EFFECT OF BORAX-BORIC ACID AND AMMONIUM POLYPHOSPHATE ON FLAME RETARDANCY OF NATURAL FIBER POLYETHYLENE COMPOSITES

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ABSTRACT

Wood fiber filled high density polyethylene composites (WPCs) were prepared using twin screw extruder and maleated polyethylene as a coupling agent. Bamboo fibers were initially treated with alkali (NaOH), boric acid - borax (Ba-Bx) and borax (Bx). The treated and untreated fibers were used in combination with ammonium polyphosphate (APP) to investigate their synergistic effects on thermal stability, flame retardancy and mechanical properties. Alkali pretreatment (5 % NaOH) of fibers showed significant improvement in performance of APP by increasing thermal stability in WPCs. The derivative thermogravimetric (DTG) results indicate significance of Ba-Bx in promoting char induction at lower temperatures (340 ºC) and thereby, improved the thermal stability in WPCs. Flammability decreased with addition of flame retardant additives. As compared to pure WPCs, composites containing APP 10 % / Ba-Bx 5 % exhibited maximum reduction in average heat release rate (HRR) by 69 %, peak heat release rate (PHRR) by 59 %, total heat released rate (THR) by 48 % and also increased time to ignition (TTI) by 62 %. However, no significant difference was found among the combinations i.e., APP with or without compounds towards reducing the flammability of WPCs. The strength properties also reduced significantly when boron compounds were added along with APP. In general, APP alone (15 %) is enough for imparting thermal stability and flame retardancy in WPCs.

Keywords: Ammonium polyphosphate, boric acid-borax, flammability, fire retardants, thermal properties, wood polymer composite.

INTRODUCTION

Wood plastic composites (WPCs) have made significant progress in thermoplastic industries and are finding application in interior automotive panels, garbage pails, crates, garden equipment, etc. (Hornsby *et al*. 1997). They have also made tremendous progress in exterior nonstructural or semi-structural building products such as door and window frames, siding, decking, cladding, floor and roof tiles, fencing, etc. (Schneider *et al.* 2000). These composites are known to possess excellent durability, dimensional stability, high rigidity, and relatively low density (Schneider *et al.* 2000, Ashori 2008). However, the potential use of WPCs is greatly restricted by their poor fire resistance property (Mouritz and Gibson 2006, Chapple and Anandjiwala 2010,

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Salemane and Luyt 2006). During a fire situation, the polymer burns and drips, leading to hazardous fire situations (Kozlowski and Wladyka-Przbylak 2008, Panagiotou and Levendis 1994). PVC is a self-extinguishing material, but they generate toxic gases while burning and create serious risk to life (Panagiotou and Levendis 1994). Therefore, from the point of view of fire safety, the users are insisting on fire resistant materials.

In order to impart flame retardancy in WPCs, many fire retardants (FR) chemicals have been introduced. Antimony based systems along with halogen compounds provide good flame retardancy, but their large-scale industrial use is restricted because of environmental issues (Kozlowski *et al.* 1999, Chen *et al.* 2006). Certain nano particles like nano clay, carbon tube, nano-SiO_2, TiO_2 and ZnO are used as FR additives for imparting flame retardancy in WPCs (Pan *et al.* 2014, Devi *et al.* 2013, Palza *et al.* 2010). However, the high price of nano additives makes their use unaffordable in commodity products such as the construction sector. Boron compounds have long been used as FR additives for wood and WPCs (Chen *et al.* 2006, Pan *et al.* 2014). Effectiveness of borax and boric acid has been widely reported (LeVan 1984, Nagieb *et al.* 2011). Borax reduces flame spread, but it promotes glowing, whereas, boric acid subdues glowing but has minimum effect on flame spread. Therefore, borax and boric acid are generally used together (Wang *et al*. 2004). Further, phosphorus-based FR (phosphoric acid) and their salts such as monoammonium phosphate and diammonium phosphate are the oldest and most commonly used FRs. Ammonium polyphosphate (APP) is considered as one of the most effective FR additives for WPCs. However, to achieve required flame retardancy, higher loading of APP is suggested, which increases cost and reduces material properties.

