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Improvement on fire retardancy of wood flour/polypropylene composites using various fire retardants

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ABSTRACT

The addition of wood flour improves the mechanical properties of thermoplastics, but also increases the burning rate of neat plastics profoundly. To modify the flammability of wood-plastic composites (WPCs), various additive-type fire retardants such as ammonium polyphosphate (APP), melamine polyphosphate (MPP), and aluminum hydroxide were added to improve the fire performance of WPCs. Both UL94 flame tests and cone calorimetry were used to evaluate the fire performance of WPCs, and the results proved that the addition of 10 wt% APP lead to enhanced self-extinguishing properties. On the other hand, polypropylene with 30 wt% of APP did not achieve self-extinguish properties. The effective parameters in the cone calorimetry test to give self-extinguishing properties were discussed by comparing the results of the burning tests. It was presumed that the most important parameters for self-extinguishing of WPCs was an average heat release rate at initial stage of burning. The effect of fire retardants on the mechanical properties of WPCs was also investigated. The tensile strength and modulus of the composites decreased with the addition of fire retardants.

1. Introduction

Wood-plastic composites (WPC) combine the best properties of the neat components and thereby exhibit outstanding performance. Wood flour is a readily available and relatively inexpensive filler that can lower resin costs, improve stiffness, and act as an environmentally friendly alternative to petroleum-based plastics [1–6]. Moreover, WPCs have the advantage of good dimensional stability (i.e., lower water uptake and better durability against fungi and insects compared with wood) during their lifetime [1,2]. WPCs are thus used in construction engineering such as decking for terrace and balconies. However, there are two specific drawbacks with using WPCs: (1) adhesion between wood flour and thermoplastics, especially for nonpolar resin such as polypropylene (PP), is not enough to improve the mechanical properties of WPCs [3–5]. (2) The high flammability of WPCs, limits their applicability in various fields. The first drawback can be overcome by the addition of maleic anhydride grafted polypropylene (MAPP). Burning behavior of WPCs for decking boards in end-use condition are well studied by Seefeldt et al. [6]. They reported that increasing the wood filler content reduced the intensity of burning. Presence of water inside the WPC and addition of talc had a positive effect on burning behavior. To investigate the fire behavior of WPCs, cone calorimeter test has been widely applied. Peak heat release rate (PHRR), total heat release (THR), and time to ignition (IT) are important parameters to describe flammability of material.

To reduce the flammability of WPCs more, fire retardants can be added during the compounding process [7–20]. Halogenated compounds based on chlorine or bromine have been found to act as effective flame retardants; however, they produce toxic gases upon combustion, which creates handling and disposal problems. Stark et al. evaluated various non-halogenated fire retardant for use in wood four/polyethylene composites based on a cone calorimeter test [7]. They examined decabromodiphenyl oxide, magnesium hydroxide, zinc borate, melamine phosphate (MP), and ammonium polyphosphate (APP) as fire retardant of WPCs, and found that magnesium hydroxide and APP improved the fire performance of WPCs the most while a bromine-based fire retardant and zinc borate improved fire performance the least. Sain et al. and Suppakarn et al. applied magnesium hydroxide and zinc borate to improve natural fiber/PP composites [8,9]. Good point of using hydroxide metal as flame retardant is that it enhances flame

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retardancy of natural fiber/PP composites without sacrificing their mechanical properties [9]. However, there is no interaction between natural fibers and magnesium hydroxide during combustion; hence remarkable improvement of frame retardancy cannot be obtained. In contrast, APP interacts with wood or natural fiber during combustion. APP can cross-link carbonaceous structures because of the formation of polyphosphate. APP interacts with wood during combustion, owing to the carbonaceous structure of wood. This interaction leads to the thick and compact char which acts thermal and gas barrier against heat source [10–12]. Schartel et al. found that addition of APP or the combination of expandable graphite (EG) and red phosphorus (RP) reduced PHRR efficiently [10]. Bad point of APP is that it deteriorates the mechanical properties of WPCs the most in conventional flame retardants [7].

Nanocomposites constitute a new development in the area of flame retardancy. The addition of nanoclay can improve not only the fire performance but also the mechanical properties of composites [17–20]. Qin et al. reported that the addition of montmorillonite considerably increases the decomposition temperature of a PP matrix as a results of the barrier effect of silicates [13]. As mentioned earlier, addition of fire retardants reduces the flammability of WPCs, but it also decreases their izod impact strength and tensile strength [8,15]. On the other hand, nanoclays can improve both properties; however, their high costs restrict their use in only highly value-added products and not in commodity products such as construction materials. Since the use of fire retardants inevitably leads to an increase in the cost of WPCs, it is preferable to reduce the use fire retardants. It is important to know the minimum amount of fire retardant to satisfy the flame retardant demand.

