



Development and Prediction of Flame Retarded Particleboard Fire Behaviour in Real Scale

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Abstract

Particleboard composites for building application has become very attractive because of their huge benefits which includes but is not limited to low cost, lightweight, durability and environmental benign. However, the vulnerability of these composite types when exposed to fire restricts their use in areas where stringent fire safety conditions may not apply. Experimental determination at bench scale of composite particleboard fire behaviour has shown that the addition of flame retardants (FR) can delay the start and spread of fire. Bench scale data obtained in the cone calorimeter (CC) may not represent accurately a real scale fire behaviour during a fire scenario as documented by various researchers. The convolution model is a significant tool for predicting in real scale, fire behaviour of composites which depends on experimental inputs from CC data. In this paper, particleboards made from wood sawdust reinforced polyester composite were processed with FR at 0, 15 and 18% loading ratio using compression moulding technique. Test specimens cut from the FR-particleboards was exposed in horizontal orientation in the CC at 50kW/m² to obtain experimental data and these were used as inputs to the prediction model. The predictive tool was used to predict the heat released rate and smoke production rate for the FR-particleboard. The results obtained shows that the FR-particleboard contributes very limited fire in real scale and compares well based on Euro-classification with particleboards from literature.

Keywords: Flame retardant, Particleboard, Convolution model, Real scale fire

1.0 INTRODUCTION

Wood residue with inherent lignocellulosic constituent embedded in polymer matrix which form a unified material structure material with distinct interface is a good example of modern-day composite materials. The development with ease of these composites during processing as well as their good mechanical properties per unit weight and durability make them favourable [1, 2]. Wood from stem contains respectively 40-45% and 20-30% cellulose and lignin less than most natural fibres [3]. The cellulosic content present in wood is responsible for the high release of flammable volatiles leading to high heat release rates. Notwithstanding, polymers also contributes a substantial amount of combustible volatiles. This has restricted their use in areas where stringent fire regulations do not exist. For the particleboard to meet current fire safety standards, several researchers [4, 5] have focused their attention to improve the flame retardancy of wood based polymer composites by trapping combustible volatiles that can cause high release rates. Previous researches [4, 6] shows particleboards can be processed with flame retardants (FR). FR are chemical substances classified as either halogenated based FR or

halogenated free FR that are incorporated into the particulate base composite during processing either by graft copolymerization [7] or intimately blended into the polymer using a high mechanical stirring device respectively. Hence, the effect of the FR on the composite fire properties can be tested experimentally in a bench scale but has shown limitations to accuracy compared to real scale testing.

A real or large-scale testing of composite materials is an important tool in the fire safety community. A real scale fire testing gives a better fire behaviour of composite materials but this approach is seemly impossible as it will require building a testing specimen to a room standard [8]. This is capital intensive and has been discouraged for purposes of academic research hence the prediction of HRR in real scale becomes a significant tool using various prediction models. Robson et al [9] predicted different polyurethane foam thickness using a modelling tool. The results obtained showed good agreement with experimental results. The convolution model (CM) is a significant tool used to predict the HRR of materials. The model is based on a time derivative area with the corresponding cone calorimeter data per unit area. Myllymaki and Baroudi [10] predicted the HRR of upholstery furniture using integral formulation. The results obtained were promising and agree with cone calorimeter data. Lie and Chan [11] predicted the HRR of industrial Nitrocellulose materials. The model was based

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on flame height data. The HRR predicted coincided well with cone calorimeter measure data. The main objective of the research paper is to develop and predict the heat release rate in real scale of a flame retardant particleboard using cone calorimeter data at 50kW.m² as input to the convolution model in Duhamel's integral. There is limited depth of information in real scale on the fire behavior particleboard. Prediction using the CM as a tool to predict the fire behaviour of particleboard is not available in literature to the best of the researcher's knowledge hence the necessity of exploring this tool and contribute to existing scientific knowledge of the fire behavior of FR particleboard.

