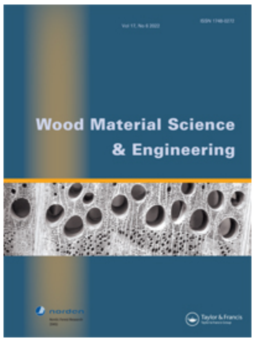

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ORIGINAL ARTICLE

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The effect of partial substitution of polyphosphates by aluminium hydroxide and borates on the technological and fire properties of medium density fibreboard

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ABSTRACT
Aim of this study was to evaluate the effect of aluminium hydroxide and borates, separately or combined with ammonium polyphosphate (APP), upon the technological and fire properties of medium density fibreboard (MDF). Fire resistant MDF was fabricated in the laboratory from Scots pine (*Pinus sylvestris* L.) fibres bonded with a high molar ratio melamine-urea-formaldehyde resin. Overall, 24 h-swelling and water absorption properties of the treated boards were improved or remained unchanged compared to untreated ones. On the contrary, the internal bond strength (IB) of the fibreboards was significantly reduced up to 48%. The fire properties of the fibreboards were assessed by the determination of limiting oxygen index and cone calorimetry. As expected, the tested fire-retardants improved the fire resistance of the boards. Furthermore, the combination of aluminium hydroxide with ammonium polyphosphate considerably upgraded the fire retardancy while the incorporation of borates into APP showed much weaker effects.

Abbreviations: EHC: effective heat of combustion; FIGRA: fire growth rate index; HRR: heat release rate; LOI: limiting oxygen index; MARHE: maximum average rate of heat emission; MDF: medium density fireboard; $pHRR_I$: first peak in HRR curve; $pHRR_{II}$: second peak in HRR curve; TFO: predicted time to flashover; THR: total heat release; TTI: time to ignition; RtFC: predicted reaction to fire class

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Polyphosphates; fire retardancy; medium density fibreboard; aluminium hydroxide; borax; boric acid

Introduction

Wood, due to its organic nature, is a combustible material. At temperatures higher than 225–275°C, wood pyrolysis and flame combustion is initiated (Hakkarainen *et al*. 2005) while carbonisation occurs between 500°C and 800°C. The combustion of wood-based panels such as fibreboards could potentially create life threatening conditions in residential buildings. To improve fire protection of wood and wood composites, fire-retardants (FRs) are commonly used (LeVan and Winandy 1990, White and Sweet 1992, Pizzi and Mittal 2003). Nowadays, this practice is very common in the building sector because stringent fire safety regulations are in effect throughout Europe (Dunky 2003, Ayrilmiş 2007, Mantanis *et al*. 2019). In wood-based panels industry, a variety of compounds are utilised, in dry or liquid form, to produce fire-resistant particleboard, oriented strand board (OSB), medium density fibreboard (MDF) and plywood (Dunky 2003, Winandy *et al*. 2008, Mazela and Broda 2015).

Usually, fire-resistant wood-based panels are produced throughout the use of ammonium polyphosphates, mono-ammonium and diammonium phosphates, boric acid, sodium tetraborate decahydrate (borax), aluminium sulphate, zinc borate, urea, guanyl-urea phosphate and other compounds (Tsunoda *et al*. 2002, Dunky 2003, Pizzi and Mittal 2003, Gao *et al*. 2006, Sun *et al*. 2012, Guo *et al*. 2018, Mantanis *et al*. 2018, Esmailpour *et al*. 2019, Tsolakis and Lykidis 2019, Lin *et al*. 2020a, 2020b, Taghiyari *et al*. 2021a, 2021b). FR additives for particleboard and OSB are mainly applied as small particles(approx. 200–600 µm)while for MDF, hardboard and plywood production, aqueous solutions or suspensions are used. Specifically, in the case of MDF, such compounds are sprayed directly on the fibres within the blowline in the form of a solution or dispersion of e.g. 50–60% solids content (Mantanis 2002). It is also suggested that wood fibres should be sprayed with FR compounds prior to resin spaying (Alexandropoulos *et al*. 1998, Liu *et al*. 2006).