Although the effect of APP and boron-based FR on properties of WPCs has been studied extensively, studies on synergistic effect of APP and boric acid-borax (Ba-Bx) on FR properties of polymer are meager (Kurt *et al.* 2012). Kurt *et al.* (2012) have investigated the utilization of boron compounds (BCs) as synergists with APP in WPCs manufacturing, however, the method adopted in present study is different in terms of pretreating the bamboo fibers with BCs and using these fibers in combination with ammonium polyphosphate (APP) for investigating their combined effects on thermal stability, flame retardancy and mechanical properties of WPCs. Moreover, the effect of alkali (NaOH) pretreatment of fibers on performance of FR additives i.e., APP and BCs has not been studied. The objective of this study is to examine the feasibility of imparting flame-retarding functions to WPCs through alkali washing of wood fibers prior to their pretreatment with BCs i.e., boric acid - borax (Ba-Bx) and borax (Bx) and use these pretreated fibers along with APP as FRs. The aim of this work is to develop economically competitive WPCs with better flame retardancy.

MATERIALS AND METHODS

Materials

Reliance make high-density polyethylene (HD50MA180) was used in this study. Polymer density is around 0,950 g/cm³ and melt flow index is 20 g /10 min (at 190 °C and 2,16 kg load). APP (phase II, degree of polymerization >1000) was procured from Advance Inorganics, New Delhi. The coupling agent (CA) maleic anhydride grafted polyethylene M603 having melt flow index of 25 g/10 min was supplied by Dupont, India. Boric acid (Ba) and Borax (Bx) were used as boron compounds (BCs). Boric acid, borax, and sodium hydroxide were obtained from M/s Himedia. All the chemicals used for experiments were analytical reagent grade and were used without further purification. Freshly harvested wood biomass was processed to pass –60+80 mesh sieve. Oven dried wood fibers were used for experiments.

Processing

A part of oven dried wood fibers was chemically treated with sodium hydroxide (5 % w/w) for 4 hrs for surface activation and removal of impurities from the cellulose fibre and for increasing adhesion and compatibility of fibers to polymer matrix (Islam *et al.* 2012, Lee *et al.* 2009). The alkali treated fibers were washed with hot distilled water (four times) and oven-dried to constant weight at 80 ºC. One unit of Bx was mixed with one unit of Ba and dissolved in warm water. A part of wood fiber was soaked in 5 % aqueous solution of Ba-Bx (Jiang *et al.* 2011). The treated wood fibers were air dried for four days followed by oven drying to constant weight at 80 ºC. Oven dried HDPE, APP, CA, and wood fibers were used for further processing. The components were pre-mixed in a double-cone blender and then extruded using a twin-screw extruder. The screw speed of 150 rpm and temperature profile of 140 °C to 160 °C in the barrel and 180 °C near nozzle was maintained. The extruded composite granules were injection moulded into test specimens using a closed loop

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60 tonnes injection moulding machine (L & J make). The injection molding process parameters were 180 °C to 190 °C temperature and injection pressure of 100 bars. Compositions of wood fiber composites (WPCs) with and without flame retardant additives are summarized in Table 1.

Table 1: Experimental formulations studied (weight in grams).

Sample	Polymer	Fiber	CA	AO	Wax	APP	FT	Ba-Bx
Control	575	400	25	10	10	-	-	-
IFR-1	575	400	25	10	10	50	-	-
IFR-2	575	400	25	10	10	100	-	-
IFR-3	575	400	25	10	10	150	-	-
IFR-4	575	400	25	10	10	100	√	×
IFR-5	575	400	25	10	10	100	×	√
IFR-6	575	400	25	10	10	100	√	√
IFR-7	575	400	25	10	10	100	√	Bx