The use of cone calorimetry can provide a wealth of information about the fire performance of WPCs In practice, however, the flammability of materials is evaluated based on UL94 flame tests, which is a standard method to test for the flammability of plastics proposed by Underwriters Laboratories, U.S.A. In fact, most of commercial product required V-0 classification in UL 94 flame tests. Self-extinguish properties in vertical burring test is required to satisfy V-0 classification. In the view point of manufactures, it is important to know which fire retardant is the most effective to reduce the flammability of WPCs, and the minimum amount of fire retardant to achieve self-extinguish properties. Increasing fire retardant loading level leads to not only increase of cost but also reduce of mechanical properties. It is preferable to use the effective fire retardant as small amount as possible.

In this study, we investigated three fire retardants, namely, aluminum hydroxide, APP, and melamine polyphosphate (MPP) to reduce the flammability of WPCs. The effects of wood flour on the burning behavior of WPCs were also investigated. We conducted a burning test based on the UL94 to investigate the performance of the three fire retardants and the minimum amount of fire retardant needed to achieve self-extinguish properties in WPCs. To interpret the results of UL 94 test, cone calorimetric analysis was carried out. Finally, tensile tests were performed to investigate the effect of fire retardants on the strength of WPCs.

2. Experimental methods

2.1. Materials

PP has been widely used for the production of WPCs because of its low density, high water and chemical resistance, and high cost-performance ratio. A high melt flow index (MFI) PP is preferable for reducing the flammability and improving the processability of WPCs [21], and here, a PP with a high MFI of 40 g/min (J108M, Prime Polymer Co., Ltd.) was selected. The wood flour (Lignoace α) was purchased from Juon in Japan. Wood flour used in this study was made from forest thinning materials of Japanese cedar through crashing, steaming, and grinding. The lignin content of the dry wood flour extract is approximately 25% based on the supplier's information. Other constituents of the wood flour are cellulose and hemi-cellulose. Aluminum hydroxide (H-42M, Showa-Denko), APP (Kinseimatec Co., Ltd.), and MPP (MPP-A, SANWA Chemical Co., Ltd.) were used as fire retardants in this study. For APP, the phosphates content is around 31 wt%, and the nitrogen content 14 wt%, according to supplier's information. No halogen-containing fire retardants were selected in order to develop environmentally friendly materials. The weight ratio of the fire retardants selected ranged from 5 to 10 wt%.

The fire retardation mechanisms of these retardants are different. Metal hydroxides such as aluminum hydroxide provide effective flame retarding effects by releasing a significant amount of water that they contain at high temperatures, thereby diluting the amount of fuel available to sustain combustion during a fire. Moreover, it also absorbs heat from the combustion zone. In contrast, APP is well known to reduce the flammability of oxygen- or nitrogen-containing polymer by generating char layer. The char layer acts as a barrier that will block heat and oxygen diffusion from the combustion zone. In polypropylene, it is necessary to combine APP with a carbonizing agent to generate the char. MPP undergoes endothermic decomposition above 350 °C, thus acting as a heat sink and cooling the combustion zone. MPP also aids in char formation, with the char shield reducing the amount of oxygen present to sustain combustion.

To improve the dispersion and adhesion of the wood flour filler, MAPP (Youmex 1010, Sanyo Chemical) was used as a compatibilizing agent. As the wood ratio in WPCs increases, the surface area of the wood flour increases. Therefore, the effective amount of MAPP depends on the amount of wood used. Here, we found the optimum amount of MAPP needed to improve the mechanical properties of WPCs was a wood:MAPP weight ratio of 100:7.

2.2. Preparation of wood flour/PP composite by the twin screw extruder method

A co-rotating twin-screw extruder (ZSK18, Coperion) with a screw diameter of 2 mm and a length-to-diameter ratio of 40 was used for all compounding. The standard compound screw was composed of conveying elements and kneading discs with a screw speed of 150 rpm and a throughput Q of 1 kg/h. The process temperature was set to 180 °C from the hopper to the die.