2.0 MATERIALS AND METHODS

2.1 Development of FR-WSP particleboard

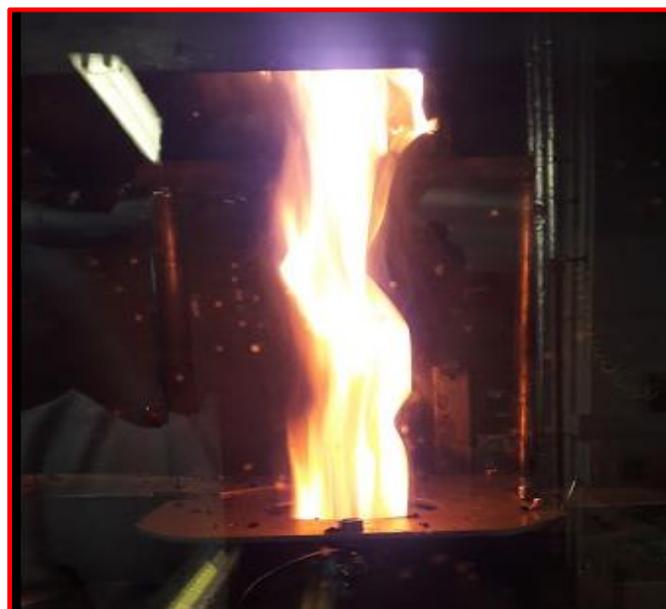
Fine ground wood sawdust (WS) as received was first treated with 5% (NaOH) solution for about 2hrs to improve the compatibility with the choice of resin: polyester. Afterwards, the particulates were washed with distilled water until blue litmus paper turned red which indicates that excess concentration of NaOH have been neutralized and then oven dried for 3hrs to remove moisture content. The ready to use wood particles were used to produce the particleboard using compression moulding technique. The required quantities of the sawdust and polyester were used to produce the particleboards were obtained using volume fraction model [12]. Five particleboards were produced with six FR comprising 10µm of aluminium trihydroxide (ATH[Al₂(OH)₃]), 15µm of Ammonium polyphosphate (APP[(NH₄PO₃)_n]), 300µm of Gum Arabic powder (GAP) and 300µm of Carbon black (CB).

2.2 Experimental method

The cone calorimeter apparatus (CCA) was used to obtain data for the heat release rate of the particleboard according to ASTM E 1354. The specimens (100mm x 100mm x10mm) cut from the OPFC fibreboard were



(a)



(b)

Figure 1: Cone calorimeter apparatus (a) Electric truncated cone shaped heater (b) Release of combustible products after removal of igniter.

wrapped in aluminium foil; along the side and bottom to reduce heat losses as specified in the standard. The specimens were exposed to 50kWm⁻² heat flux horizontal orientation. An electric truncated cone shaped heater as shown in Fig 1a cause thermal decomposition and release combustible products from the specimen surface. The height between the cone heater and the surface of the specimen is maintained at 25mm. Ignition is produced by an intermediate piloted spark igniter located above the specimen and removed when the combustible products ignite as shown in Fig 1b. The process was repeated multiple times and a sensible result was recorded.

2.3 Theoretical Approach

The convolution model in Duhamel's integral (DI) was used to predict the particleboard heat release rate (HRR) and smoke production rate (SPR) for a single burning item in real scale. The DI is as shown in Eq. 1

$$HRR_{SBI} = \int_0^i \dot{A}_{hrr,eff}(\tau) \dot{q}''_{cc}(t - \tau) d\tau \approx \sum_{i=1}^N \Delta A_{hrr,eff} \cdot \dot{q}''_{cc}{}^{N-1} \quad [1]$$

$$SPR_{SBI} = \int_0^i \dot{A}_{spr,eff}(\tau) \dot{S}''_{cc}(t - \tau) d\tau \approx \sum_{i=1}^N \Delta A_{spr,eff} \cdot \dot{S}''_{cc}{}^{N-i} \quad [2]$$

Where: $\dot{q}''_{cc}{}^{N-1}$ = HRR per unit area as recorded in the cone calorimeter, $\dot{S}''_{cc}{}^{N-i}$ = SPR per unit area [1/s] measured in the cone calorimeter at time step N-i, $\Delta \dot{A}_{hrr,eff}$ is the time derivative of the effective heat release [m²], $\Delta ASPRef, i$ increment in the effective

smoke producing area at time step $I_{,N}$ is the total number of data recordings after ignition.

The effective HRR area and SPR area in Eq.1 and 2 were respectively obtained as shown below:

$$A_{hrr,eff} = A_{max} \left[1 + \left(1 + \frac{t - t_{ig}}{t_{ig}} \right) \exp \left(-\frac{t - t_{ig}}{t_{ig}} \right) \right] \quad [3]$$

$$A_{Spr,eff} = K_{Spr} \cdot A_{HRR,eff} \quad [4]$$

From Eq. 3 the time to ignition t_{ig} was corrected using Eq. 5. This is necessary as the model was developed to be used for a heat flux at 40kW/m^2 .

$$t_{igCorr} = t_{igCone} \left(\frac{ConeFlux}{SBIFlux} \right) \quad [5]$$

Similarly, in Eq. 4 the HRR was corrected using Eq.6

$$HRR_{Corr} = HRR_{Cone} \left(\frac{ConeFlux}{SBIFlux} \right)^{0.5} \quad [6]$$

Where: t_{igCorr} = corrected ignition used in the model, t_{igCone} = ignition time in the cone calorimeter, HRR_{Corr} = corrected HRR, HRR_{Cone} = cone calorimeter HRR, $ConeFlux$ = flux in the cone calorimeter 50kW/m^2 and $SBIFlux$ = corresponding reference flux for the cone SBI model being 40kW/m^2 .

