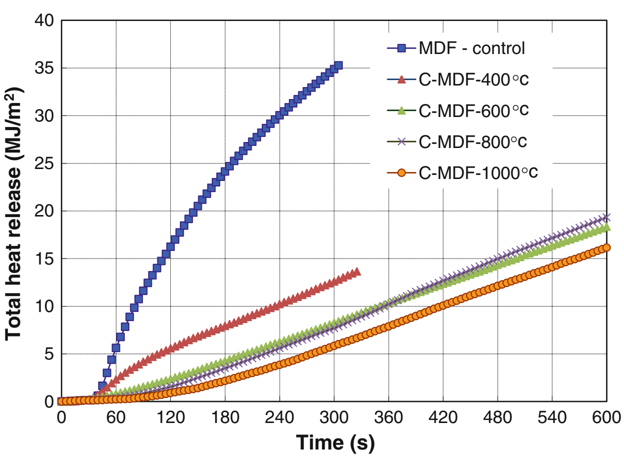


Fig. 3 Total heat release (THR) of virgin MDF and c-MDFs

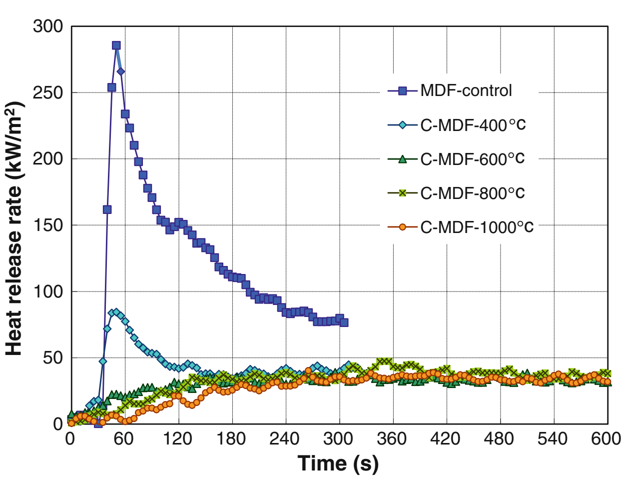


Fig. 4 Heat release rate (HRR) of virgin MDF and c-MDFs

The c-MDF and flame retardant-treated plywood cannot be compared for mechanical strength or ability, but if the place does not need much strength, c-MDF may able to replace for that flame retardant-treated plywood. Because of the c-MDF had higher HRR performance than flame retardant-treated plywood, but to secure meeting the regulation, c-MDF-800 and 1000 °C will be preferred to use in indoor construction materials.

Smoke production

The amount of CO, CO_2, and other off-gas generated from virgin MDF and c-MDFs during the cone calorimeter test were shown in Table 3. The average amount of CO emission from c-MDF at 400, 600, 800, and 1000 °C (0.100, 0.209, 0.155, and 0.069 kg/kg, respectively) was higher than virgin MDF (0.006 kg/kg). The highest CO emission was observed on c-MDF-600 °C and CO emission decreased with increasing carbonization temperature. Also, the average amount of CO_2 emission from c-MDF at 400, 600, 800, and 1000 °C (1.509, 3.023, 3.247, and 2.595 kg/kg, respectively) was higher than virgin MDF (1.149 kg/kg). The virgin MDF produced less CO and CO_2 which was possibly due to complete combustion during the test while c-MDFs generated more CO and CO_2 by incomplete combustion. The CO and CO_2 emission from virgin MDF and c-MDFs may depend on source of flammable material.

However, total amount of smoke release data showed that c-MDFs produced significantly lower amount of smoke release than virgin MDF (Table 3). During the carbonization process, most smoke was removed from MDF. In comparison between virgin MDF and c-MDF-1000 °C, virgin MDF produced approximately 440 times more than c-MDF-1000 °C. This means c-MDF-1000 °C does not produce smoke than virgin MDF while in fire. Lower smoke release can be an important advantage for using indoor flame retardant material because it may help to reduce fire death by smoke.