First, the wood flour and PP were dried in an oven at 80 °C for 24 h. Then, PP, MAPP, wood flour, and the fire retardant were dry mixed thoroughly before they were fed into the twin-screw extruder and compounded under the conditions mentioned above. The WPCs extruders were immediately quenched in water and then cut into strands before being chopped into granules and dried.

All specimens were injection molded into dumbbell-shaped bars using a single screw injection-molding machine (PLASTR ET-40V, Toyo Machinery & Metal) with a barrel temperature of 210 °C. An end-gated mold was used for molding dumbbell-shaped samples according to the standard JIS K7113. The thickness and width of the specimens are 4 and 10 mm, respectively. Tensile tests were conducted using these samples, while flammability tests, were conducted using striped specimens obtained by cutting both the ends of the dumbbell-shaped samples.

2.3. Thermogavimetric analysis (TGA)

To investigate the decomposition behavior of constituent materials used in this study, TGA analysis was conducted. The weight of each material during heating was measured using a DTG-60H instrument (Shimadzu Co.). The temperature was increased from room temperature to 600 °C at a heating rate of 5 °C/min in argon atmosphere.

2.4. Flammability tests

A flammability test based on the UL-94 standard is commonly applied to evaluate and classify the fire performance of a material. Therefore, a horizontal burning test and a vertical burning test was conducted to investigate the effect of fire retardants on the flammability of WPCs. In the horizontal burning test, the sample was held horizontally and a flame fueled by natural gas was applied to light one end of sample for 20 s. The height and angle of a flame with respect to the vertical direction were 10 mm and 30°, respectively. The time taken for the flame to reach from the first reference mark (20 mm from the end) to the second reference mark (80 mm from the end) was measured in this study. A wire sheet was held 10 mm away from the specimens to consider the effect of dripping, which is the downward fall of fire source. Prior to the test, the specimens were dried at 80 °C for 24 h. The tests were conducted at least three times for each specimen.

If the specimen showed incombustibility or self-extinguishing properties in the horizontal burning test, a vertical burning test was also conducted. Here, the sample was held vertically and a flame 20 mm in height was used to light one end of sample for 10 s. The distance between the end of the sample and the burner flame was maintained at 10 mm. After this, the burning time was measured. When the specimen combustion stopped, the sample was ignited again for 10 s to determine the class of the sample through the combustion time, dripping of sample, and burning state.

2.5. Cone calorimetry

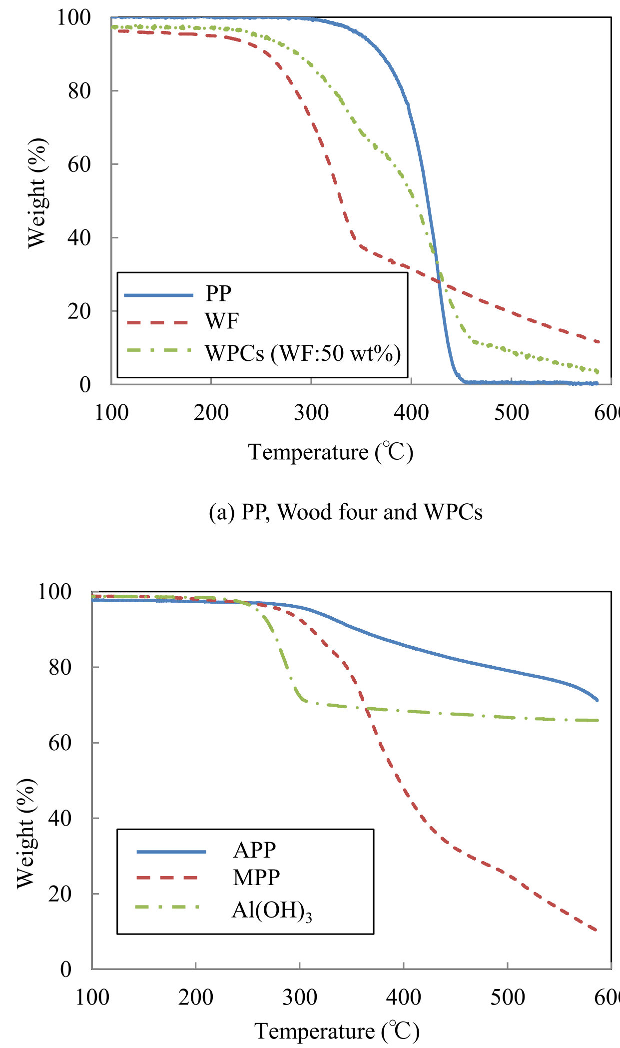
Cone calorimeter tests were performed on a Cone III combustion analysis system (Toyo Seiki Seisaku-sho Ltd.). The boards were fabricated using a hot press and samples with dimensions 100 × 100 mm were cut from the boards with a thickness of 3.3 mm. The samples were then wrapped in aluminum foil and placed in a horizontal orientation above a conical radiant electric heater located 25 mm above the samples. An external heat flux of 50 kW/m^2 was applied to the samples. From these cone calorimeter tests, the IT, HRR, and weight loss of the sample were observed and recorded. HRR is defined as the heat evolved from a specimen per unit time and is determined by the amount of oxygen consumed during burning.