CA-Coupling agent; AO- Anti oxidant; APP-Ammonium polyphosphate; FT- Fiber treated with NaOH; Ba-Bx-Boric acid Borax; Bx-Borax

Testing

Flexural and tensile tests were conducted as per ASTM D790-15 (2015) and ASTM D638-14 (2014), respectively, using Shimadzu make model AGIS10, 10 kN universal testing machine. For tensile test, dumbbell shaped specimens were used (Type I) with span length of 100 mm. Crosshead speed was 5 mm/min. Flexural strength was determined using standard specimens (127 mm x 13,2 mm x 6,2 mm) and crosshead speed of 2,8 mm / min. Five replicates were evaluated for each treatment group. The thermal degradation properties were studied under nitrogen atmosphere. Thermo-gravimetric analysis (TGA) was carried out using TGA Q500 V20.2 Build 27. A known quantity of sample was placed in a platinum crucible and heated from ambient to 800 °C at heating rate of 10 °C/min and 60 ml/min air flow rate. Three replicates were evaluated for each treatment group. The thermal degradation profiles of the samples were derived by applying the derivative thermogravimetry technique (Haykira-Acma 2003). The flammability properties of WPCs were measured using cone calorimeter at CIPET, LARPM Bhubaneswar. The compounded specimens were compression moulded into standard size specimens (100 mm x 100 mm x 4 mm) for cone calorimeter test. Heat release rate was determined as per ISO 5660-1 (2015). An external heat flux of 50 kW / m^2 was applied. The flammability was also performed with limited oxygen index (LOI) as per ASTM D2863-19 (2019) and two replicates were evaluated for each treatment group. The data analysis was performed using SPSS statistical software. One way ANOVA was performed to understand statistically significant differences in each treatment group.

RESULTS AND DISCUSSION

Mechanical performance

The effect of FRs on strength properties of WPCs has been evaluated. The results are presented in Table 2. In case of WPC prepared with untreated fibers (pure WPC, IFR 1, IFR2 and IFR3) addition of APP had insignificant influence on flexural modulus or strength but tensile strength at 150 g of APP (IFR3) exhibited significant decline from 32 MPa to 26 MPa. This suggests that higher loading of APP has affected interfacial adhesion between fiber and polymer matrix. When treated fibers were used for making WPC along with APP, a marginal increase in flexural strength (FS) was observed which was statistically higher than with untreated fibers (IFR2 v/s IFR4). This shows the influence of alkali washing of fibers on FS of WPCs, added with APP. Ikhlef *et al.* (2012) studied the effect of alkali washing and reported improvement in strength properties of composite due to improved interfacial adhesion between matrix and cellulosic fiber. The addition of boron compound in the formulation resulted in significant loss in strength (both tensile and flexural) and flexural modulus of APP incorporated composites irrespective of fiber treatment. FS and FM of IFR1, IFR2, IFR3 and IFR4 samples doesn't change significantly. This shows that addition of APP alone (up to 15 %) doesn't reduce FS and FM of WPCs. However, significant reduction in FS (10 % to 14 %) and FM (6 % to 18 %) is seen in IFR5, IFR6 and IFR7 combinations where, BCs was added along with APP. Similarly, TS values are also found to be minimum in groups which has BCs in their compositions (IFR5, IFR6 and IFR7).

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Table 2: Tensile and flexural properties of WPC treated with fire retardants

Samples	Flexural Modulus (MPa)	Flexural Strength (MPa)	Maximum displacement (mm)	Tensile Strength (MPa)
Pure WPC	2520 (± 52)[c]	37 (± 1,0)[bcd]	3,3 (± 0,3)[b]	32 (± 0,4)[d]
IFR-1	2522 (± 62)[c]	38 (± 0,6)[d]	2,9 (± 0,3)[ab]	31 (± 0,1)[cd]
IFR-2	2408 (± 130)[bc]	36 (± 0,9)[b]	2,8 (± 0,1)[a]	31 (± 0,2)[cd]
IFR-3	2552 (± 53)[c]	36 (± 0,4)[bc]	2,8 (± 0,1)[a]	26 (± 0,8)[b]
IFR-4	2510 (±13)[c]	38 (± 0,3)[cd]	3,0 (± 0,1)[ab]	30 (± 0,4)[c]
IFR-5	2244 (± 99)[ab]	33 (± 0,5)[a]	2,6 (± 0,05)[a]	26 (± 0,3)[b]
IFR-6	2393 (± 4)[bc]	33 (± 0,1)[a]	2,7 (± 0,05)[a]	23 (± 2,0)[a]
IFR-7	2172 (± 10)[a]	32 (± 0,4)[a]	2,9 (± 0,2)[ab]	23 (± 0,1)[a]