Forthcoming changes in the European legislation may lead to the exclusion of boric acid in several wood applications including fire-protection. Moreover, since 2006, the use of halogen-based compounds in the industrial sector of wood products in Europe is prohibited (European Commission 2006). Nevertheless, borates are still used as FRs due to their smoke suppressing properties (LeVan and Tran 1990, LeVan and Winandy 1990, Wang *et al*. 2002, Dunky 2003). Borax and boric acid are commonly used since they can reduce surface flame spread and enhance carbonisation (LeVan and Tran 1990, LeVan and Winandy 1990, Tondi *et al*. 2014). Boron-based compounds are preferred due to their thermal resistance (Tsunoda *et al*. 2002, Wang *et al*. 2004, Özdemir

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and Tutuş 2013). Over the past few years, ammonium polyphosphates (APP) have been commonly used as FR additives, because they are very efficient and present low toxicity (Watanabe *et al.* 2009, Wang *et al.* 2017, Mantanis *et al.* 2019). APP based FRs are used as aqueous coatings applied by spray, dip, or pressure treatments. APP induces a carbon layer effect on the combustion behaviour of materials blocking the access of oxygen and heat, therefore inhibiting further combustion (Watanabe *et al.* 2009). However, APPs are acidic, present low hydrolytic stability, and can also lead to the increased smoked generation during combustion (Wang *et al.* 2017). Consequently, they are typically combined with other compounds such as boric acid, borax, magnesium sulphate, ferric sulphate, or potassium alum (White and Sweet 1992, Wang *et al.* 2002, Wang *et al.* 2004). These additives result in favourable smoke properties and hinder corrosive side effects over a long period of time (Mazela and Broda 2015). Aluminium hydrates(e.g. aluminium hydroxide) are low-cost, halogen free FR's that have also been tested in similar applications, but publications regarding their use in conjunction with borates and APP are limited (Sulaiman *et al.* 2008, Hashim *et al.* 2015, Liang *et al.* 2017).

Therefore, the purpose of the work was to investigate the effect of aluminium hydroxide and borates upon the physical and mechanical properties as well as the fire properties of ammonium polyphosphate-treated medium density fibreboards which were fabricated in the laboratory. The fire properties of the fibreboards were assessed by well-known methods such as limiting oxygen index (LOI) and cone calorimetry.

Materials and methods

Fibres and binder

For the production of fibreboards, Scots pine (*Pinus sylvestris* L.) fibres were supplied by Kronospan Bulgaria EOOD (Veliko-Tarnovo, Bulgaria) and sieved to acquire a suitable size between 0.5 and 1 mm. Then, the fibres were oven dried at 75°C for 24 h to reach a target moisture content of approx. 7%. A commercial MUF resin was used as a binder. The most important properties of the resin were: formaldehyde/urea (F/U) molar ratio: 1.55, melamine content: 20%, solids content: 64.7%, viscosity: 240 cp, gel time: 54 s, water tolerance: 1/0.8, and pH: 9.10. The gluing factor was 21% (per dry fibres), in all the cases. No hardener was used when FRs were applied, while wax emulsion (1 wt% perdry fibre mass) was applied in all produced fibreboards.

Fire retardants

Three halogen-free FRs, prepared in Laboratory of Wood Science and Technology (Karditsa, Greece), were used in this work (Table 1). The first fire retardant (FR-A) was formulated using a 50% (w:w) solution of APP (type: APP-W-303) provided by Century Multech (NY, USA). Solution pH was 6.70 and density was 1.30 g/cm^3. APP is an inorganic salt of ammonia and polyphosphoric acid at short chains (<20), having a P_2O_5 content of not less than 60%.

Table 1. Fire retardants tested in this research work.

Denotation	A	B	C
Fire retardant	Standard FR (100% ammonium polyphosphates)	80% A +20% aluminium hydroxide	80% A +20% boric acid and borax (mix 1:1)
Solids content, %	50	50	50

The second FR (FR-B)was prepared in the laboratory by joining together FR-A (80% on dry mass) and aluminium hydroxide, $Al(OH)_3$ (Penta S.A., Praha, Czech Republic) at 20wt%per dry FR mass. FR-B had a density of 1.31 g/cm^3, solids content of 50%, and pH of 6.30. FR-B was prepared in the form of suspension and sprayed directly on the dry fibres, after adequate mixing.