2.6. Tensile tests

The tensile properties of the dumbbell-shaped PP/wood flour composites with added fire retardants were measured using a universal testing machine (AG-100kN, Shimadzu) operated at a constant crosshead speed of 1 mm/min. The average tensile strength was calculated by testing five samples.

3. Results and discussion

3.1. Thermal degradation of constituent



(a) PP, Wood four and WPCs

(b) Various fire retardants

Fig. 1. TGA results under argon atmosphere.

Fig. 1 shows the thermal degradation behavior of PP, wood flour, WPC, and fire retardants used in this study. The pure PP volatilized in a single step, from 300 °C to 450 °C, without char formation. The initial decomposition temperature of wood flour was lower than that of pure PP, which started at approximately 200 °C. It is well known that wood flour decomposes in the order of hemicellulose (200–300 °C), cellulose (300–400 °C), and lignin (200–900 °C) [22]. The sharp weight reduction around 300 °C was due to the decomposition of both hemicellulose and cellulose. The gradual weight reduction above 350 °C was due to the decomposition of lignin. Char residuals were observed after the thermal analysis of wood flour. The thermal decomposition behavior of the WPC was an average of that of PP and wood flour. No synergistic effects were found for the combination of wood flour and PP used in this study.

With respect to APP, a weight reduction is observed at 300 °C owing to the release of NH_3 and H_2O [23]. The decomposition of MPP also started at 300 °C owing to the volatilization of N_2 and NH_3. The vaporized melamine acted as an inert gas source, diluting the oxygen and fuel gases present at the point of combustion. The initial decomposition temperatures of MPP showed almost the same value with APP; however, the weight reduction of MPP was greater than that of APP. The decomposition of aluminum hydroxide started at 250 °C and resulted in Al_2O_3 and water. In this study, we ensured that the decompose temperature of fire retardants was less than that of PP, and therefore, the fire retardants work effectively during the decomposition of PP by decomposing before PP.

3.2. The flammability of WPCs with various fire retardants

Fig. 2 shows the effect of wood flour content on the horizontal burning rate of WPCs. It was found that the horizontal burning rate increased with increasing wood flour content. The specific heat of PP is 1.7–1.9 kJ/kg K and that of wood flour is 1.2 kJ/kg K [7]. PP has a higher specific heat, defined as the amount of heat energy required to raise the temperature of the unit mass by one unit of temperature. It means that the temperature of wood flour is easier to elevate than that in the case of PP. Wood flour also has a lower decomposition temperature than that of PP as shown in Fig. 1. Therefore, the burning rate of WPCs increased with the addition of wood flour. On the other hand, the heat release rate of wood flour was lower compared to PP (Fig. 3). Therefore, the addition of wood flour decreases the heat release rate of WPCs, and in turn, the burning rate of WPCs also decreases at a high wood flour content (40–60 wt%). In any case, the burning rate of WPCs was higher than that of PP. Addition of wood flour also accelerates the burning speed of PP.

Table 1 summarizes the burning rate and flame classifications for PP and WPCs with the three fire retardants. The addition of fire retardant, in each case, slightly decreased the burning rate of PP. Melting and dripping, which provide other ignition sources, were also observed for all PP samples. The addition of 10 wt% of fire retardant did not modify the fire performance of PP. In general, more than 30 wt% is required for any fire retardant to provide good self-extinguishing properties to thermoplastics [23,24]. We also confirmed that addition of 30 wt% APP gave self-extinguish properties to PP in horizontal burning tests, on the other hand it could not modify the burning behavior in vertical burning tests. Thus, PP including 30 wt% of APP was classified with a HB flammability rating. Here, less than 30 wt% of APP or MPP is not enough to form a char layer that can block heat and oxygen from the combustion zone.

