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Fire Resistance and Reaction-To-Fire of *Shorea macrophylla* and *Acacia mangium* Particleboards Treated with Boron and Phosphorous-based Fire Retardants

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ABSTRACT

Fire resistance and reaction-to-fire of Engkabang (*Shorea macrophylla*) and *Acacia mangium* particleboards, which were treated with zinc borate (ZBr) and monoammonium phosphate (MAP), were investigated in this study. Ten percent of the fire retardants were incorporated into the particleboards in powder form during resin-particle mixing process. The fire resistance of the boards was assessed using insulation and integrity failures. Meanwhile, reaction-to-fire was conducted to examine the effectiveness of the fire retardants to delay ignition and reduce weight loss. The study showed that ZBr was excellent in improving insulation and integrity failures of the boards as compared to MAP. Zinc borate delayed the increase of unexposed face temperature up to 18 min and reduced the weight loss down to 0.57% (ZBr-treated *A. mangium*), but MAP was shown to be better than ZBr in delaying ignition (i.e. up to 41s for *A. mangium* and 20s for *S. macrophylla*). The ineffectiveness of the fire retardants to reduce weight loss of the boards (MAP-treated and ZBr-treated *S. macrophylla* and MAP-treated *A. mangium* might be due to leaching and volatization of phosphoric acid and boric acid in the formulations of the particleboards which would then cause the chemical loading to be lower than the actual chemical loading. It is suggested to extend the research especially in determining the chemical loading of each treated boards during and after they are exposed to fire. This is essential to prove the claim that chemical loading is decreased due to the leaching of phosphoric acid and volatization of boric acid.

Keywords: Fire retardants, insulation failure, integrity failure, weight loss, particleboard

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INTRODUCTION

Particleboard is often used as in ceiling, partitioning and panelling construction. This product can be manufactured from low quality wood, mill residues, lignocellulosic materials from agricultural waste including wheat, rice straw, kenaf, rubberwood and empty oil palm fruit bunches (Basturk, 1993; Cai *et al*., 2004; Izran *et al*., 2010c; Zaidon *et al*., 2007; Izran *et al*., 2010). It is important to note that particleboard has gained its popularity until now as the prices of lumber are unstable in both developed and underdeveloped countries. Consequently, to meet the demands of particleboard production, exploration of more alternative materials is crucial to ensure continuous supply. Engkabang jantung (*Shorea macrophylla*) and *Acacia mangium* possess qualities that are suitable for particleboard production (Izran *et al.,* 2010b). Particleboards from these fast growing species provide acceptable strength properties that surpass the British Standard requirements (Izran *et al*., 2010a). In order to add value to the particleboards made of *S. macrophylla* and *A. mangium*, especially for safety reasons in high rise buildings, their combustibility properties need to be assessed and reduced. In particular, the combustibility needs to be reduced down to meet the requirements set by Uniform Buildings by Law 1984 (UBBL 1984). This can be achieved through incorporation of fire retardants. In fact, the application of fire retardant can be done in two ways: 1) by treating fibres with fire retardants before they are mixed with resin and compressed to particleboard, or 2) by adding fire retardants during resin-fibre blending process. Both the methods were found to be effective in reducing the combustibility of particleboards (Izran *et al.,* 2010). The combustibility of a material for building construction can be assessed through fire resistance test and reaction-to-fire test. Fire resistance exhibits means of quantifying the ability of an element to withstand exposure to high temperatures through insulation and integrity evaluations (BSI, 1987), whereas reaction-to-fire is a test to examine the time taken for ignition to occur as well as the weight loss of the tested samples after the exposure to fire. This paper reports the fire resistance and reaction-to-fire of particleboards made from *S. macrophylla* and *A. mangium* particles mixed with boron-based and phosphorous-based fire retardants.