Values are mean ± standard deviation of minimum triplicate determination. Values in column with different lowercase superscript letter are statistically significant ($p < 0,05$).

Wang *et al*. (1996) studied interaction of boric acid with polymer constituents of a wood/polystyrene composite material and reported that boric acid gets chemically bonded with wood components during manufacturing of composite materials. This may alter the efficiency of coupling agent in improving the compatibility of fiber with the polymer. Addition of APP in small quantity (up to 10 %) is not influencing tensile or flexural properties but higher loading (15 %) was indicating adverse impact. Kurt *et al.* 2012, found that 25% APP loading resulted in a very sharp decrease in TS value (49,04%) of WPCs, however, TS decreased between 18 % to 27 % in groups where BCs was added along with APP.

Thermal degradation under inert atmosphere

The results on thermal degradation of WPCs under inert atmosphere are summarized in Table 3. The pyrolysis of biomass can be divided into three different zones i.e., moisture evaporation, initial devolatilisation and major devolatilisation zone (Kumar and Chandrashekar 2014). Figure 1 shows that DTG curve of wood fibers, WPCs and APP. The initial weight loss, between 40 °C to 100 °C is mainly due to removal of moisture and lighter volatiles. After moisture evaporation, weight loss resulting at 150 °C to 350 °C is attributed to thermochemical decomposition and subsequent de-volatilization of samples (Haykira-Acma 2003, Kumar *et al.* 2021). The pure APP showed one sharp decomposition peak (T_{peak1}) at 200 °C with initial devolatisation temperature at 110 °C. During initial thermal degradation, mainly ammonia and moisture escapes as volatiles from APP. The major decomposition temperature of APP ranges from 550 °C to 650 °C, with T_{peak2} of 648 °C, which is mainly due to the generation of highly cross-linked pyro/polyphosphoric acid (Stark *et al.* 2010). The residue char in pure APP at 500 °C and 700 °C was around 63 % and 19 %, respectively. Figure 2 shows the DTG curve of WPCs with and without APP. A clear shift in major devolatisation temperature towards higher side is observed by increasing the amount of APP in WPCs Figure 2. For pure WPC, major devolatilization temperature (T_{MD}) ranged from 350 °C to 480 °C. T_{MD} shifted to higher temperature range (385 °C to 520 °C) with addition of APP. The shift in T_{MD} to higher temperature range indicates towards thermal stability provided by APP (Table 3). Among IFR1, IFR2 and IFR3 samples, highest T_{MD} was observed in IFR3 samples. For IFR3, T_{MD} ranged from 420 °C to 520 °C, with T_{peak2} of 488 °C. The initial devoaltisation temperature (T_{ID}) ranged from 190 °C to 320 °C in IFR1, IFR2, IFR3 and IFR4 samples. T_{ID} shifted towards higher temperature (200 °C to 340 °C) when BCs are added with APP as FRs (IFR5, IFR6 and IFR7) Table 3.

Table 3: TGA under pyrolysis (N_2) conditions.