In the case of WPCs, the horizontal burning rate was observed to decrease with the addition of any fire retardant. Both melting and dripping was not observed for any WPC sample. The addition of $Al(OH)_3$ slightly decreased the burning rate of WPCs. Note that we conducted the tests with other types of $Al(OH)_3$ and magnesium hydroxide ($Mg(OH)_2$) fillers. The results which showed the best fire performance in these types of fillers are listed in Table 1 for simplification. This type of filler cannot give self-extinguishing properties to the material system used in this study. For a WPC sample with 10 wt% APP or MPP, horizontal burning tests showed no increase in flame spread, thus showing good self-extinguishing

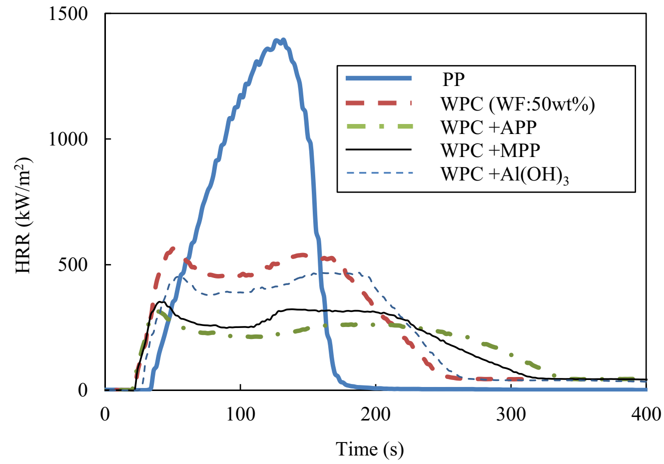


Fig. 3. HRR versus burning time for PP, WPC (WF = 50 wt%) and WPCs (WF = 50 wt%) with 10% fire retardant.

properties. We also conducted a vertical burning test for WPCs with APP or MPP. All samples with APP showed good self-extinguishing properties even though the samples were burned for 10 s twice. No dripping was observed during the tests. Therefore, this material can be classified with a V-0 flammability rating, which is the highest class in this test. In contrast, the flammability of WPC with MPP did not classify with a V-0 rating. The flame of WPC with MPP was glowed to the clamp of sample. It could not satisfy the conditions of V-2, the lowest class in the vertical burning test. Therefore, WPC samples with MPP fire retarding agents were classified as a HB. Both specimens created enough char during the test; however, the expansion rate after the test was different. The expansion rate of WPCs with APP after the horizontal burning test was 90% and that of MPP was 78%. APP could form thicker char layer during combustion compared to MPP.

It is worth noting that the addition of 10 wt% APP did not improve the fire performance of PP, on the other hand it could give excellent fire performance for WPCs, though the addition of wood flour facilitated the burning rate. A positive synergistic action was observed between wood flour and APP. As mentioned above, 30 wt % APP was not enough to form a charred layer in PP. In the case of WPC, there are many sources of char in wood flour. Therefore, 10 wt % APP was enough to provide a char layer that could restrain the spread of a flame. APP is capable of improving the fire performance

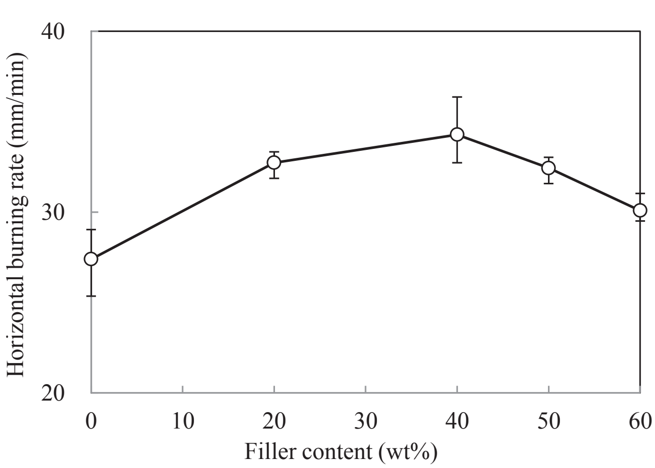


Fig. 2. Effect of wood flour content on horizontal burning rate of WPCs.

Table 1
Burning rate and flame classifications of PP and WPCs with fire retardants.