MATERIAL AND METHODS

The materials used in this study were the particles of *Shorea macrpophylla* and *Acacia mangium*. Meanwhile, monoammonium phosphate (MAP) and zinc borate (ZBr) fire retardants (10% w/w oven-dried dried particles) were used as treating chemicals. Adhesive E2-grade urea formladehyde resin was used as a binder. The woods were flaked, chipped and screened into particles ranging from 1 to 2 mm in size. Then, the particles were dried to 5 ± 2% moisture content (MC) using an industrial oven which was set at the temperature of 105±2°C for 24 h. A single homogenous layered board (340 mm x 340 mm x 12 mm), with a target density of 700 kgm^{-3}, was fabricated. The final MC of the particleboards was ca. 12%. The fire retardants were incorporated into the particleboards in powder form during blending of furnish. The particles were first blended with UF resin (12% w/w oven-dried dried particles) + wax (1% of solid resin) + hardener (3% of solid resin) in a mixer. The furnish was then incorporated separately with 10% MAP and 10% ZBr. This was followed by forming the furnish into the former and pressed. The furnish was then hot-pressed for 6 min for the particles treated with MAP and 9 min for those treated with ZBr. For the untreated furnish, it was pressed for 7 min. The variation in the time of pressing was due to the influences of the chemicals on delaying and aggravating curing of the UF resin (Izran *et al*., 2010b). A total of twelve boards were fabricated, with 4 boards each for the untreated, MAP-treated and ZBr-treated. One board from each group was used for the fire resistance test and the remaining three boards were utilized for the reaction-to-fire test. The fire resistance required samples with a dimension of 340 mm x 340 mm x 12 mm, whereas, early burning performance needed slightly smaller sample in the size of 225 mm x 225 mm x 12mm.

Fire Resistance Test

This test was conducted in a fire furnace, in accordance with British Standard 476: Part 22 (BSI 1987). The dimension and weight of the treated and untreated boards were measured. After that, the boards were fixed to the furnace using cement. Four thermocouples were attached on the unexposed side of the tested boards. These thermocouples were connected to a recorder which was responsible to record temperature change of the unexposed side. The temperature of the furnace fire was also measured using thermocouples in the furnace which was connected to a computer. The temperature of the furnace was set at 27-30°C before the test. The sample was then heated by fire in the furnace. At the same time, the temperature increment of the unexposed face was recorded at five-minute intervals until the temperature reached 183°C (insulation failure) or until the board collapsed (integrity failure).

Intergrity is the ability of the particleboard to prevent collapse or sustain flaming. Based on the standard, intergrity failure happens when: (1) the tested sample collapses or sustained flaming occurs for more than 10 seconds on the unexposed face, (2) when fire and hot gases cause flaming to the cotton pad, and (3) when cotton pad is not suitable to be included in the test. The failures are: (i) when the occurrence of 60mm diameter gap gauge can penetrate a through gap and its end projects into the furnace and it can be moved in the gap for a distance of at least 150 mm, or (ii) when the occurrence of 25 mm diameter gap gauge can penetrate a through gap and its end projects into the furnace. Insulation is the ability to delay excessive increase in the temperature of the unexposed face. The standard indicates that insulation failure occurs when: (1) the temperature of the unexposed face increases more than 140°C above its initial mean temperature, or (2) the temperature recorded at any position on the unexposed face using thermocouples is more than 180°C above the intial mean temperature of the unexposed face. The unexposed face is the particleboard surface which is not exposed to fire in the furnace.

Integrity failure influences insulation failure because as the board collapses, evaluation of insulation failure is stopped even though the temperature of the unexposed face has not achieved the standard temperature. The calculation of the time-temperature relationship in the furnace is automatically done by the software installed in the computer. The calculation is according to the formula stated in the standard for fire resistance test (BSI 1987).

Reaction-to-Fire Test

The boards for the test were oven-dried at 103±2°C until the oven-dry weight was achieved (IW). Before the test was conducted, 1 ml of ethanol was dispersed on the surface of the board. This was to encourage combustion on the board when exposed to fire. Each board was placed inclined at 45°, 3 cm above a bunsen burner and the time taken for the board to ignite was recorded. The combustion on the board was left for 2 min. The burned board was re-weighed (WAB). The weight loss of each board was calculated using Equation 1 below:

$$\text{Weight loss (\%)} = \left(1 - \frac{WAB}{W}\right) \times 100\% \qquad [1]$$

The data of the weight loss and flaming duration were analyzed using ANOVA to evaluate the efficacy of the fire retardants on the fire performance of the boards.