The effective smoke producing area $A_{Spr,eff}$ in Eq.4 is dependent on the burning product. The value of K_{SPR} is

based on a combination of 5 different variables connected to heat release and smoke production in the cone calorimeter. This is determined through three sets of Fisher's discriminant functions as shown:

$$\left. \begin{aligned} F_{A1} &= -0.583x_1 + 31.986x_2 + 2.810x_3 \\ &\quad + 0.003424x_4 + 15.035x_5 - 98.974 \\ F_{A2} &= -0.603x_1 + 26.9800x_2 + 2.511x_3 \\ &\quad + 0.01991x_4 + 14.373x_5 - 72.318 \\ F_{A3} &= -0.885x_1 + 32.428x_2 - 1.653x_3 \\ &\quad - 0.01048x_4 - 5.302x_5 - 67.779 \end{aligned} \right\} [7]$$

If **A1** then, $K_{SPR} = 0.3$ for products with low smoke production, If **A2** then, $K_{SPR} = 1.0$ for products with medium smoke production and, If **A3** then, $K_{SPR} = 2.5$ for products with high smoke production. Hence, the effective smoke producing area in Eq. 4 can be determined provided the heat release area is known.

The variables in Eq. 7 are defined as follows:

$x_1 = THR_{300s}$ = the total heat release after 300s obtained from cone calorimeter, $x_2 = \ln(HRR_{max})$ = the maximum value of the heat release in the cone calorimeter, $x_3 = \ln(SPR_{max})$ = the maximum value of SPR in the cone calorimeter, $x_4 = t_{ig}$ (or alternatively t_{SPR}) = the time to ignition in the cone calorimeter, $x_5 = I_{HRR}$ is the index variable describing the applied route for development of $A_{SPR,eff}$ in the HRR (SBI) prediction model. I_{HRR} takes the values 1, 2 and 3 if HRR-route I, II and III are applied respectively as shown in Fig 2.

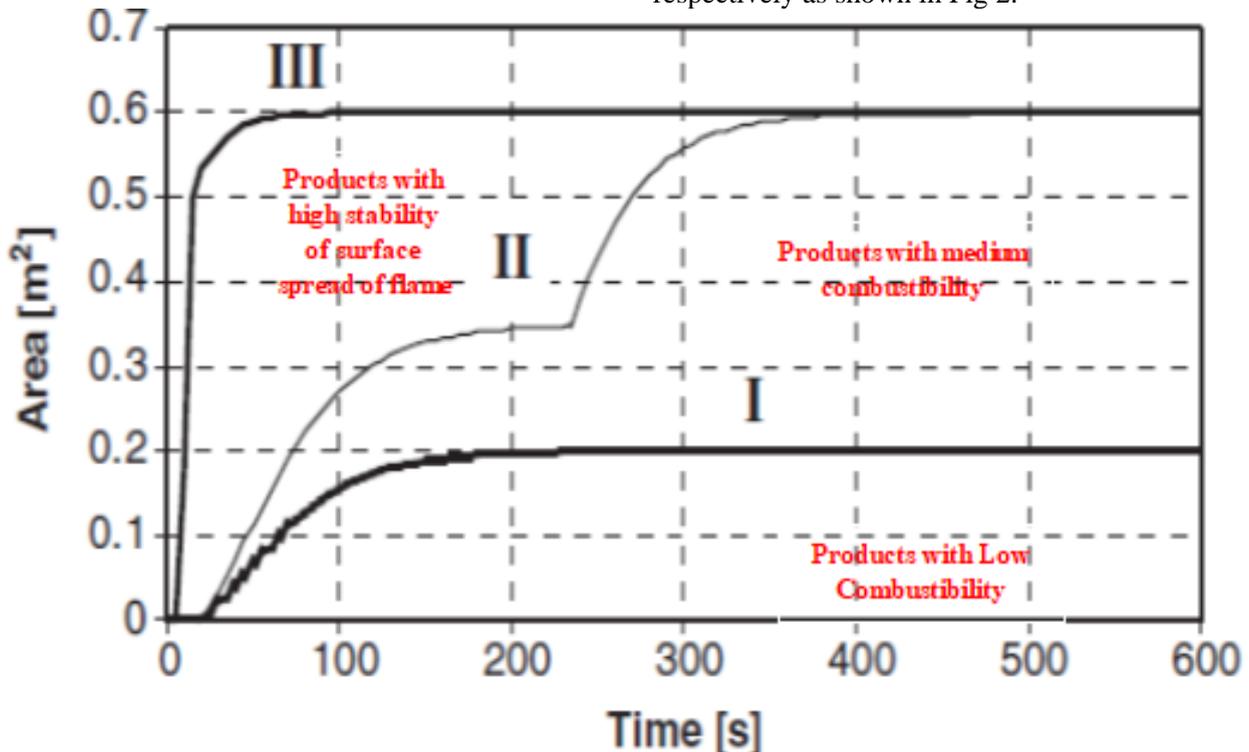


Figure 2: Suggestions of three different routes for development of the effective heat releasing area in the SBI test