The third fire retardant (FR-C) composed of FR-A (80 wt% per dry mass) mixed with pure boric acid (Penta S.A., Praha, Czech Republic) and disodium tetraborate decahydrate (borax), in a mass ratio of 1:1. Borates were added at a 20% level based on the dry FR mass.

Loading of fibres with fire retardants was 12 wt% per dry fibre mass for all cases. Untreated (control) panels were also produced without the addition of FRs.

Fabrication of fibreboards and evaluation of board properties

Laboratory-scale fibreboards were produced in the facilities of the Department of Mechanical Wood Technology, University of Forestry (Sofia, Bulgaria). The target dimensions and density of boards were 350×350×10 mm^3 (length × width × thickness) and 800 kg/m^3, respectively. Air-dry fibres having a moisture content of approx. 7–8%, were blended with each FR mixture using an airless spray gun. Several minutes later, MUF glue mix (at 50% solids content) was slowly spayed on the fibres and blended altogether. The gluing factor was 21 wt% per dry fibre mass, for all cases. The moisture content of the fibres after blending was 27–28%.

Consequently, the glued fibres were gently separated with a shredder and oven dried at 80°C,under continuously circulating air, until they reached a moisture content of 12–13%. Then, a fibre mat was formed and cold pre-pressed in a conventional single opening hydraulic laboratory press (PMC ST 100, Italy).

The pre-pressed mat was hot-pressed at a pressure of 4.0 MPa. The total press time was 140 s (i.e. press factor: 14 s/mm). All treated and untreated fibres were pressed to 10 mm final thickness, at a press temperature of 220°C. A total of sixteen fibreboards were fabricated in this work. Then, the fibreboards were conditioned in a climate chamber (60 ± 5% relative humidity and 23 ± 2°C) for three days.

Determination of physical and mechanical properties of fibreboards was carried out in accordance with the European standards (Table 2) at the facilities of the Department of Mechanical Wood Technology. The mass of the test samples was measured using a precision laboratory balance Kern (Kern & Sohn GmbH, Balingen, Germany) with an accuracy

Table 2. Dimensions and number of specimens for the tests carried out in this work.

Property	Test Norm	Specimen dimensions (mm)	Number of specimens
Density	EN 323	50 × 50	12
Moisture content	EN 322	20 × 20	12
Internal bond strength	EN 319	50 × 50	12
Thickness swelling in water (24 h)	EN 317	50 × 50	12
Water absorption (24 h)	EN 317	50 × 50	12
Desiccator test	EN ISO 12460-4	150 × 50	3
Fire test – Reaction to fire	ISO 5660-1	100 × 100	3
Limiting oxygen index	EN ISO 4589-2	10 × 10 × 150	5

of 0.01 g. Dimensions of the samples were measured using digital calipers with an accuracy of 0.01 mm. Thickness swelling and water absorption were measured after 24 h of immersion in water. The internal bond strength of the fibreboards was determined using a universal testing machine Zwick/Roell Z010 (Zwick/Roell GmbH, Ulm, Germany). Formaldehyde emission was determined at the Laboratory of Wood Science and Technology (Greece) according to EN ISO 12460-4 (2012) (Desiccator test).

LOI tests

Fire tests were performed using the Limiting Oxygen Index (LOI), according to the European standard EN ISO 4589-2 (2017). LOI test was carried out on 5 conditioned specimens per treatment. The technique evaluates the influence of FRs on the fire properties of treated fibreboard in a small scale (White 1979). It is normally conducted by passing a mixture of oxygen and nitrogen over burning a specimen, until a critical level of oxygen is reached. This exactly corresponds to a value of LOI. Typically, LOI values of approx. 21% are reached for natural wood and untreated fibreboard specimens (White 1979, Campo 2008). In any case, higher LOI values correspond to enhanced fire resistance, especially when the value exceeds the threshold of 50% (Campo 2008).