Sample	Initial devolatisation temperature range (ºC)	T Peak1 (ºC)	Char devolatisation temperature range (ºC)	T peak2 (ºC)	Maximum rate of weight loss at peak temperature (mg/min)	Residue (%) at 500 ºC	Residue (%) at 700 ºC
Biomass	210-330	300	360-470	410	0,205	2,0	1,2
Pure WPCs	200-350	330	350-480	474	1,772	12,3	1,4
IFR-1	190-320	290	385-500	471	2,047	18,4	5,7
IFR-2	190-320	290	385-500	479	1,650	20,7	7,3
IFR-3	190-320	300	420-520	488	1,094	23,3	12,5
IFR-4	190-320	280	380-500	473	0,857	20,7	8,0
IFR-5	200-330	300	340-510	484	1,043	24,1	10,5
IFR-6	200-330	310	340-510	467	0,922	22,6	9,5
IFR-7	200-340	330	340-510	481	1,156	18,1	7,7
IFR-8*	110-220	190	550-660	648	2,052	62,7	19,5

* IFR-8- Pure APP

For IFR3, char residue at 500 ºC and 700 ºC was 23 % and 13 %, respectively. Figure 3 shows the DTG curve of neat WPC, IFR2 and IFR4 samples. Among these combinations, maximum weight loss at peak temperatures (T_{peak2}) was 1,8 mg/min, 1,7 mg/min and 0,9 mg/min in pure WPC, IFR2 and IFR4, respectively (Table 3). The rate of weight loss indicates the reactivity of the samples. IFR4 showed lowest rate of thermal degradation i.e., 0,9 mg/min (Table 3). Figure 4 shows DTG curve of neat WPC, IFR4 and IFR6 samples. T_{MD} ranged from 380 ºC to 500 ºC in IFR4, whereas, it ranged from 340 ºC to 510 ºC in IFR6 (Table 3). This shift in T_{MD} towards lower side (340 ºC) in IFR6 sample can be attributed to early charring in WPC, caused by boric acid. Wang *et al.* 2004 concluded that boric acid catalyzes the dehydration and other oxygen-eliminating reactions of wood at a relatively low temperature (approximately 100 ºC - 300°C) by catalyzing the isomerization of the newly formed polymeric materials and by forming aromatic structures, which contributes partly to the effects of boric acid on promoting the charring and fire retardation of wood. Figure 4 confirms the significance of boric acid in promoting char formation at lower temperatures. Figure 5 shows DTG curve of WPC, IFR6 and IFR7 samples. Among IFR6 and IFR7 samples, rate of weight loss at T_{peak2} was found to be minimum (0,74 mg/min) in IFR6 samples. Further, the char residues in IFR6 and IFR7 at 500 ºC was 23 % and 18 %, respectively. This shows that char residue with higher thermal stability is formed with Ba-Bx/APP, as compared to borax with APP. The overall result shows the usefulness of alkali washing of fibers and use of BCs as synergist in combination with APP for obtaining improved thermal stability in WPCs.
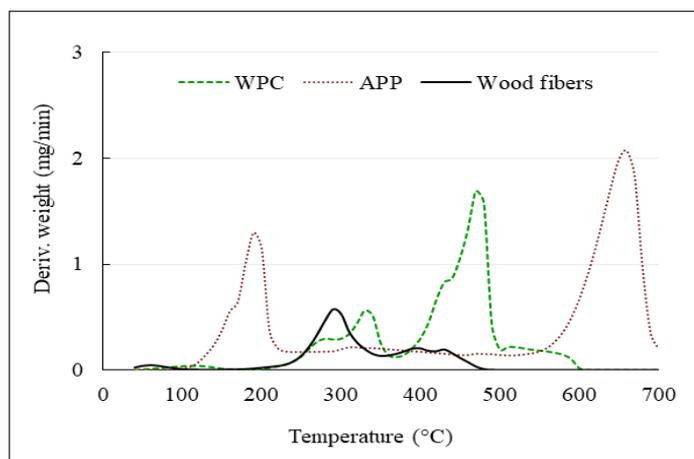
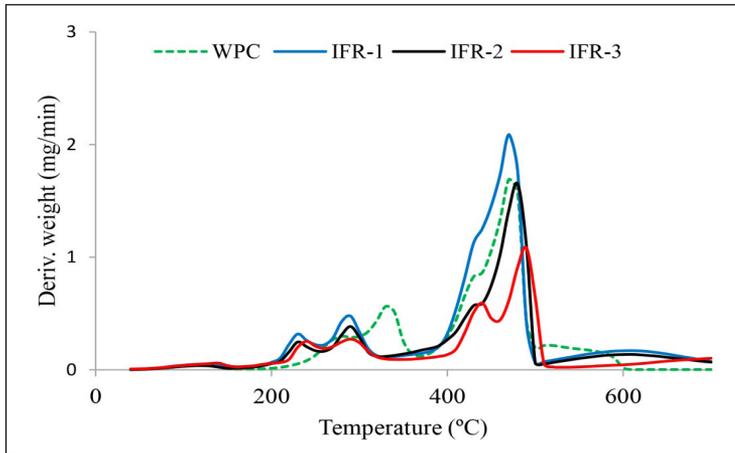**Figure 1:** DTG curve of WPC, APP and Wood fibers.

