Received: 21 October 2014 | Revised: 6 August 2017 | Accepted: 7 November 2017

DOI: 10.1002/fam.2492

WILEY

RESEARCH ARTICLE

Cone calorimeter testing of foam core sandwich panels treated with intumescent paper underneath the veneer (FRV)

Mark A. Dietenberger[1] | **Ali Shalbafan**[2] | **Johannes Welling**[3]

[1] USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA

[2] Department of Wood and Paper Science and Technology, Faculty of Natural Resources and Marine Sciences, Tarbiat Modares University, PO Box 46414-356, Noor, Iran

[3] Thuenen-Institute (TI) of Wood Research, 21031 Hamburg, Germany

Correspondence
Ali Shalbafan, Department of Wood and Paper Science and Technology, Faculty of Natural Resources and Marine Sciences, Tarbiat Modares University, PO Box 46414-356, Noor, Iran.
Email: ali.shalbafan@modares.ac.ir

Funding information
Thuenen Institute of Wood Research; Tarbiat Modares University

Summary

Surfaces of novel foam core sandwich panels were adhered with intumescent fire-retardant paper underneath the veneers (FRV) to improve their flammability properties. The panels were evaluated by means of cone calorimeter test (ASTM E 1354). Variables tested were different surface layer treatments, adhesives used for veneering, surface layer thicknesses, and processing conditions, having the objective of obtaining similar or better flammability as that of solid particle boards. Previous research showed that sandwich panels without FRV compared to panels with FRV generally had much higher heat release rates, somewhat higher heat of combustion and much higher smoke production due to the polymeric foam component of tested panels. The present study shows that using FRV adhered to the surface layer of sandwich panels dramatically improved flammability properties; the best FRV performance resulted from panels produced with thicker face layer (5 mm) and lower press temperature (130°C) and adhered with an acrylic thixotropic adhesive. Such protected foam core particleboard has heat release rate profiles as low as that is typical of commercially available fire-retardant–treated plywood, thus implying a low flammability rating when tested in accordance with both single burn item (Euro Class B anticipated) and steiner tunnel (North America Class A anticipated) tests.

KEYWORDS

cone calorimeter, fire retardant, foam core particle board, intumescent paper, sandwich panel

1 | INTRODUCTION

Novel, low-density foam core particleboards can be produced in one single production step and may replace conventional particleboards.[1] In principle, such boards can be manufactured in an existing production line of standard particleboards with relatively small machine modifications. Expandable polystyrene (EPS) has been used for *in situ* foaming for core layer materials on the laboratory scale. Once implemented in an industrial production line, the EPS may generate marketability challenges and concerns regarding fire safety of the innovative products.

Cone calorimeter testing has gained worldwide acceptance and is especially useful for the research and development of new products.[2] The nature of foam core particleboard construction makes the cone calorimeter optimal for evaluating flammability, compared with other laboratory-scale tests such as the limiting oxygen index and the micro-combustion calorimeter.[3,4] The cone calorimeter (ASTM E 1354) measures reaction-to-fire parameters with respectable correlations to full-scale fire behavior,[5-7] helping make it the bench-scale fire test of choice. Ignition time, heat release rate (HRR), total heat release (THR), heat of combustion, mass loss rate (MLR), combustion products, and specific extinction area are the main parameters measured and analyzed. The insulation performance of thick wood-based boards in the fire resistance test could be forecast from the results of the cone calorimeter test, especially when the second peak of HRR appeared.[8] In the cone calorimeter tests of wood-based panels, the surface layer density and particles geometry were the dominant parameter for the time to ignition (TTI) and initial HRR.[5,8]

The fire performance of sandwich panels can be improved if the right core material is used and, more importantly, if the face layers are adequately restrained during formation.[9] Mass loss and flammability of different polymeric foam materials used in sandwich panels

Nomenclature: A, area, m^2; a, b, & c, fire growth coefficients, Equation 2; c_f, $(y_f - y_c)/\delta_f$; Cp, heat capacity, J/Kg; k, thermal conductivity, kW/Km; $\dot{Q}$, rate of heat release (RHR), kW; $\dot{q}''$, heat flux, kW/m^2; T, temperature, K; t, time, s; w, burner width, m; y, surface distance, m; δ, feature dimension, m; ρ, material density, kg/m^3; τ, time constant, s; ω, exponential time decay coefficient, 1/s
Subscript definitions: b, propane ignition burner; f, flames adjacent to material; ig, ignition condition; m, material property or condition; p, pyrolyzing condition; w, wall of the room

having metal sheet as face layers were analyzed in a different study.[10] It was mentioned that delamination occurred frequently in sandwich panels because of the resin degradation between face and core layers. The very limited flammability studies that are available on thin foam core sandwich panels with particleboard facing (≤19 mm) indicate the need for a comprehensive investigation of their fire performance.[11]