RESULTS AND DISCUSSIONS

Fire resistance of A. mangium *and* S. macrophylla *particleboards*

The fire resistance of the boards is presented in Table 1. The treated and untreated boards were found to achieve integrity failure before insulation failure, except for the *A. mangium* boards that were treated with ZBr. The boards collapsed before their unexposed surfaces reached the maximum temperature of 183°C above the mean initial temperature and the minimum 140°C above the mean initial temperature. Compared to MAP, however, ZBr was superior as it was able to delay integrity failure by 8 minutes (for *A. mangium* boards) and 6 minutes (for *S. macrophylla* boards). During intergrity failure, the minimum temperature of the unexposed surfaces of the boards (*A. mangium* and *S. macrophylla*) treated with ZBr was 186°C and 57°C, respectively, whereas the maximum temperature were 226°C and 58°C, respectively. Meanwhile, the *A. mangium* boards that were treated with ZBr suffered insulation failure for both the minimum and maximum temperatures at 19th minute. Similar results were also observed for the boards treated with MAP, where the results varied between the two species used. The MAP-treated *A. mangium* boards performed better than MAP-treated *S. macrophylla* boards, where the times taken for them to achieve integrity failures were 16 and 13 minutes, respectively. The temperatures of the unexposed surfaces above the mean initial temperature during the integrity failure were also found to be different, with the minimum of 88°C and the maximum of 98°C for MAP-treated *A. mangium* boards, and the minimum of 96°C and the maximum of 152°C for *S. macrophylla*, respectively. The MAP-treated *S. macrophylla* board exhibited almost similar results with those of the untreated boards (both *A. mangium* and *S. macrophylla*); however, it failed to reduce the increment in the temperatures of the unexposed surfaces more effectively than the untreated boards (minimum 88°C and maximum 98°C for *A. mangium* and the minimum 96°C and maximum 152°C for *S. macrophylla* above the mean initial temperature). The untreated boards faced integrity failures at 12 minutes after the exposure to fire in the furnace (minimum 80°C and maximum 97°C for *A. mangium* and minimum 71°C and maximum 77°C for *S. macrophylla* above the mean initial temperature).

TABLE 1
Fire resistance of *A. mangium* and *S. macrophylla* particleboards

Samples	TIF (min)	Temp UE (°C) Min (≤140°C)	TempUE (°C) Max (≤183°C)
AM-Cont	12	80	97
AM-ZBr	20	186 (Insulation failure at 19 min)	226 (insulation failure at 19 min)
AM-MAP	16	88	98
SM-Cont	12	71	77
SM-ZBr	18	57	58
SM-MAP	13	96	152

TIF: Time for integrity failure, TempUE Min: Minimum temperature of the unexposed face, TempUE Max: Maximum temperature of the unexposed face. Note: All the samples achieved integrity failure before insulation failure, except for the *A. mangium* boards treated with ZBr

Physical Observations on Fire Resistance Test Samples

Observations were also made to record the physical changes of the boards during the test until they collapsed. In particular, the physical changes of ZBr-treated *S. macrophylla* boards began 2 minutes after the exposure. At this time, smoke was found to be present on the upper **horizontal part** of the board. This happened constantly until the 12th minute. At the 12th minute, the smoke became denser, indicating the exposed face started to burn badly. At the 14th minute, char established on the top left side of the unexposed face and continuous flaming occurred at the 18th minute, and this brought to integrity failure. The same result was observed for the *A. mangium* board treated with ZBr (see Fig.1).

The MAP-treated *A. mangium* board started to show changes after 2.5 minutes, with a leakage of smoke at the top of the unexposed surface of the board. Later, the leakage spread to both the lateral edges of the board. Meanwhile, char started to form at the smoke leakages after 12 minutes. After 15 minutes, cracks began to appear along the upper most surface of the board and ignition occurred after 16 minutes