Figure 2: DTG curve of WPC, IFR1 (APP 5 %), IFR2 (APP 10 %) and IFR3 (APP 15 %) samples.
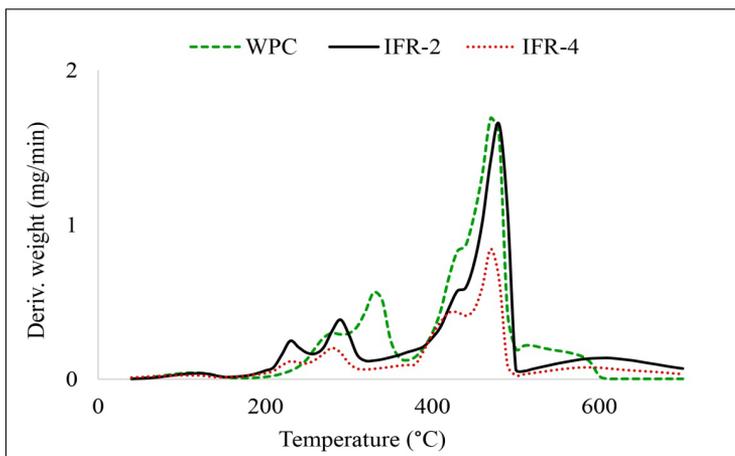

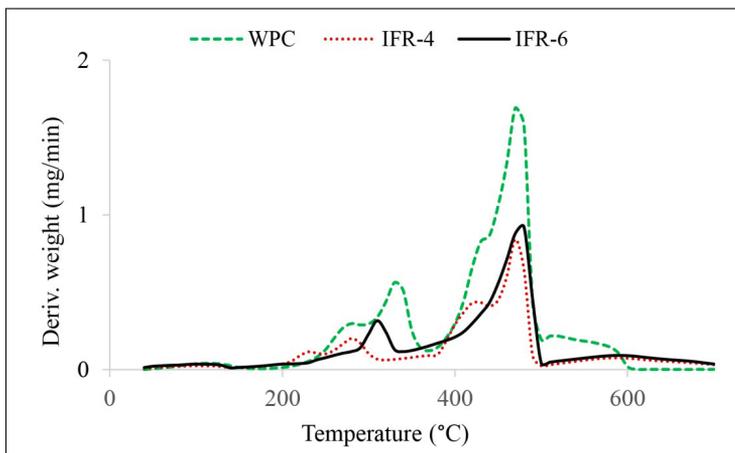**Figure 3:** DTG curve of WPC, IFR2 (APP 10 %) and IFR4 (APP 10 %+ Fibers treated with NaOH).