Composition based on weight (%)						Test results	
PP	WF	MAPP	Fire retardants			Average burning rate (mm/min)	Class based on UL94
			APP	MPP	$Al(OH)_3$		
100						27.4	HB
90			10			22.7	HB
70			30			Self-extinguish	HB
90				10		25.2	HB
90					10	27.5	HB
46.7	50	3.3				32.4	HB
41.7	50	3.3	5			22.2	HB
39.7	50	3.3	7			19.2	HB
36.7	50	3.3	10			Self-extinguish	V-0
41.7	50	3.3		5		22.5	HB
36.7	50	3.3		10		Self-extinguish	HB
41.7	50	3.3			5	22.2	HB
36.7	50	3.3			10	20.9	HB
58	30	2	10			21.2	HB

of WPCs. Stark et al., and Li et al. also reported that APP showed better fire retardant property compared to other fire retardants such as MPP, $Al(OH)_3$, and $Mg(OH)_2$ [7,13]. APP interacts with wood flour and yields a crosslinked ultraphosphate and a polyphosphoric acid with a highly crosslinked structure. On the other hand, there is no interaction between wood flour and metal hydroxides.

Owing to the interaction between wood flour and APP, the addition of wood flour can reduce the minimum amount of APP required to give good self-extinguishing property or V-0 class rating. The addition of 50 wt% wood flour can reduce the required amount of APP from 30 wt% to 10 wt%. This could potentially contribute to the mechanical properties and cost performance of WPCs. Note that in the case of WPCs with 30 wt% wood flour, the addition of 10 wt% of APP did not improve the fire performance class of WPCs as shown Table 1. This indicates that the minimum amount of APP needed to improve the fire performance of WPCs depends on the wood flour content. We also conduct various types of wood flour made of Japanese cedar to confirm the generality of the results, and found that the required amount of APP for WPCs (50 wt%) to achieve self-extinguishing properties was around 10–14 wt%, depending on a constituent or size of wood flour.

3.3. Cone calorimetry study

The cone calorimetry test based on the oxygen consumption principal was used to evaluate the fire performance of these materials. The HRR measured by cone calorimetry is a very important parameter in these tests as it expresses the intensity of a fire. From a reaction-to-fire point of view, a HRR 1 or 3 min from ignition as well as the PHRR and time of ignition give important information on the first stage of fire development [25,26]. We will use the experimental values obtained to compare them with the results of the burning test (UL94).

Representative HRR versus time curves for PP, WPC, and WPC with 10 wt% fire retardant are shown in Fig. 3. The HRR of PP gradually increased until a peak value was reached, which sharply decreased owing to the consumption of the material. The HRR of WPCs reached a peak value early during the test and then reached a second peak later in the test. All fire retardants reduced the PHRR of WPCs without changing the tendency of HRR curves.

Cone calorimetry results for PP, WPC, and WPC with all fire retardants are shown in Table 2. A higher IT and lower HRR are preferable to reduce the flammability of materials. The ignition time for WPC was found to be low compared to PP despite the addition of fire retardants. The lower specific heat of wood flour compared with PP means that less heat is required to start the combustion of wood flour. In addition, the decomposition temperature of wood is lower than that of PP, as shown in Fig. 1. These facts contribute to the lower IT and higher burning rate of WPCs compared to PP. The PHRR and average HRR were observed to decrease with the addition of wood flour. This is because wood flour had a lower peak HRR and average HRR than that of PP, placing the fire performance of WPC between PP and wood flour [7].

Table 2
Cone calorimeter results for PP, WPC and WPC with 10 wt% of fire retardant.

	IT[a] (s)	Peak HRR[b] (kw/m^2)	THR[c] (MJ/m^2)	Average HRR (kW/m^2)		
				60 s	180 s	Total
PP	31.6	1395	117	521	645	434
WPC (WF:50 wt%)	21.4	563	93.4	416	456	336
WPC + APP	19.6	312	78.9	230	235	136
WPC + MPP	20.4	352	98.6	262	284	83.7
WPC + $Al(OH)_3$	24.8	467	99	341	400	96.5

[a] Ignition time (IT).
[b] Heat release rate (HRR).
[c] Total heat release.

The addition of a fire retardant can reduce the PHRR of WPCs. In this study, aluminum hydroxide was found to increase the IT the most. This may be due to the high heat capacity of aluminum hydroxide. The addition of aluminum hydroxide was also found to contribute to the reduced burning rate of WPCs by releasing significant amount of water. However the latter cannot promote self-extinguishing properties. In terms of average HRR, WPCs containing APP performed better than WPCs containing aluminum hydroxide. Since the interaction between wood flour and APP can create a layer of char during combustion, APP can then reduce the HRR of WPCs the most. Overall, it seems that the PHRR and average HRR are dominant factors for determining the flammability of WPCs as indicated by Babrauskas et al. [25,26].