A previous study[12] involved cone calorimeter test of samples exposed to irradiance of 35 kWm^{-2}. Of the variations in surface layer thicknesses, core foam densities, and processing temperatures for the 19-mm-thick panels, it was surface layer thicknesses that had the most impact on fire behavior of sandwich structures.[12] The addition of flame retardants into the composite mixture was one of the well-known ways to improve the reaction-to-fire properties (eg, HRR) of composites.[13,14] Flame retardants can improve fire safety and that a key reason for the beneficial effect of flame retardants is that they decrease HRR.[15] Furthermore, flame retardants in large quantity increase weight and may have a negative effect on the mechanical properties and long-term stability of a component.[16,17] Some researchers[18-20] recommended using intumescent layers in comparison to those of conventional flame retardants. The study showed[12] that the HRR for the sandwich panels were much higher (by about 100% or more) than those of the conventional particleboard panel. Because increasing surface layer thickness was beneficial for reducing HRR, the use of a veneer with fire-retardant adhesive or intumescent cloth was suggested to seal in the volatiles and provide insulation to prevent foam degradation for a relevant period. Detailed analysis of evolved gases and temperature profile from foam core particleboards when exposed to 50 kWm^{-2} in the cone calorimeter test proved HRR reduction by about 25% when a veneer was added to the panel, and an HRR reduction of 50% when the intumescent veneer was added.[21] Since it was possible to protect the EPS from degradation at 350°C with the added panel surface veneers, it was suggested to further study potential surface treatments, adhesives, panel board thickness, intumescent paper presence, and the board manufacturing temperatures. This work reports the results of those variations. The previous study focused on the pyrolysis features investigated with measurements of temperature, weight loss, and volatile empirical formulation that would suggest additional surface treatment designs to reduce flammability, while this study focusses on the panel combustion properties such as the TTI, HRR, fuel consumption, and combustion emissions as defined in the standards so that a connection can be made with full-scale reaction-to-fire tests, and better ascertain the end use of the panel products. The next section describes the materials used, the panel construction process, and variations in the surface treatment, and the results section primarily uses HRR measurements to assert improvements in the panel flammability.

2 | MATERIALS AND METHODS

2.1 | Production of the panels with face layer variations

Foam core particleboards, with a nominal thickness of 19 mm, were manufactured from a 3-layered mat without additional gluing between face and core layers. For the face layers, the wood particles were mixed with 12% urea formaldehyde resin (Kaurit 350, BASF, Germany) based on oven dry mass of the wood particles and the hardener was 1% ammonium sulfate based on solid content of the resin. Expandable polystyrene (EPS, Terrapor 4, Sunpor, Austria) with a granule size of 0.3 to 0.8 mm was used as the foam core material. According to the data sheet of Terrapor 4, it contains a small amount of flame retardant. This material also contains 5.7% pentane (by weight) as the blowing agent. According to Sunpor between 2% and 3% of the initial pentane remains in the foam cells after expansion, depending on process parameters.

The 3-layered mat was pressed in a laboratory-scale single opening hot-press (Siempelkamp, Germany). The press cycle consisted of 3 consecutive stages: pressing phase, foaming phase, and stabilization phase by the internal cooling of the press plates. For the present study, the temperature of the press plates was set to 130°C (1-EPS; A, B, C panels) and 160°C (2-EPS, D, E, F panels), respectively. The panels were produced with various surface layer thicknesses of 3, 4, and 5 mm for each press temperature (Figure 1). For each surface layer thickness, 4 panel replicates were produced. Shalbafan et al[22] described in detail the pressing schedules and foaming conditions.

A conventional beech veneer (1-mm thickness) with and without intumescent paper (1-mm thickness) underneath the veneer was used. The fire-resistive adhesives used for veneering the samples were Firobond Ultra Adhesive (Product 141) and acrylic thixotropic adhesive (Product 46), named FUA and IA (Intumescent Adhesive), respectively. Both adhesives were supplied by ENVIROGRAF, UK.

The amount of adhesive used for veneering was 235 gr/m^2. Conventional particleboards and sandwich panels without veneer were used as reference samples in this series of tests. Four panels of each series were produced as replicates, and one 100- by 100-mm sample was cut from each panel for the fire performance test in triplicates and with 1 sample retained for other detailed tests.[12] Table 1 provides identifiers for all test materials used in this study.