Weight loss

After 5 to 10 min combustion, weight reduction of samples was determined (Table 4). The weight reduction of virgin

Table 3 Emission contents of total smoke release, CO and CO_2

Samples	CO_{mean} (kg/kg)	CO_{2mean} (kg/kg)	CO/CO_2	Total smoke release (m^2/m^2)
Virgin MDF	0.006	1.149	0.005	94.281
c-MDF-400 °C	0.100	1.509	0.066	7.455
c-MDF-600 °C	0.209	3.027	0.069	6.880
c-MDF-800 °C	0.155	3.247	0.048	2.522
c-MDF-1000 °C	0.069	2.595	0.027	0.213

Table 4 Weight loss of samples during cone calorimeter test

Sample	Virgin MDF	Carbonized MDF			
		400 °C	600 °C	800 °C	1000 °C
Initial weight (g)	79.79	40.94	36.88	40.55	53.67
Density (g/cm^3)	0.76	0.48	0.52	0.54	0.56
Weight loss by time change (%)					
After 5 min	28.72	19.10	11.67	11.39	10.99
After 10 min	64.37	29.70	20.63	17.80	16.02

MDF (28.72 %), c-MDF-400 °C (19.10 %), c-MDF-600 °C (11.67 %), c-MDF-800 °C (11.39 %), and c-MDF-1000 °C (10.99 %) was observed after 5 min combustion. The weight loss of c-MDFs may be caused by loss of moisture and thermal gasification of wood and char in sample. In 10-min combustion samples, virgin MDF (64.37 %) had more weight reduction than c-MDF-400 °C (29.70 %), c-MDF-600 °C (20.63 %), c-MDF-800 °C (17.80 %), and c-MDF-1000 °C (16.02 %). The c-MDF-800 and 1000 °C have lower weight reduction, and between c-MDF-800 °C and 1000 °C has only 2 % difference. Based on these results, minimum carbonization temperature should be at least 800 °C for using flame-retardant material. Also, increasing carbonization temperature yields low weight reduction and high-flame retardancy. Even though flame retardants were applied to wood products, severe weight loss of wood products was observed during the combustion [26]. Severe weight loss of woody materials occurred during fire and may negatively affect in various ways during its combustion. The c-MDF was already passed through the fire, so it shows lower weight loss.

Smoke toxicity

Only virgin MDF and c-MDF-800 °C were chosen and tested for smoke toxicity because c-MDF-800 and 1000 °C was satisfied flame retardancy regulation. Based on smoke toxicity test, the average stop motion time of mouse was monitored on virgin MDF (5.79 min) and c-MDF-800 °C (14.12 min). As described above, smoke should be passed such that the mouse is active at least for 9 min during the smoke exposure based on KS F 2271 [24]. The virgin MDF did not satisfy the regulation for internal finish material (9 min), while c-MDF-800 °C satisfied the regulation. Replacement of inflammable materials with c-MDF may reduce smoke damage during fire.

Change of surface characteristics

Figure 5 shows surface appearance of virgin MDF and c-MDF after cone calorimeter test. The virgin MDF produced smog and flame during combustion process and then turned black color with crack. The c-MDF at 400 and 600 °C was broken or cracked on surface, while c-MDF at 800 and 1000 °C was turned gray on somewhat area by oxidation. Crack, hole, and penetration were not observed on c-MDF at 800 and 1000 °C. Based on the surface appearance data, MDF should be carbonized above 800 °C for using as construction material due to no difference in physical appearance between original and burned sample.

Conclusion

Crack-free c-MDF manufacture method has been established using plate press in vacuum furnace. Many researches have been conducted involving use of c-MDF for industry. We attempt to evaluate c-MDF uses as indoor construction material due to its advantages such as adsorbing toxic substances and electromagnetic shielding. Before, using as indoor construction material, c-MDF should satisfy the flame-retardant regulation. On increasing carbonization temperature of MDF, there are decreasing in the weight reduction and increasing in flame-retardant. On MDF carbonized above 800 °C, no external damage was observed and THR and HHR were determined 7 MJ/m^2 and 40 kW/m^2, respectively. Based on the results, c-MDF at 800 and 1000 °C satisfied class III flame retardancy

Fig. 5 Surface appearance of virgin MDF and c-MDFs after cone calorimeter test

which means these carbonized boards can be used as indoor construction material. Even though c-MDF produced more CO and CO_2 than virgin MDF, the total amount of smoke was significantly lower on c-MDF than virgin MDF. The c-MDF satisfied smoke toxicity, while virgin MDF did not. Therefore, c-MDF can be a useful material for replacement of indoor construction material such as firewall, sound-absorbing material, and electromagnetic shielding material.