It is worth noting that although the difference between the HRR of WPCs with APP and WPCs with MPP was small (Table 2), the difference in flammability class was significant (V-0 and HB). In this average HRR range (230–280 kW/m^2), the flammability of WPCs was sensitive to the value of average HRR. If the average HRR is reduced to the value that cannot achieve the decomposition temperature of WPCs, WPCs have the self-extinguishing property. In this view point, it can be anticipated that average HRR at initial burning stage (60 s–180 s) is the most important parameters for flammability of WPCs.

Fig. 4 shows the weight-loss behavior of WPCs from cone calorimetry tests. Here, the fire retardants can be ordered in terms of reducing decomposition as follows: APP > MPP > $Al(OH)_3$. The weight percent residue after 400 s was 7 wt% for WPC, 12 wt% for WPC with $Al(OH)_3$, 19 wt% for MPP, and 22 wt% for APP. It was found that APP created the char reside the most after combustion. This results indicate that formability of char residue correlates with the flammability of WPCs.

To investigate the char formability of WPCs with various flame retardant, we conducted simple tests. The sample ($25 \times 25 \times 4$ mm) was placed in a furnace controlled at 550 °C. After ambient time, the sample was taken out from the furnace, and cut to measure the thickness of char layer. The thickness of char layer was measured using optical microscope. One to five tests were conducted for each sample. Fig. 5 shows the relationship between thickness of char layer and exposed time in a furnace. It is obvious that the presence of APP in WPC accelerates the char forming during thermal degradation. In contrast, $Al(OH)_3$ delays the stating time of char

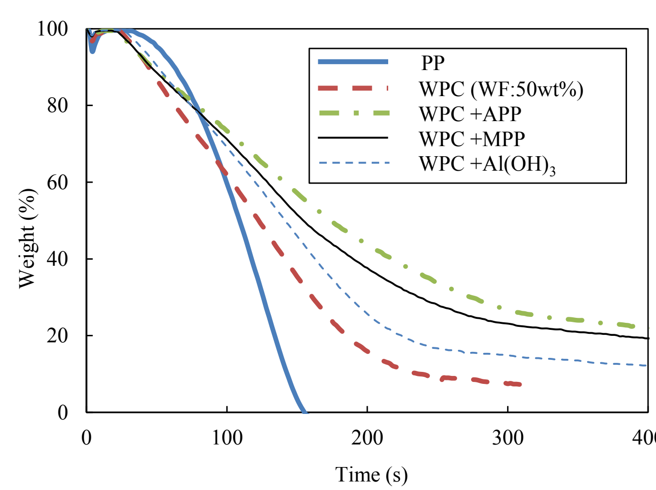


Fig. 4. Weight of sample versus burning time for PP, WPC (WF: 50 wt%) and WPCs (WF:50 wt%) with 10 wt% fire retardant.

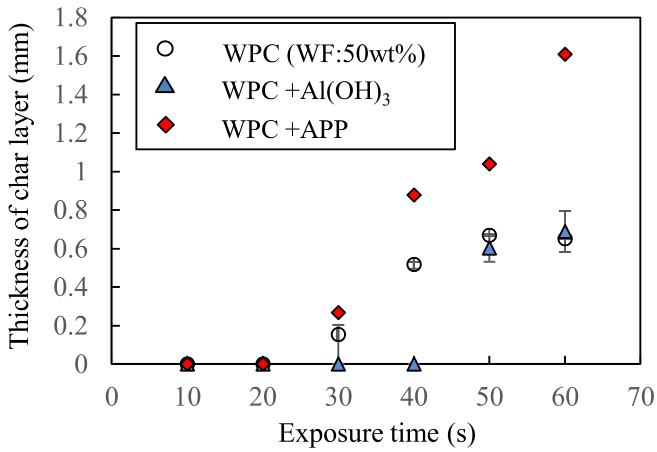


Fig. 5. Relationships between exposure time (550 °C) and the thickness of char layer.

forming due to the endothermic decomposition of $Al(OH)_3$. These results are consistent with the results of IT obtained by cone calorimetry test. It seems that there is close correlation between thickness of char and PHRR shown in Fig. 3. Formation of thick char layer reduces the PHRR by barrier properties of heat and gas. Addition of APP to WPC not only reinforces the char through crosslinking but also facilitates the char forming process during thermal degradation. This facts lead to the remarkable reduction in PHRR of WPCs. Since this mechanism is not specific to PP, also observed for PE [7], it opens the possibility of formulation self-extinguishing material from a large class of polymers.