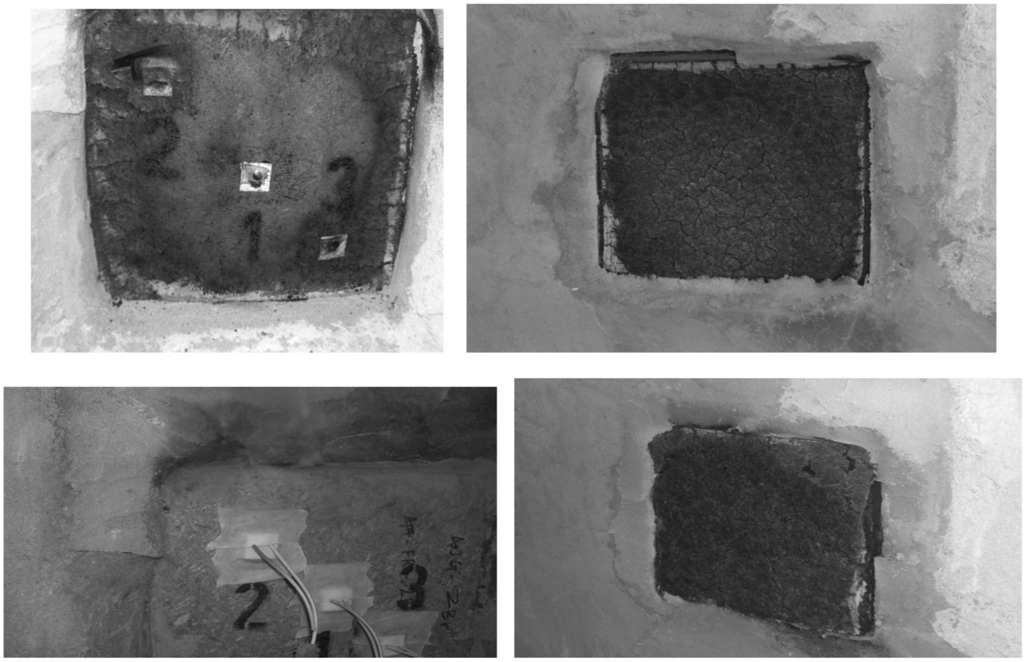

Fig.1: (From left to right) Before and after the test of the ZBr-treated boards (Above: *A. mangium* and below: *S. macrophylla*)

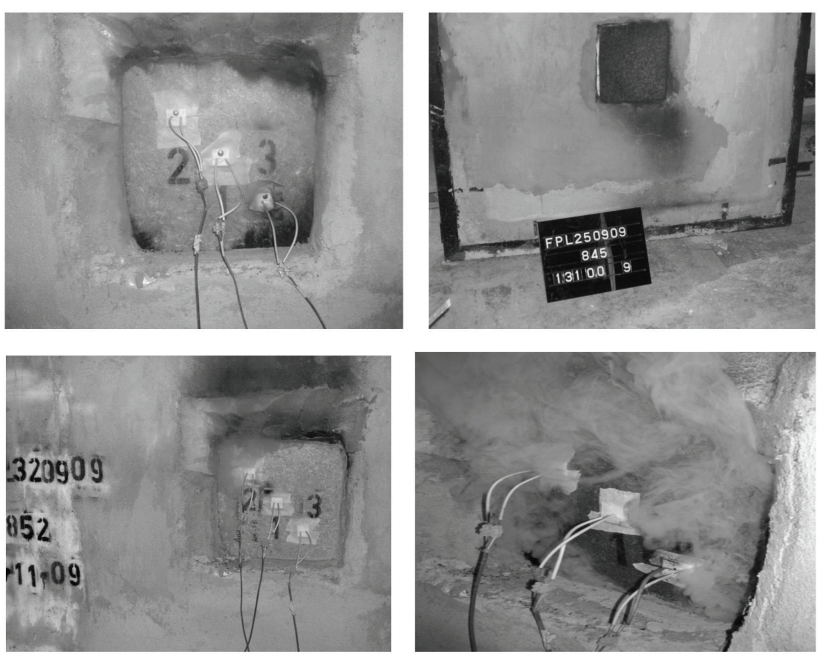

Fig.2: (From left to right) The MAP-treated boards before and after the test
(Above *A. mangium*; Below: *S. macrophylla)*

with a continuous flaming for more than 10s (Fig.3). As for the MAP-treated *S. macrophylla* board, smoke leakage was detected along all sides of the vertical joints between the wall surface and the tested board at 1.22 minutes. There were no significant changes until the 10th minute, where the board started to bend inside the furnace and charring occurred on the four sides of the board. The charring became worse on the right side of the board after 12 minute-exposure and caused a gap of 6mm to occur at the bottom-right side of the board. The gap increased to 25 mm at 13th minute, contributing to integrity failure (Fig. 2).