The composite panels developed were classified according to fire growth rate index (FIGRA) and smoke production growth rate index (SMPGRA) as shown respectively in Eq. 8 and 9. The calculation of the FIGRA is described in detailed in Hee et al [13]. FIGRA is defined as the growth rate of the burning intensity, HRR, during a test, for example the SBI test. FIGRA is calculated as the maximum value of the functional heat release rate over the elapsed test time as shown:

$$\text{FIGRA Index} = 1000 \times \max\left(\frac{\text{HRR}(t)}{t}\right) \text{ [kW/s]} \quad [8]$$

3.0 RESULTS AND DISCUSSIONS

Figure 3 shows the profiles predicted by the model compared to the cone calorimeter data at 50kW/m² and coincide well with each other. The profile is a series of predicted heat release rate (HRR_{SBI}) curves in the single burning item (SBI). The predicted profile is seen to grow along the same paths with the measured profile in the cone calorimeter until it reaches its peak HRR and then declined. The prediction of the first peak is usually adequate for predicting correctly the fire behaviour of the particleboards in real scale. The early part of the curve is of major importance in determining the fire growth rate (FIGRA) used in the Euro-classification [14]. The FIGRA

SMOGRA is calculated as the growth rate of the maximum value of the smoke production rate over the elapsed test time as shown:

$$\text{SMOGRA Index} = 10,000 \times \max\left(\frac{\text{SPR}(t)}{t}\right) \text{ [m}^2\text{s}^{-2}] \quad [9]$$

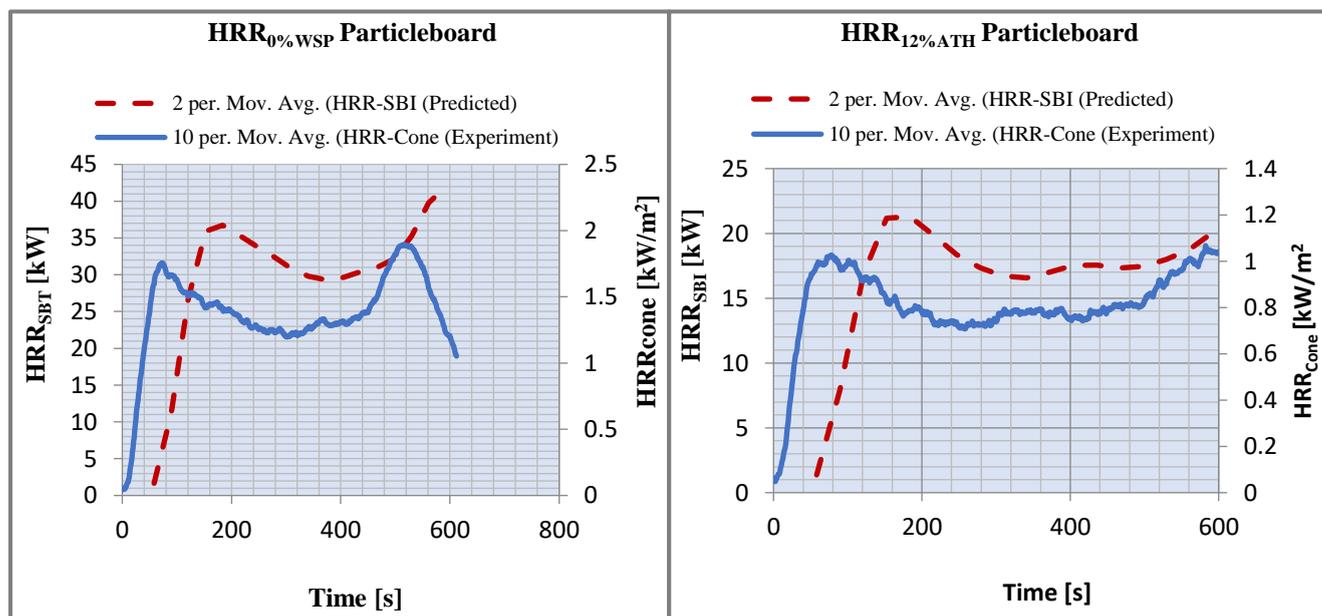
Where:

HRR_(t) = the heat release rate average over 30s [in kW],
 SPR_(t) = the smoke production rate averaged over 60s [m²s⁻¹], t = time elapsed after the beginning of the test (s).

values obtained for the particleboards shows that 18%ATH/APP-GAP-particleboard has the least FIGRA value at 37kW/s and then followed by 15%APP-GAP/CB-particleboard and 12%APP-GAP-particleboard respectively at 57kW/s and 58kW/s compared to those without flame retardant at 388kW/s (0%-WSP) as shown in table 1. This suggests that the APP-GAP effect made the particleboard to contribute limited fuel load to a sustained fire in real scale by trapping the release of combustible volatiles. GAP dehydrates the acid released from APP upon heating to form a stable char structure that prevented the release combustible volatiles.