2.2 | Sample preparation and testing procedure

All samples were conditioned at 23°C and 50% relative humidity for at least 2 weeks prior to testing to meet equilibrium moisture content.

FIGURE 1 The 6 different panel constructions [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Panel specification code

Code	Processing Temperature, °C	Surface Layer Thickness, mm	Veneer	Adhesive
B02	130	4	None	None
A11	130	3	Beech	IA
A21	130	3	Beech	FUA
AV1	130	3	FR	IA
BV1	130	4	FR	IA
CV1	130	5	FR	IA
AV2	130	3	FR	FUA
BV2	130	4	FR	FUA
CV2	130	5	FR	FUA
E02	160	4	None	None
D11	160	3	Beech	IA
D21	160	3	Beech	FUA
DV1	160	3	FR	IA
EV1	160	4	FR	IA
FV1	160	5	FR	IA
DV2	160	3	FR	FUA
EV2	160	4	FR	FUA
FV2	160	5	FR	FUA

Tests were performed according to the ASTM E 1354 test method with a cone calorimeter apparatus (Atlas Electrical Devices, Chicago, Illinois) at the Forest Product Laboratory in Madison, Wisconsin. Samples were exposed in the horizontal orientation to irradiance of 50 kWm^{-2} upon opening the water-cooled thermal shutter and using an electric spark for piloted ignition.

Specimens were tested in the optional retainer frame with a wire grid over the test specimen. The 100- by 100-mm specimens were wrapped with aluminum foil on the sides and bottom and placed in the specimen holder lined with ceramic batting. After ignition of the surface layer, the elevated temperature eventually reaches the foam core layer. This temperature stimulates the remaining pentane in the foam to cause the expansion of the foam during the test. Additional surface expansion will occur when the intumescent paper is used. To overcome excessive spalling and foam expansion that results in direct contact with the cone heater, a surface wire grid was used in all the cone tests to restrain the heated surface. The use of the wire grid as such would reduce the intumescent performance somewhat that relies on its low thermal conductivity and large foam thickness to reduce drastically the heat fluxes entering the panel surfaces and protecting the EPS core. At least the results can be interpreted as being conservative. Ignitability was determined by observing the time for sustained ignition of the specimen for a 4-second period. All tests were done at least in triplicate, and the statistics were done accordingly to ASTM E 1354. Observations of HRR, MLR, effective heat of combustion (EHC), and smoke extinction area (SEA) as functions of time are obtained, although primarily the HRR profile is examined in detail to evaluate flammability in this paper.

2.3 | Flammability methodology

The evaluation of flammability using the cone calorimeter data has differing approaches as discussed in the introduction. A simple flammability evaluation is to use HRR profile as tested in the cone calorimeter of the solid particle board as the reference material to match or exceed with the replacement sandwich panels, as considered in this paper. Or the summary properties of TTI, peak heat release rate (PHRR), THR, average MLR, average smoke extinction area (SEA), and EHC for the solid particle board should be equaled or exceeded. The end use of the innovative panels will place the emphasis on certain regulatory tests, which in this case the single burning item test (SBI) for European market and the Steiner Tunnel (ASTM E84) for the North American market. These full-scale tests would obviously need to done once the sandwich panel equals or betters that of solid particle board in the small-scale fire test.

However, surface treatments of sandwich panels may result in dramatic improvements in the small-scale flammability assessment to where it may be worthwhile to consider correlations developed between the cone calorimeter test measurements and the regulatory tests as available in the literature. The correlations provided by Tsantaridis et al[23] in the case of SBI and Dietenberger and White[6] in the case of Steiner Tunnel are selected for the following reasons. Both these correlations require using radiant heat fluxes set at 50 kWm^{-2} and achieving piloted ignition with a spark plug as was done with the sandwich panels. Correlations based on other radiant heat fluxes settings, ignition conditions, or nonwood-based materials as discussed earlier are not considered here. Both of these references were based on extensive comparisons between cone calorimeter tests and the regulatory tests and seemed applicable to the current evaluation. For comparison with SBI, Tsantaridis et al[23] was able to consider groupings of TTI values to exceed in conjunction with HRR values not to exceed to conservatively predict the SBI categories. The rule of thumb for Euro Class D criteria using cone calorimeter data is TTI >15 seconds and peak HRR (PHRR) <250 kWm^{-2}, for at least 600 seconds from the start of heat exposure. Furthermore, the simple rules[23] for Euro Class B are with TTI >40 seconds and PHRR <100 kWm^{-2} and for Euro Class C with TTI >30 seconds and PHRR <180 kWm^{-2}.Meeting these criteria indicates that a product having these properties conservatively meets the requirements of a certain Euro Class in the SBI test.