Char appeared on the untreated boards of *A. mangium* and *S. macrophylla* after 12 minutes. The untreated boards reached integrity failure when cracks in a size of more than 6 mm were formed. The cracks encouraged flaming for more than 10 seconds, and this constituted to the failure (Figure 3). The test revealed that the fire performance of the *S. macrophylla* and *A. mangium* particleboards improved when treated with ZBr and MAP. For fire resistance, ZBr showed a better efficacy than MAP, suggesting that boron-formulated fire retardant performed better than the phosphorous-based fire retardant in term of delaying insulation failure and integrity

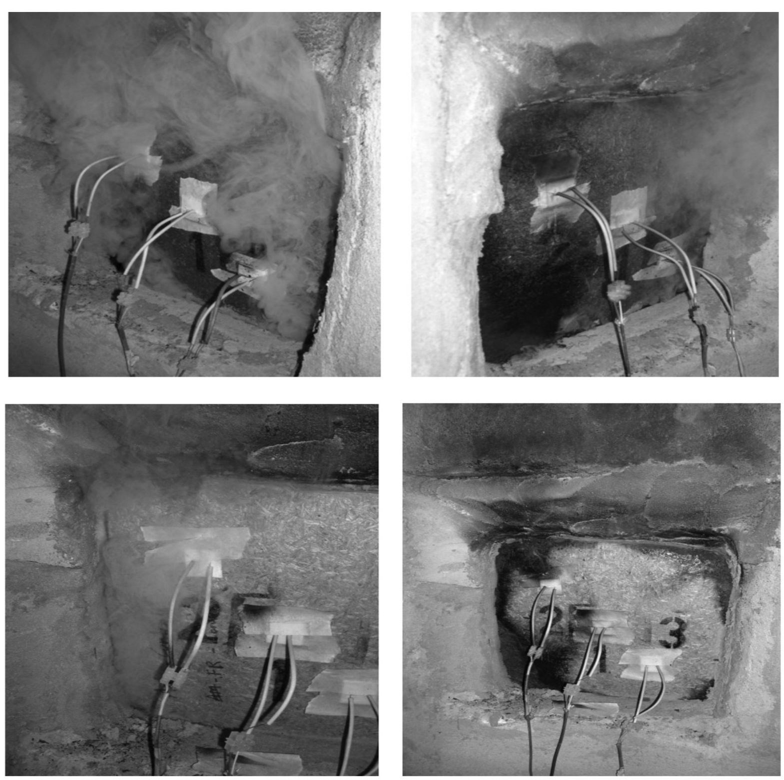

Fig.3: (From left to right) The control samples before and after the test
(Above: *A. mangium*; Below: *S.macrophylla*)

failure. The findings are in agreement with those by Izran *et al.* (2010). Boron increases the production of carbon rather than carbon monoxide or carbon dioxide. The creation of surface layer of char helps to block oxygen from the surface and cause the gases to escape much slowly (Stark *et al.*, 2009). Phosphorous compounds in MAP acts similar to boron, but the boron compounds in ZBr can penetrate deep into wood particles covering their outer parts to provide a perfect protection, and thus, prolonging the time taken for the heat to transfer through the cross-section of the board (Kolowski & Wladkya, 2001). These may explain why the ZBr-treated boards have a low rate of unexposed surface temperature increase as compared to the MAP-treated boards.

Reaction-to-Fire

The results of the reaction-to-fire test are summarized in Table 2. The results indicate that the treatments are ineffective in reducing weight loss, but are effective to lengthen flaming duration. The results seem to contradict that of the previous study which revealed that boron-based and phosphorous-based fire retardants should be effective in reducing weight loss (Izran *et al.,* 2010; Abdul Rashid & Chew, 1990). Meanwhile, the treated boards experienced larger weight loss as compared to the untreated ones, except for the *A. mangium* that was treated with ZBr. The weight loss recorded for the untreated *A. mangium* and *S. macrophylla* was 0.87% and 0.41%, respectively. Meanwhile, the *Acacia mangium* and *S. macrophylla* treated with ZBr had weight losses of 0.57% and 1.04%, respectively. In comparison, compared to the untreated boards, the ZBR-treated *S. macrophylla* boards suffered larger weight loss by 157.54%. Different results were obtained for the *A. mangium* boards that were treated with the same fire

TABLE 2
Reaction-to-fire test for *A. mangium* and *S. macrophylla* particleboards