Table 1: Predicted FIGRA and SMOGRA indices showing level of hazards of the WSP particleboard

Specimen I. D	FIGRA [kW/s]	SMOGRA [m ² /s ²]
0% WSP	388	39
WSPC _{12%ATH}	231	29
WSPC _{12%APP-GAP}	58	10
WSPC _{15%ATH/CB}	174	17
WSPC _{15%APP-GAP/CB}	57	3
WSPC _{18%ATH/APP-GAP}	37	0



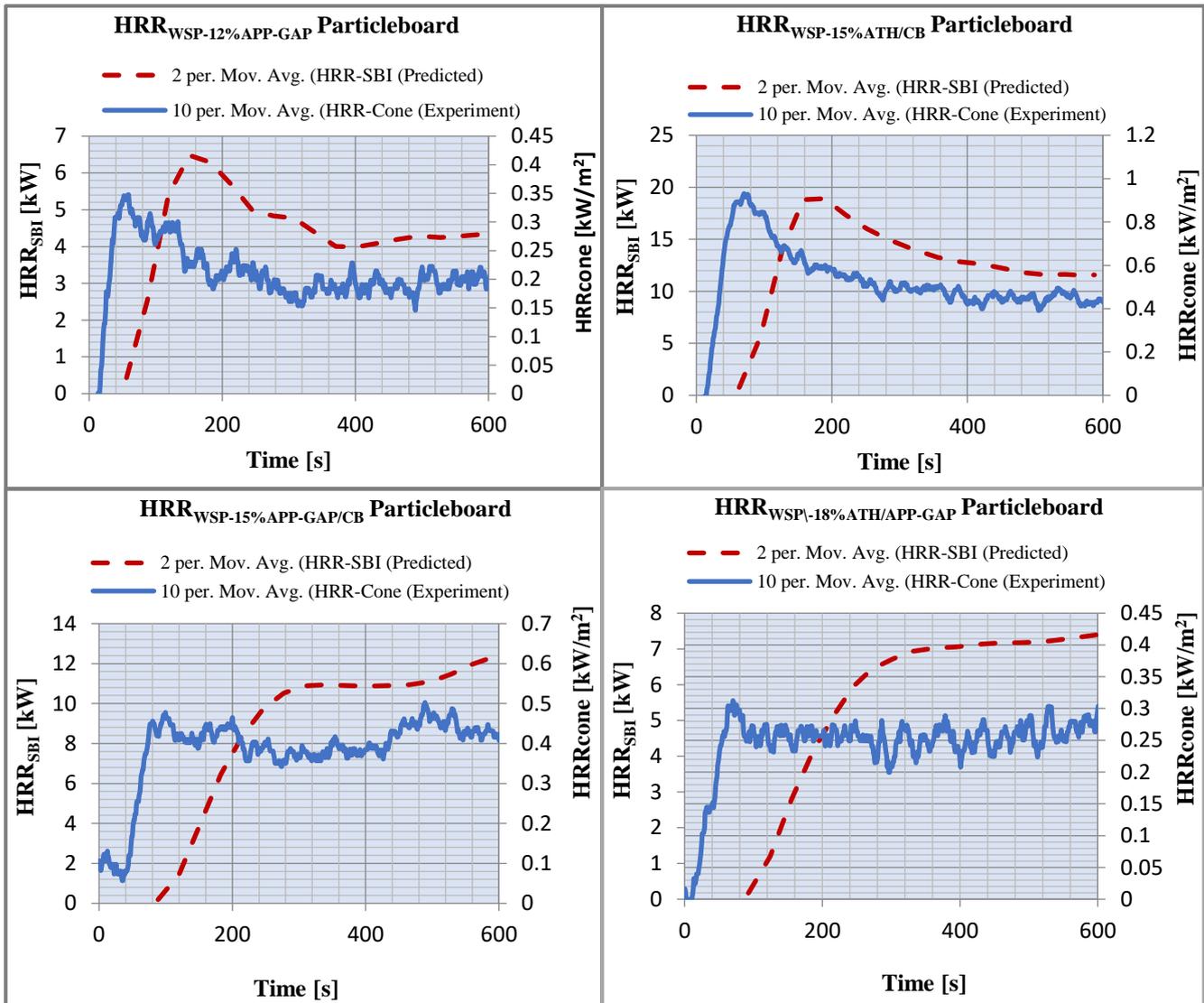
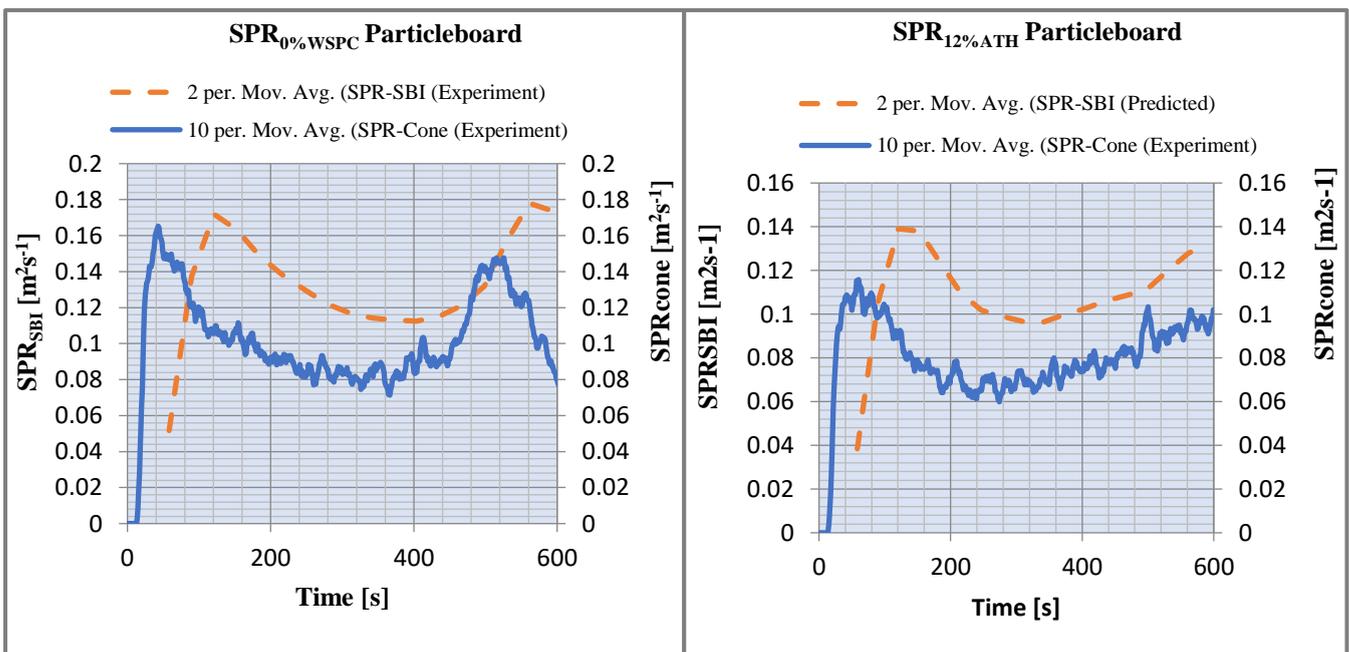