References

1. Grexa O, Horváthová E, Bešinová O, Lehocký P (1999) Flame retardant treated plywood. Polym Degrad Stab 64:529–533
2. Sweet MS (1993) Fire performance of wood: test methods and fire retardant treatments. In: Lewin, Menachem (eds) Recent advances in flame retardancy of polymeric materials. Proceedings of the 4th annual BCC conference on flame retadancy; 1993 May 18–20; Stamford, CT. Business Communications Co. Inc., Norwalk pp 36–43
3. Kozłowski R, Władyka-Przybylak M (2008) Flammability and fire resistance of composites reinforced by natural fibers. Polym Advan Technol 19:446–453
4. Zawachki BE, Jung RC, Joyce J, Rincon E (1975) Smoke, burns, and the natural history of inhalation injury in fire victims: a correlation of experimental and clinical data. Ann Surg 185(1):100–110
5. Browne F (1958) Theories of the combustion of wood and its control. USDA, Forest Service, Forest Products Laboratory. Report no. 2136
6. Stark NM, White RH, Mueller SA, Osswald TA (2010) Evaluation of various fire retardants for use in wood flour-polyethylene composites. Polym Degrad Stab 95:1903–1910
7. Salthammer T, Fuhrmann F, Uhde E (2003) Flame retardants in the indoor environment—part II: release of VOCs (triethylphosphate and halogenated degradation products) from polyurethane. Indoor Air 3:49–52
8. NFPA 269 (2000) Standard test method for developing toxic potency data for use in fire hazard modeling, National Fire Protection Association, USA
9. Chow CL (2003) Importance of smoke toxicity in fire hazard assessment. Int J Eng Perform-Based Fire Codes 5(4):16–148
10. Beitel JJ, Beyler CL, McKenna LA, Williams FW (1998) Overview of smoke toxicity testing and regulations. Naval Research Laboratory Washington, DC. NRL/MR/6180-98-8128
11. Daniliuc A, Deppe B, Deppe O, Friebel S, Kruse D, Philipp C (2012) New trends in wood coatings and fire retardants. Eur Coating J 7(8):20–25
12. Levchik S, Weil ED (2000) Combustion and fire retardancy of aliphatic nylons. Polym Int 49:1033–1073
13. Östman B, Voss A, Hughes A, Hovde PJ, Grexa O (2001) Durability of fire retardant treated wood products at humid and exterior conditions review of literature. Fire Mater 25:95–104
14. Babrauskas V, Peacock R (1992) Heat release rate: the single most important cariable in fire hazard. Fire Saf J 18:255–272
15. Hirschler MM (1994) Fire retardance, smoke toxicity and fire hazard. In: Proceedings of Flame Retardants'94, British Plastics Federation Interscience Communications, 1/26-27, 1994, London, UK
16. Rowell RM, Susott RA, DeGroot WF, Shafizadeh F (1984) Bonding fire retardants to wood. Part 1. Thermal behavior of chemical bonding agents. Wood Fiber Sci 16(2):214–223
17. Hirschler MM (1992) Heat release from plastic materials. Chapter 12 a. In: Babrauskas V, Grayson SJ (eds) Heat release in fires. Elsevier, London, pp 375–422
18. Levin BC (1992) The development of a new small-scale smoke toxicity test method and its comparison with real-scale fire tests. Toxicol Lett 64–65:257–264
19. Kwon JH, Park SB, Ayrilmis N, Kim NH, Kwon SM (2012) Electromagnetic interference shielding effectiveness, electrical resistivity and mechanical performance of carbonized medium density fiberboard. J Compos Mater 47(16):1951–1958
20. Kercher AK, Nagle DC (2002) Evaluation of carbonized medium-density fiberboard for electrical applications. Carbon 40:1321–1330
21. ISO 5660-1 (2002) Reaction-to-fire tests—heat release, smoke production and mass loss rate—part 1: heat release rate (cone calorimeter method). International Organization for Standardization, Switzerland
22. ISO 5660-2 (2002) Reaction-to-fire tests—heat release, smoke production and mass loss rate—part 2: smoke production rate (dynamic measurement). International Organization for Standardization, Switzerland
23. ASTM E 1678 (1997) Standard test method for measuring toxicity for use in fire hazard analysis. American Society for Testing and Materials, Philadelphia, PA, USA
24. The Building Standard Law (2011) Testing method for incombustibility of internal finish material and element of buildings (in Japanese). Korea Standards Association, Seoul, Korea
25. KS F 2271 (2011) Testing method for incombustibility of internal finish material and element of buildings (in Korean). Korea Standards Association, Seoul Korea
26. Lee BH, Kim HS, Kim SM, Kim HJ, Lee BW, Deng Y, Feng Q, Luo J (2011) Evaluating the flammability of wood-based panels and gypsum particleboard using a cone calorimeter. Constr Build Mater 25:3044–3050
27. Park JS, Lee JJ (2008) Ignition and heat release rate of wood-based materials in cone calorimeter tests. Mokchae Konghak 32(2):1–8
28. Hashim R, Sulaiman O, Kumar RN, Tamyez PF, Murphy RJ, Ali Z (2009) Physical and mechanical properties of flame retardant urea formaldehyde medium density fiberboard. J Mater Process Technol 190:635–640