Samples	Weight (g)		Weight loss (g)	Percentage of weight loss (%)	Flaming duration (s)
	Before test	After test			
			S. macrophylla		
Untreated	439.73[7.59]	437.94[7.38]	1.79 [0.83][a]	0.41 [0.19][a]	10.33 [2.10][a]
ZBr-treated	443.19[3.18]	438.58[8.16]	4.61 [5.37][b]	1.04 [1.22][b]	10.17[10.07][b]
MAP-treated	408.88[25.98]	404.36[28.40]	4.52 [3.04][c]	1.13 [0.78][c]	20.12 [21.55][c]
			A. mangium		
Untreated	388.87[48.21]	385.37[46.71]	3.5 [2.01][d]	0.87 [0.43][d]	8.00 [0.49][d]
ZBr-treated	436.02[7.67]	433.54[9.56]	2.48 [1.9][e]	0.57 [0.45][e]	19.27 [9.5][e]
MAP-treated	445.68[17.36]	434.60[21.48]	11.08[7.86][f]	2.51 [1.81][f]	41.21 [8.51][f]

Values are means of 3 samples. The values in parentheses are standard deviation; Means within a column followed by the same alphabets are not significantly different at p≤0.05 between the species; Means within a column followed by the same numbers are not significantly different at p≤0.05 between the chemicals.

retardant, where weight loss was observed to be smaller than the untreated ones by 41.12%. This means a larger weight loss was recorded for the boards treated with MAP. The weight loss for *A. mangium* and *S. macrophylla* was larger than the untreated boards by 216.57% and 152.51%, respectively.

However, the fire retardants were found to be effective in lengthening the on-set of flaming for ignition, except for the *S. macrophylla* boards that were treated with ZBr. Meanwhile, monoammonium phosphate (MAP) was more effective than ZBr in delaying ignition. *Shorea macrophylla* and *A. mangium* boards treated with MAP each took 20 seconds and 41 seconds for ignition, whereas those treated with ZBr took 10 seconds and 19 seconds each for ignition, respectively. The comparisons show that the MAP-treated *A. mangium* boards were the most difficult to ignite. As for the control samples, *S. macrophylla* and *A. mangium* boards took 10 and 8 seconds to ignite, respectively.

The percentage loss in weight can be used as a measure of the tendency of the boards to burn once they are ignited (Abdul Rashid, 1982). Thus, it can be concluded that the MAP-treated *S. macrophylla* and *A. mangium* boards were relatively easier to burn even though they were much harder to ignite. The ineffectiveness of the fire retardants to reduce weight loss was expected due to the hygroscopicity of the fire retardants (MAP and ZBr). This is because they absorb moisture from the surrounding. MAP is water soluble and leachable (Izran *et al.,* 2009). As for ZBr, apart from its hygroscpicity, it contains boric acid in its formulation which makes it easily volatized when it is exposed to heat due to low chemical stability. Zaidon *et al.* (1995) discovered that different amounts of boric acid volatize at different temperatures. Thus, it was rather expected that the existence of moisture from the surrounding, due to the hygroscopicity and heat from the Bunsen burner, could speed up the leaching of phosphoric acid through water vapours as well as through volatization of boric acid which caused the amount of the chemicals to become slightly lower than the actual chemical loading incorporated into the particleboards. These could decrease the effectiveness of the fire retardants to protect the boards from thermal degradation caused by the fire. These also explain the reason for the greater weight losses recorded for the treated boards as compared to the untreated ones. However, ZBr is leaching resistant and for this reason, the weight losses of the boards treated with MAP were larger than those treated with ZBr. The failure of ZBr to lengthen the flaming duration of *S. macrophylla* particleboards might also be due to the mechanism explained above.

CONCLUSION

The two fire retardants undertaken in this study were effective in improving fire resistance but not the reaction-to-fire of *S. macrophylla* and *A. mangium* particleboards. In specific, zinc borate performed better than MAP in improving the insulation and integrity of the boards, except for the *A. mangium* boards. The ZBr-treated boards were also found to be better than MAP in terms of weight loss after burning. The MAP-treated boards ignited less readily compared to those treated with ZBr. The results for the weight loss of the treated *S. Macrophylla* particleboards were inferior to the untreated particleboards. Hence, it is suggested that the research be extended, especially in determining the chemical loading of each of the treated boards, during and after they are exposed to fire. This is essential to prove the claim that the chemical loading decreases due to the leaching of phosphoric acid and the volatization of boric acid.

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