For comparison with Steiner Tunnel Test results, Dietenberger and White[6] offered multiple comparison techniques. The first uses the analytical solution of flame spread for the Steiner Tunnel using the HRR profiles in the cone calorimeter that are exponentially decreasing for predicting flame position with time. That is, the total HRR from both burner and material is modeled with exponentially decaying material HRR profile as function of time after initial ignition and of initial ignited area, as given by Dietenberger and White[6]

$$\dot{Q}_t = \dot{Q}_b + \dot{Q}''_{m,ig} A_{ig} \exp(-\omega_m t) + \int_0^t \dot{Q}''_{m.ig} \exp(-\omega_m (t-\xi)) \dot{A}_p \; d\xi \quad (1)$$

where rate of pyrolysis area motivated by flame extension is modeled as

$$\dot{A}_p = \frac{a + bA_p + c\dot{Q}_t}{\tau_m} = \frac{A_f - A_p}{c_f \tau_m} \quad (2)$$

The various terms are related to the cone calorimeter data by either fitting a decaying exponential function to the HRR profile or approximately using the summary data as follows.[6] The materials behave as thermally thick materials at fluxes of 50 kW/m^2, making the formula for material time constant to be proportional to the TTI as

$$\tau_m = k\rho C_p \left(\frac{T_{ig}-T_m}{\dot{q}''_w-\dot{q}''_{ig}}\right)^2 \approx (4/\pi)\mathrm{TTI} \quad (3)$$

For materials that are thermally thin, the time constant is equal to TTI. The material HRR decay parameter is related to the THR of a completely charred, 12.5-mm-thick sample by the equation

$$\dot{Q}''_{m,ig}/\omega_m = \int_0^\infty \dot{Q}''_{m,ig}\exp(-\omega_m t)\,dt \approx (12.5/\delta_m)\int_0^\infty \dot{Q}''_{m,cone}\,dt = \mathrm{THR}(12.5/\delta_m) \quad (4)$$

$$\dot{Q}''_{m,ig} \approx \mathrm{PHRR} \quad (5)$$

The remaining coefficients *a*, *b*, *c*, and C_f as well as burner HRR, initial ignition area, and imposed heat flux are characteristics of the flame spread apparatus, which is the Steiner Tunnel in this case. The burner also has a time response to reach full heat flux that needs to be added to the cone calorimeter's TTI to obtain the actual TTI in the Steiner Tunnel.[6] The Laplace solution was provided to Equation 1 for apparatus HRR and which was then substituted into Equation 2 to solve for the flame extension area and therefore predict the flame spread index (FSI) using the conversion formula provided in ASTM E84. Only some materials can be defined well by a cone calorimeter HRR profile that is exponentially decreasing with time. The second comparison technique became apparent after close examination of the flame spread solution to define an acceleration parameter, β, as the formula[6]

$$\beta = b + c\dot{Q}''_{m,ig} - \omega_m \tau_m \quad (6)$$

That is, the flame spreading is accelerating for $\beta > 0$ and dampening for $\beta < 0$. Substituting in Equations 3 to 5 and using the Steiner Tunnel coefficients, we obtain the alternate calculation as

$$\beta = -0.0855 + \mathrm{PHRR}\left(0.00188 - \frac{(4/\pi)\mathrm{TTI}}{\mathrm{THR}(12.5/\delta_m)}\right) \quad (7)$$

The Class A (FSI < 25) materials correlated with, $\beta < 0$, the Class B (25 < FSI < 75) materials correlated with $0 < \beta < 0.184$, and the Class C (FSI > 75) materials correlated with $\beta > 0.184$.[6] The high accelerated flame spread of Class C materials presented difficulty with the reliability of correlation in that regime. Examination of Equation 7 shows that for if PHRR <45.5 kwm^{-2} or if THR/TTI <677 kWm^{-2} (for material thickness of 12.5 mm), the Class A FSI can be conservatively achieved. Also setting β = 0.184 and TTI to 0, the PHRR <143 kWm^{-2} that would conservatively meet Class B FSI condition. Although it is conceivable to focus only on a single 1 of the 3 flammability summary parameters of TTI, PHRR, or THR to achieve the Class A FSI condition, for practical purposes it is better to increase TTI or decrease PHRR and THR in incremental amounts until the flame spread damping condition β = 0 is just reached. The presence of the retaining grid is likely to affect the PHRR somewhat conservatively while the TTI and THR should be unaffected. These comparison techniques were used in the current study.