Fire performance

Fire performance of fibreboards was determined by the cone calorimeter (Dual Cone Calorimeter; Fire Testing Technology Ltd., East Grinstead, UK). Both the cone calorimeter and the testing procedure followed the ISO 5660-1 standard (2015). The heat flux from cone heater to the sample surface was 50 kW m^{-2}. Dimensions of the samples were: 100 mm × 100 mm × 10 mm (length × width × thickness). Both the heat flux from the cone heater and dimensions of the samples were in accordance with the ISO 5660-1 standard and followed the same procedure as per other similar works (Fateh *et al.* 2017, Qian *et al.* 2017). The sample surface area exposed to heat flux, from the cone heater (exposed surface), was 100 mm × 100 mm (length × width). Orientation of exposed surface of the samples was horizontal.

Consequently, fire performance was assessed by the heat release rate (HRR), total heat release (THR), time to ignition (TTI), first peak in HRR curve ($pHRR_I$), second peak in HRR curve ($pHRR_{II}$), time to $pHRR_I$, time to $pHRR_{II}$, effective heat of combustion (EHC), fire growth rate index (FIGRA), maximum average rate of heat emission (MARHE), predicted time to flashover (TFO) and predicted reaction to fire class (RtFC). The HRR, THR, TTI, $pHRR_I$, $pHHR_{II}$, time to $pHRR_I$ and time to $pHRR_{II}$ were evaluated by the cone calorimeter directly. The MARHE and FIGRA values were calculated from the measured heat release rate, in compliance with Zhang (2008). The TFO was predicted from the estimated TTI and HRR values in compliance with Kokkala *et al.* (1993). The RtFC was predicted from parameters such as THR, sample density and sample mass loss in accordance with the procedure of Hansen and Kristoffersen (2007).

Statistical analysis

The effect of aluminium hydroxide and borates on the mechanical and physical properties as well as fire performance of investigated fibreboard samples was assessed by the analysis of variance (ANOVA) at a significance level $\alpha = 0.05$ performed using MATLAB 2020b (MathWorks, Natick, MA, USA).

Results and discussion

Physical properties

The physical properties of MDF produced in the laboratory, are shown in Table 3. Mean densities varied between 781 and 805 kg/m^3, close to the target density of 800 kg/m^3. Furthermore, thickness swelling (TS) and water absorption (WA) of treated fibreboards were unchanged or decreased, after the treatment with the FRs, as compared with the non-treated boards.

In particular, the 24 h swelling values of MDF panels were reduced from 6.2% (untreated sample), to 5.5% (treated with FR-A), 2.4% (treated with FR-B), and 5.2% (treated with FR-C). Nevertheless, the statistical analysis showed that in the case of FR-A and FR-C, the effect of the FR loading on the thickness swelling was not statistically significant ($p > 0.05$). On the other hand, statistically significant reduction of swelling was only observed in the case of treatment with FR-B, probably meaning that the replacement of APP by aluminium

Table 3. Physical and mechanical properties of laboratory fabricated fibreboards.

Property		Type of FR treatment: Control	A	B	C
Density	(kg/m^3)	781[a] (45)[b]	793 (35)	805 (52)	794 (32)
IB	(N/mm^2)	0.93 (0.12)	0.63 (0.09)	0.51 (0.11)	0.44 (0.07)
TS	(%)	6.2 (1.3)	5.5 (1.6)	2.4 (1.1)	5.2 (1.8)
WA	(%)	24.5 (2.7)	23.6 (3.1)	18.4 (2.2)	25.1 (3.2)
Desiccator	(mg/L)	5.035	0.679	0.665	0.659

[a]Mean.
[b]Standard deviation.

hydroxide decreased the hygroscopicity of the boards, which is in accordance with findings published by Wang *et al*. (2017).