Figure 4: DTG curve of WPC, IFR4 (APP 10 % + NaOH treatment) and IFR6 (NaOH treatment + APP 10 % + Ba-Bx).
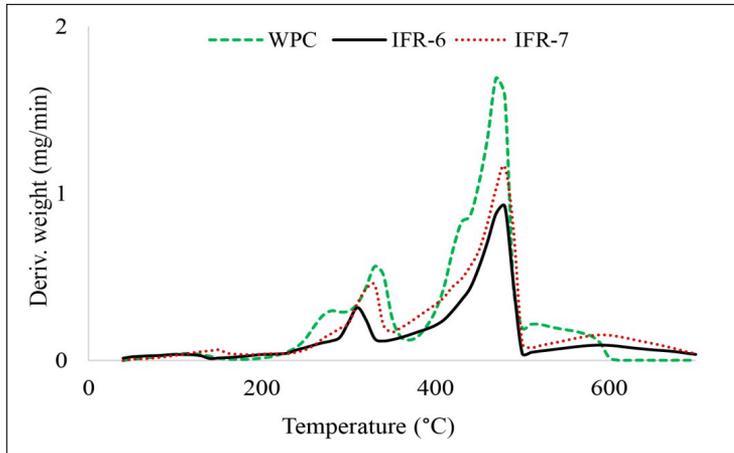
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Figure 5: DTG curve of WPC, IFR6 (NaOH treatment + APP 10 % + Ba-Bx) and IFR7 (NaOH treatment + APP 10 % + Bx).

Flammability properties

The flammability properties of WPCs (with and without flame additives) were determined by cone calorimeter and LOI tests. The results on average heat release rate (HRR), the peak HRR, total heat release rate (THR), time to ignition (TTI), time to flame out (TTF), mass loss rate (MLR) and limited oxygen index (LOI) are summarized in Table 4.

Table 4: Cone calorimeter and LOI results of WPCs with and without flame additives

Sample code	Average HRR (kW/m^2)	Peak HRR (kW/m^2)	THR (MJ/m^2)	TTI (s)	TTF (s)	MLR (g/s)	LOI (%)
WPC	196 (±25)[c]	457 (±37)[d]	64 (± 2)[d]	13 (±4) NS	297 (±20)[a]	19 (±3)[e]	16,1 (±0,1)[a]
IFR-1	125 (±11)[b]	370 (±23)[c]	57 (± 2)[cd]	12 (±7) NS	320 (±46)[a]	15 (±1)[cd]	16,8 (±0,2)[b]
IFR-2	110 (±7)[b]	353 (±15)[c]	56 (± 2)[c]	13 (±1) NS	347 (±34)[ab]	13 (±1)[bc]	16,9 (±0,1)[b]
IFR-3	80 (±7)[a]	235 (±7)[b]	52 (± 6)[c]	20 (±1) NS	453 (±40)[c]	8 (±1)[a]	19,2 (±0,1)[e]
IFR-4	64 (±1)[a]	196 (±26)[ab]	42 (± 3)[b]	16 (±1) NS	457 (±71)[c]	12 (±0,7)[abc]	17,9 (±0,1)[d]
IFR-5	64 (±1)[a]	186 (±0,6)[ab]	44 (± 3)[b]	20 (±1) NS	401 (±23)[bc]	10 (±1)[ab]	17,7 (±0,1)[d]
IFR-6	60 (±3)[a]	186 (±4)[ab]	33 (± 0,3)[a]	21 (±3) NS	332 (±9)[ab]	18 (±0,3)[de]	17,3 (±0,1)[c]
IFR-7	59 (±1)[a]	179 (±0,4)[ab]	32 (± 0,5)[a]	18 (±3) NS	300 (±6)[ab]	20 (±0,1)[e]	16,2 (±0,1)[a]

Value in parenthesis is standard deviation. Values in column with different lowercase superscript letter are statistically significant (p<0,05).
NS: Not significant
THR (MJ/m^2): Total heat release
TTI (s): Time to ignition
TTF (s): Time to flame out
MLR (1000 mg/s): Mass loss rate