3.4. Mechanical performance

Figs. 6 and 7 show the effects of the three fire retardants on the tensile strength and elastic modulus of WPCs. Here, a 50% strength improvement was observed with the addition of 50 wt% wood flour. We confirm that if MAPP was not added to a WPC, the strength of a WPC was lower than the strength of PP. Therefore, interfacial adhesion is important in this system. The addition of fire retardants decreased the tensile strength of WPCs. The addition of 10 wt% APP decreased the strength most, with a reduction ratio of approximately 14%. The results of the elastic modulus were similar to the tensile strength. The addition of APP decreased the modulus most, and the reduction ratio was found to be 8%. In summary, the

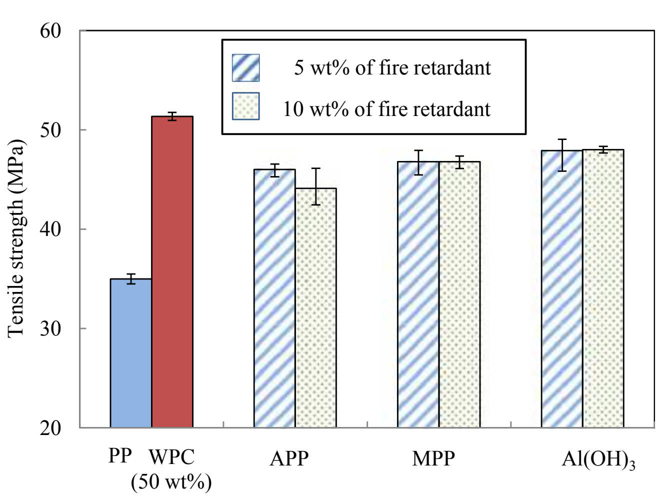


Fig. 6. Effect of fire retardants on the tensile strength of WPCs.

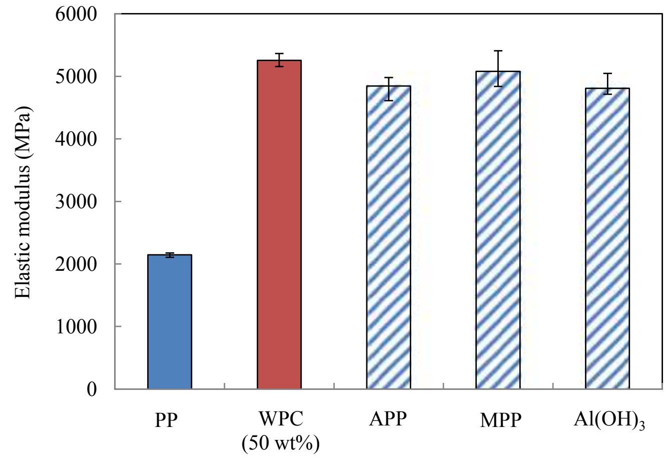


Fig. 7. Effect of fire retardants on the elastic modulus of WPCs. Amount of fire retardant is 5 wt%.

addition of 10 wt% APP has the potential for introducing good self-extinguishing properties in WPCs, though with a slight reduction in mechanical properties.

4. Conclusion

The effective use of fire retardants required to improve the fire performance of WPCs was investigated. The flammability of WPCs with various fire retardants was also evaluated using burning tests based on UL94 and cone calorimetry analysis. It was found that WPCs with 10 wt% APP showed the best fire performance at vertical burning, with a flammability class of V-0, indicating high self-extinguishing properties. In this study, 10 wt% was the minimum amount needed for a fire retardant to obtain a flammability class of V-0, with 50 wt% wood flour in WPCs. Our results indicate that the addition of wood flour reduced the amount of APP required to improve the fire performance of WPCs. This is due to the interaction between wood flour and APP. APP interacts with wood during combustion, owing to the carbonaceous structure of wood. This interaction leads to thick char layer which acts as thermal and gas barrier against heat source. This mechanism (interaction between APP and wood flour or natural fiber) will be applied to other polymer systems. Aluminum hydroxide was found to have the worst burning rate owing to the absence of interaction with wood flour. The addition of 10 wt% fire retardant, in each case, decreased the tensile strength of WPCs by around 7–14%.

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