As depicted in Table 3, a similar trend was observed for WA properties of the boards. Exactly, untreated MDF showed a 24 h water absorption of approx. 24.5%, while the FR treated panels showed similar values, that is, 23.6% (FR-A) and 25.1% (FR-C) without statistically significant difference among each of them and control boards ($p > 0.05$). As demonstrated in thickness swelling, FR-B treatment induced statistically significant reduction of water absorption. Notable exception was the treatment with FR B, in which, the WA of the treated panels was found ca. 18.4%. This was a significant decrease in WA, roughly 25%, thus meaning that the incorporation of aluminium hydroxide in APP obviously improved drastically the moisture properties of the fibreboards, namely, TS and WA.

It is common knowledge that thickness swelling provides a representative value of the dimensional stability of fibreboards. Lower swelling values indicate increased stability of the wood panel.

Regarding the emission, desiccator tests showed that the formaldehyde release of MDF boards was largely reduced. Control boards exhibited emission values of 5.035 mg/L, according to EN ISO 12460-4 method, a reasonably high emission due to the very high molar ratio (F/U) of resin used. As expected, the incorporation of ammonium polyphosphate resulted in much lower formaldehyde emissions. Specifically, the fibreboard panels, treated with FR additives A, B, and C, exhibited desiccator values of 0.679, 0.665 and 0.659 mg/L, respectively. According to the bibliography, such emission values correspond to approximately 4–5 mg/100 g as per the Perforator method (Bulian *et al*. 2004, Risholm-Sundman *et al*. 2007), i.e. therefore classifying the produced boards to the E1 class.

This substantial drop in formaldehyde emission of panels was expected, since it is a well-known fact that ammonium phosphate is a very vigorous formaldehyde catcher (Alexandopoulos *et al*. 1998, Dunky 2003, Mantanis *et al*. 2018, Antov *et al*. 2020). The effect of the investigated FRs on formaldehyde release of MDF was statistically significant ($p >$ 0.05). Likewise, the results regarding the formaldehyde release of FR treated panels, as shown by the Desiccator method, were quite noticeable.

Internal bond (IB) is a critical indicator of the bonding strength in wood panels, especially in fibreboards. From the results obtained in this work, it obvious that the IB of the FR treated fibreboards was significantly inferior to that of the control boards. Average IB of untreated MDF was approx. 0.93 N/mm^2. The addition of APP based additives evidently resulted in a detrimental effect on the tensile strength of the fibreboards. In particular, the mean internal bond strength of the panels treated with the FR-A, FR-B and FR-C, was 0.63, 0.51 and 0.44 N/mm^2, respectively. In fact, this reveals a large IB decrease of approx. 32%, 45%, and 52%. Comparable results were reported by Ayrilmis (2007) in his study on fire-retardant treated MDF containing monoammonium and diammonium phosphate, as well as by Mantanis *et al*. (2019) in their work on APP-treated MDF panels. IB strength losses can be attributed to the chemical and mechanical changes in the wood cell-wall structure, and also to the contamination of fibre surfaces by loosely adhering deposits of fire additives in the glueline. These probably interfered with the attainment of intimate fibre-to-fibre contacts (Winandy 2001, Ayrilmis 2007, Mantanis *et al*. 2019).

Fire properties evaluated with LOI

The limiting oxygen index of control (untreated) and treated samples is shown in Table 4. All FR treated MDF samples exhibited significantly (about 2.5 times) higher LOI, as compared with that of control. As a matter of fact, this outcome revealed the high efficiency of investigated FR treatments during this laboratory-scale test of flammability. Nevertheless, for a final clue in respect to the efficiency of investigated retardants, fire performance tests were necessary to be carried out. Obtained LOI results (Table 4) indicated that the best behaviour during laboratory flammability tests (LOI) was shown by FR-B. This finding concurred with results published by Wang *et al*. (2014).

Fire performance evaluated with cone calorimeter

The heat release rate and the total heat release from the investigated FR-treated and untreated (control) samples following cone calorimeter flammability tests are depicted in Figure 1. The time to ignition (TTI), first peak in HRR curve, second peak in HRR curve, time to $pHRR_I$, time to $pHRR_{II}$, effective heat of combustion, MARHE and FIGRA, are demonstrated in Table 5.