The best result on LOI was seen with IFR3 (Table 4). Compared to pure WPCs, LOI was increased by 19 % in IFR3. All FRs showed positive influence on flame properties of WPCs. Peak HRR decreased from 457 kW/m^2 to 179 kW/m^2, which is approximately 61 % lower than pure WPCs. Average HHR and peak HRR (kW/m^2) in IFR2 and IFR4 combinations decreased from 110 and 353 to 64 and 196, respectively. Compared to pure WPC, higher reduction in HRR was seen in IFR4 (67 %) than IFR2 (44 %). This shows alkali washing enhances performance of APP decreasing HRR in WPCs. The order of decrease in average HHR (kW/m^2) is as follows; Pure WPC = 196 > IFR1 = 125 > IFR2 = 110 > IFR3 = 80 > IFR4 and IFR5 = 65 > IFR6 = 60 > IFR7 = 59 (Table 4). Through IFR6 and IFR7 combinations, maximum reduction in average heat release rate (HRR) was by 69 %, peak heat release rate (PHRR) by 59 %, total heat released rate (THR) by 48 % and time

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to ignition (TTI) was increased by 62 % as compared to pure WPCs. However, the statistical analysis indicated no significant difference among different combinations (IFR3, IFR4, IFR5, IFR6 and IFR7) towards reducing HRR in WPCs (Table 4). This shows that APP (15 %) is equally effective in reducing HRR as it is with combination of BCs along with APP. THR (MJ/m^2) reduced significantly with addition of FRs (Table 4). The result indicated significant increase in TTF in IFR3 and IFR4 samples (Table 4). This shows that 15% APP is appropriate amount for achieving effective flame retardancy in WPCs. THR decreased from 64 MJ/m^2 to 32 MJ/m^2 in IFR7, which is approximately 50 % lower than pure WPC. Wang *et al.* 2004 found that during combustion, borates form an impenetrable glass coating on a materials surface and restricts the supply of oxygen which prevents further propagation of flame from one part to another. The FRs combination showed no significant difference in prolonging the TTI during fire (Table 4). The most delayed ignition was in IFR6, where TTI is prolonged by 62 %, as compared to pure WPC. The same may be attributed to the positive impact of Ba-Bx which promotes early char formation in samples during fire. During combustion, borax suppresses flame spread but promotes glowing. Boric acid, on the other hand, increases the rate of depolymerization of cellulosic fibers and enables char production at considerably lower temperature (120 ºC to 180 °C) and suppresses glowing (Shafizadeh 1984). It also prevents the flame spread to some extent by releasing water (Shafizadeh 1984). Table 4 shows average MLR of WPCs with and without the flame additives. It is evident that the incorporation of FRs decreases the MLR of WPCs during combustion. For IFR3, the average MLR decreased most from 19 g/s to 8 g/s, which is approximately 58 % lower than that of neat WPC (Table 4). This shows that APP (15 %) is most effective in reducing average MLR in WPCs.

CONCLUSIONS

Effect of BCs and APP on flame retardancy, thermal stability and mechanical properties in WPCs have been investigated. Prior to its pretreatment with BCs, wood fibers were washed with NaOH. Alkali washing of wood fibers showed positive influence on flexural strength, thermal stability and HRR of WPCs. The addition of BCs with APP, initiated early char formation in WPC. Best results on thermal stability in WPC were obtained under condition i.e., NaOH 5 % / Ba-Bx 5% / APP 10 %. Second best result was with addition of 15 % APP alone, wherein, major devolatilization temperature shifted to higher temperature range i.e., 385 ºC - 520 ºC. The combination i.e., alkali washing of fibers/BCs/APP also showed better flame retardancy in WPCs, leading to improvement in peak HRR, THR and TTI. However, the best results on MLR, TTF and LOI was obtained by using APP (15 %) as FR. Keeping in view the above results on thermal stability and flame retardancy, the appropriate combination recommended for further research is NaOH 5 % / Ba-Bx 5% / APP 15 %. The strength properties of WPCs reduced significantly on adding BCs in the composition. In general, the effect of combination of Ba-Bx and APP leads to better thermal stability and flame retardancy in WPCs.

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