Figure 3: Shows predicted curves of the heat release rate in the SBI compared to cone calorimeter HRR data of the WSP particleboard



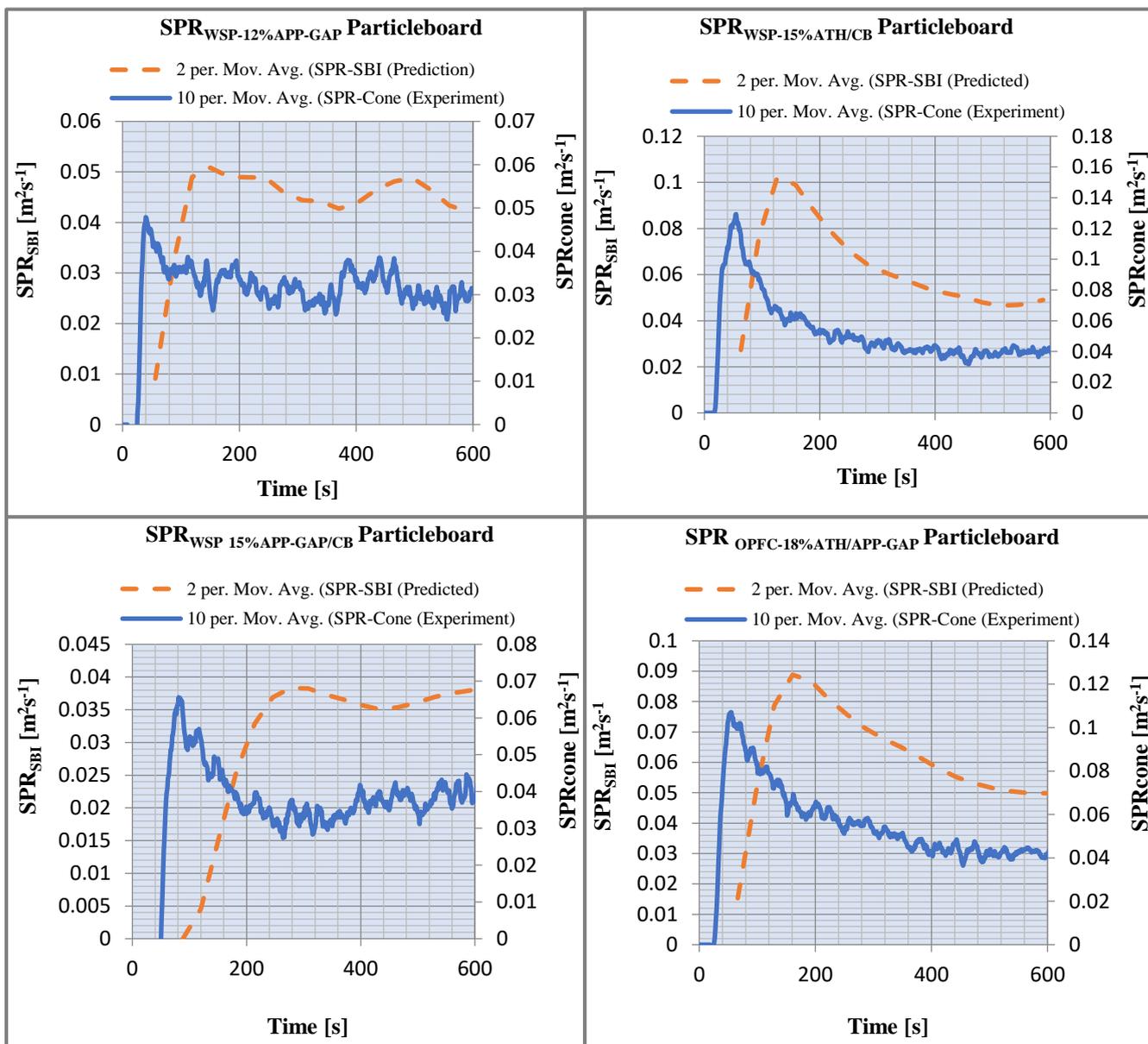
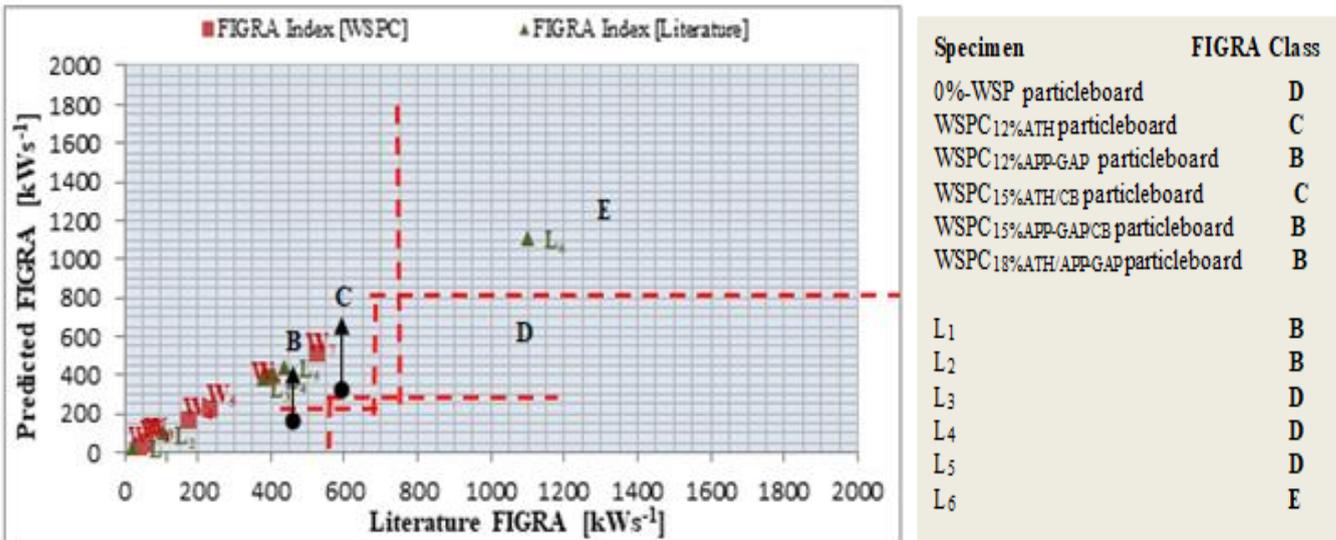