Comparison of treated samples (A, B, and C) with control sample (Figure 1) showed that the treated samples exhibited only one marked $pHHH_I$, which was considerably lower (roughly 2.2–3.6 times) in comparison with the $pHHH_I$ of untreated samples. Besides, FR treated samples displayed only flat $pHRR_{II}$, while the $pHRR_{II}$ of untreated was very sharp and very high (almost 5–8 times). Characteristically, Figure 1 depicts the major impact of FR treatments used on the fire performance of MDF boards.

More revealing data is found in Table 5. This table shows that the investigated FR treatments caused positive increases in key parameters such as the time to ignition (up 23% to 73%), the time to $pHRR_I$ (up to 29%) and the time to $pHRR_{II}$ (up 39% to 79%). Furthermore, the used treatments also positively reduced $pHRR_I$ (ca. 3.6 times) and $pHRR_{II}$ (ca. 8 times), EHC (roughly 2 times), FIGRA (ca. 2 times) and MARHE (5–6 times). Comparison of obtained results (Figure 1 and Table 5) with data from the works of White and Sumathipala (2013) and Martinka *et al*. (2018) proved that the control samples showed typical values for wood and wood panels, while the FR treated samples exhibited significantly higher fire-retardancy properties, i.e. lower values in: HRR, FIGRA, MARHE, EHC, $pHRR_I$, and pHRRII. Wang *et al*. (2017) have

Table 4. LOI test results of MDF treated with the FR additives A, B and C.

	Treatments			
	Control	**FR-A**	**FR-B**	**FR-C**
LOI (%)	23.1 (0.6)*	57.7 (1.4)	60.1 (2.2)	59.7 (1.1)

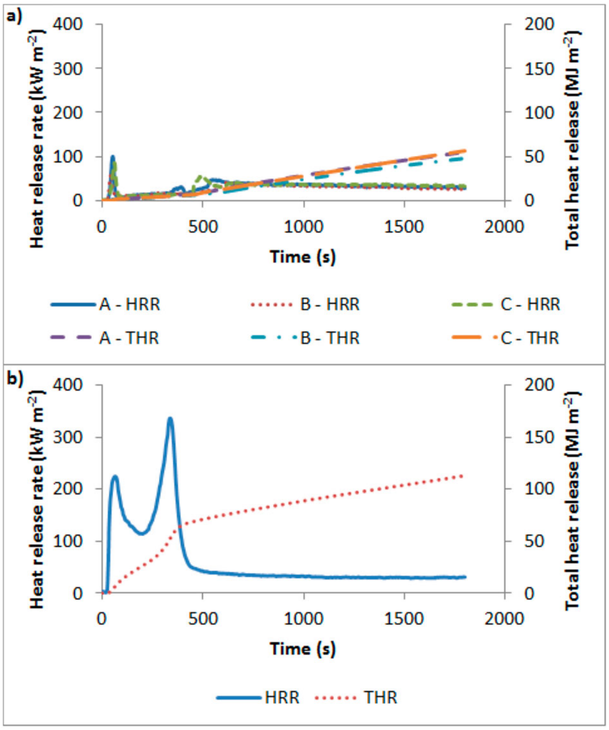

Figure 1. Heat release rate and total heat release from investigated FR treated MDF (a), and from untreated MDF boards (b).

also reported that substitution of APP with aluminium hydroxide decreased the heat release rate and smoke generation during combustion. They attributed this phenomenon to the fact that aluminium hydroxide could act as a physical barrier which protects the underlying substrate.

The flashover category and reaction to fire class of treated and control MDF samples are presented in Table 6.

Table 6 demonstrates that all treated samples showed significantly improved fire characteristics, compared to control samples, thus, all three reached the fire class B. Noticeably, reaction to fire class B is the best FR class in which wood and wood-based panels can be classified. There are not known wood-based materials belonging to A1 or to A2 fire class. Treatment with FR-B was found to have a predicted time to flashover higher than 1,200 s, which is commonly referred to as '*no flashover*'. The significantly lower MARHE of treated MDF is apparent from the results in Table 5.

Besides the fact that MDF samples treated with FR B, proved to obtain exceptionally high fire retardancy characteristics, the other two investigated FR constituents (A: based on ammonium polyphosphate; C based on a blend of ammonium polyphosphate along with borates) also showed to be quite effective fire retarding additives (Tables 5 and 6).

Table 5. Fire performance of treated MDF samples with the three FRs (A, B, C).

	Control	A	B	C
Time to ignition (s)	30 [a] (2) [b]	43 (3)	37 (2)	52 (5)
$pHRR_I$ (kW m^{-2})	228 (13)	102 (14)	63 (23)	91 (13)
$pHRR_{II}$ (kW m^{-2})	408 (42)	50 (2)	46 (9)	72 (45)
Time to $pHRR_I$ (s)	48 (6)	53 (2)	46 (2)	62 (3)
Time to $pHRR_{II}$ (s)	335 (16)	468 (110)	602 (46)	591 (86)
EHC (MJ kg^{-1})	17.7 (0.4)	8.7 (0.5)	7.5 (0.5)	8.7 (0.9)
FIGRA (kW m^{-2} s^{-1})	3.5 (0.5)	1.9 (0.3)	1.4 (0.6)	1.5 (0.3)
MARHE (kW m^{-2})	167.1 (8.7)	33.2 (2.5)	27.8 (1)	32.3 (2.4)

[a]Mean.
[b]Standard deviation.

Table 6. Predicted times to flashover and predicted reaction to fire class of the control and FR treated MDF samples with the cone calorimeter test.

Sample	Control	A	B	C
Time to flashover (s)	< 120	120–600	No flashover	120–600
Predicted reaction to fire class (-)	D	B	B	B

From the results obtained, it seems that aluminium hydroxide addition into the APP-based system, resulted in a largely upgraded fire resistance of fibreboards, compared to the results obtained using pure APP system. This effect is probably a result of the accumulation of Al_2O_3 (generated by the decomposition of aluminium hydroxide) on the surface of the fibres thus protecting the substrate by delaying heat and mass transfer (Witkowski *et al*. 2012).

On the contrary, the blending of borates (boric acid and borax), together into the aqueous ammonium polyphosphate solution, causes a certain, but much lower upgrading of the fire performance of MDF panels, as demonstrated in Table 5. Thus, the beneficial effect of borates added to the APP system (already well-known in the art), seemed to be lower to that of aluminium hydroxide.

Conclusions

Three liquid fire retardants were investigated in this study for the treatment of wood fibres for producing laboratory scale FR-MDF boards. The target was to reveal possible effects of aluminium hydroxide, as well as of borates (borax + boric acid) on the fire efficacy imparted to MDF by a conventional ammonium polyphosphate system.

As experimental results showed, there were no increases in thickness swelling and water absorption properties caused by the addition of the investigated FR additives into the MDF boards, which were glued with a high molar ratio MUF resin. Markedly, FR-Btreatment, in which APP was partially substituted by aluminium hydroxide (by 20%), caused the least detrimental effects regarding both 24 h thickness swelling and 24 h water absorption. Also, it was observed that the FR additives used in this work, caused a slight brown colour on the surfaces of the fibreboards.

In general, internal bond of FR treated panels was negatively affected by the FR additives, with noticeable decreases, up to 52%. This large reduction in treated MDF was caused, possibly, either by the chemical changes in fibre cell-wall structure, or by the interference of the deposits of FRs within the bonding lines.

All three investigated fire retardants clearly showed significant upgrading of the important fire characteristics, namely: LOI, TTI, HRR, THR, $pHRR_I$, $pHRR_{II}$, time to $pHRR_I$, time to $pHRR_{II}$, MARHE, FIGRA, EHC, TFO and RtFC of the treated MDF as compared to control. A new fire-retardant additive, based on a blend of ammonium polyphosphate and aluminium hydroxide, resulted in exceptionally high fire performance, e.g. LOI above 60%; time to flashover above 1,200 s; pHRR[l] 63 kW m^{-2}, and MARHE below 30 kW m^{-2}. This proved that the incorporation of aluminium hydroxide into a conventional APP fire-retardant system can enhance fire retardancy of fibreboards significantly. On the other hand, the incorporation of borates such as boric acid and borax into the same APP showed an improvement, but in a lower extent.

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Disclosure statement

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