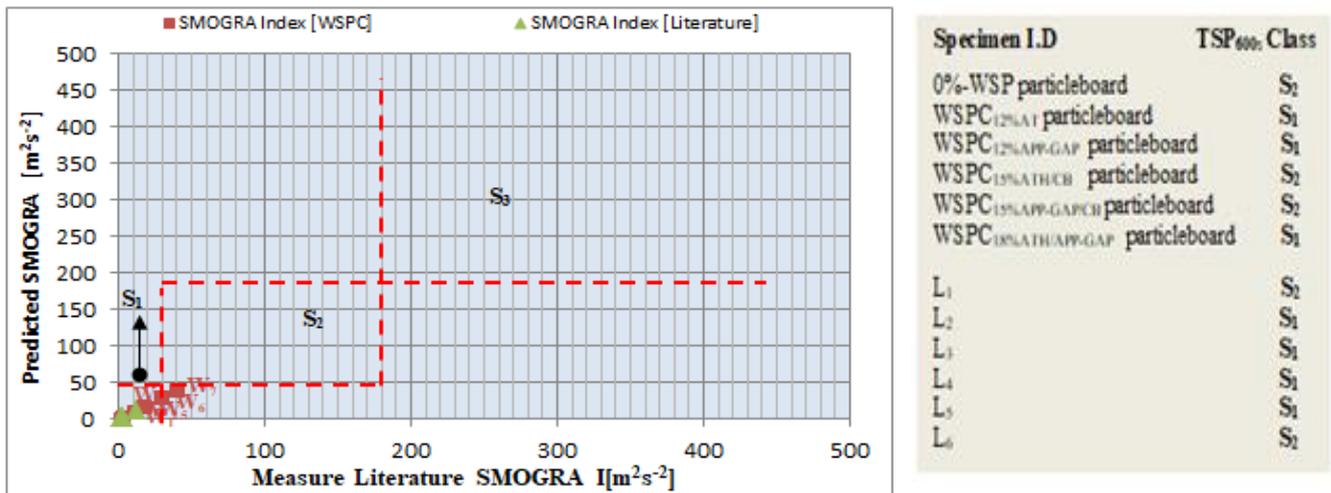
Figure 4: Shows predicted curves of the Smoke production rate in the SBI compared to cone calorimeter SPR data of the WSP particleboard

Figure 4 show the corresponding smoke production rate (SPR) and reveals a similar corresponding trend with the heat is released rate and suggests the release of smoke accompanied with toxic gases as heat is evolved into the atmosphere. Smoke production is an important fire property in determining the suitability of materials for building applications. The SMOGRA value obtained reveals that the 18%ATH/APP-GAP-particleboard followed by 12%APP-GAP-particleboard suppressed better the smoke produced with a SMOGRA of $3\text{m}^2/\text{s}^2$ and $10\text{m}^2/\text{s}^2$ respectively compared to those without FR at $39\text{m}^2/\text{s}^2$ as shown in table 1. This implies that mechanism of APP-GAP interacted with the heat released to produce less smoke in real scale. In Figure 5 a comparison of the

various particleboards with those from literature was classified based on Euro-classification system. It shows the FIGRA and SMOGRA for 12%APP-GAP-particleboard, 15%APP-GAP/CB-particleboard and 18%ATH/APP-GAP particle board falls within the same cell with flame retardant chip board and flame-retardant fire-retardant spruce panel from literature and suggests the panels fall within similar fire safety standard. It indicates that the particleboards contributed very limited fuel load in real scale and was placed as class B-S₁ materials suitable for used for walls and ceilings, interior furnishing, and doors and separating walls applications. The poorest particleboard on the other hand was found for 0%-WSP particleboard with FIGRA and SMOGRA placed in class D-S₂.



(a)



(b)

Figure 5: Comparison of literature and predicted (a) FIGRA indices (b) SMOGRA Indices of the WSP particleboard. The dashed lines indicate the class limits.

L_1 = Flame retardant chip board, L_2 = Flame retardant Fire Retardant Spruce Panel, L_3 : Melamine-faced particle board, L_4 : Ordinary particle board, L_5 : Mass timber (spruce) unvarnished, L_6 : Low density fibreboard

4.0 CONCLUSIONS

This main objective of this research paper is to develop and predict with the convolution model in Duhamel’s integral, the effect of flame retardant on the heat release rate and smoke production in real scale. Therefore, this paper concludes as follows:

- i. Six flame retardants processed with WSP particleboard shows that it is effective in reducing heat release rate and smoke production rate with the 18%ATH/APP-GAP-particleboard exhibiting superiority in real scale as it contributed limited fire and smoke by FIGRA and SMOGRA classification respectively.
- ii. The convolution model in Duhamel’s integral for the HRR_{SBI} and SPR_{SBI} shows closely related trajectory with the cone calorimeter data at

- iii. The FIGRA values for 12%APP-GAP-particleboard, 15%APP-GAP-particleboard and 18%ATH/APP-GAP-particleboard were predicted to be 58kW/s, 57kW/s and 3kW/s respectively while SMOGRA values were predicted to be 10 m²/s², 17 m²/s² and 3 m²/s² respectively which placed the class of particleboards in B-S₁ indicative of very limited contribution to fire in real scale.
- iv. Based on FIGRA and SMOGRA predictions, the for 12%APP-GAP-particleboard, 15%APP-GAP-particleboard and 18%ATH/APP-GAP-particleboard could be safe to meet fire safety standards for interior furnishing of buildings applications.

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