3 | RESULTS AND DISCUSSIONS

3.1 | Heat release rate of panels

The size of a fire is directly correlated to the HRR as Equation 2 indicates. Additionally, the HRR will increase as a fire spreads unless the HRR can be made to decrease rapidly enough or be kept to a low value to counter the increase in pyrolysis surface area as implied by Equation 1. Thus, the practical goal for fire retardancy is preventing fire growth via a reduction of HRR rather than merely preventing ignition. Since the steiner tunnel test (ASTM E 84) and the SBI (EN 13823) both last 10 minutes, means that the first 600 seconds of the cone calorimeter test are emphasized for flammability assessment. Additionally, the ASTM E 84 specimen is backed by a heavy cement board that absorbs heat from the exposed specimen, thereby drastically reducing the second HRR peak[6] and extending the period of surface oxidation. However, there are real-world fires in which insulation backing is more the norm.

3.1.1 | Particle board results

As a baseline comparison, conventional particleboards prepared without the foam core were tested in the cone calorimeter, as including the wire grid, which reduces the exposed surface area to the irradiance by 12%. The HRR profiles (Figure 2), at least during the first 600 seconds, are similar to most untreated wood products, with the PHRR around 200 kW/m^{-2} and the steady around 100 kWm^{-2}. For comparison, oriented strand board with similar HRR profile as in Figure 2 was predicted and measured to have an FSI Class C rating.[6,7] Additionally, Tsantaridis et al[23] provided the rating Euro class D to similar materials, particularly if they were near an HRR of 100 kWm^{-2}.

3.1.2 | Foam core particle board results

Figures 3 to 5 show the strong, and yet similar, dual peak HRR profiles of foam core particleboard that is very flammable. Both PHRRs occur within the first 600 seconds of the test with the first PHRR reaching approximately 300 kWm^{-2} and the second PHRR at approximately 500 kWm^{-2}. Obviously, these HRR profiles are much higher than the reference particle board results discussed previously, indicating a very flammable condition that needs some discussion. The first peak is the result of initially ablating the surface exposed to a combined cone heater and flame radiance on the surface. The HRR then decreases as a result of surface charring and the thermal wave process following the ablative process. In essence, the pyrolysis front develops and is decreasing in movement speed and, with the char density staying constant, the volatilization mass rate is also decreasing. Because the volatile heat of combustion is fairly constant for initially dry wood, the HRR is also decreasing.[24,25] The HRR eventually begins to rise as a result of the thermal wave termination at the insulated, bottom surface, which means the sample is entering the thermally thin regime that broadens the thin pyrolysis zone and also accelerates the pyrolysis front movement. For a surface layer sufficiently thin and backed by an insulation board, such as EPS, the dual peaks in the HRR merge together into a single initial peak, such that the surface layer is treated as thermal capacitance that controls the heating process and, therefore, the pyrolysis process.[24,25] However,

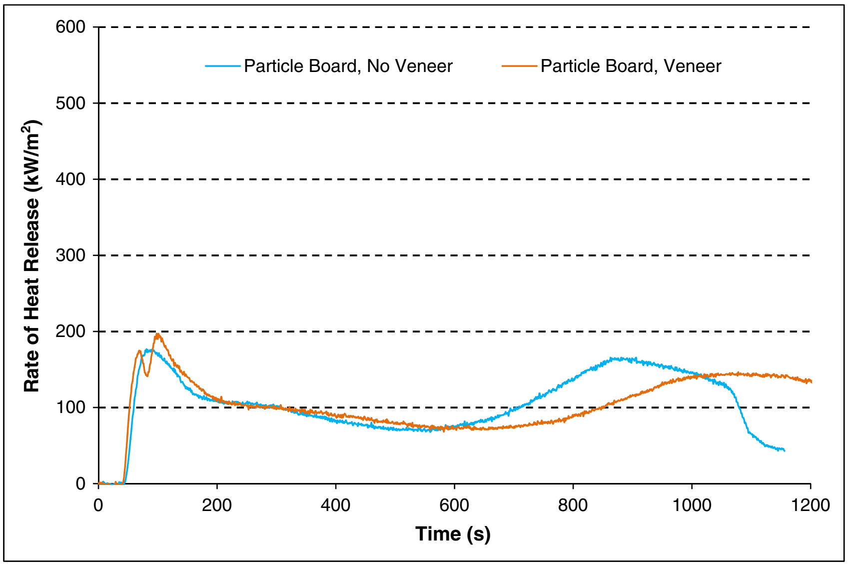

FIGURE 2 HRR of the baseline wood product as particleboard [Colour figure can be viewed at wileyonlinelibrary.com]

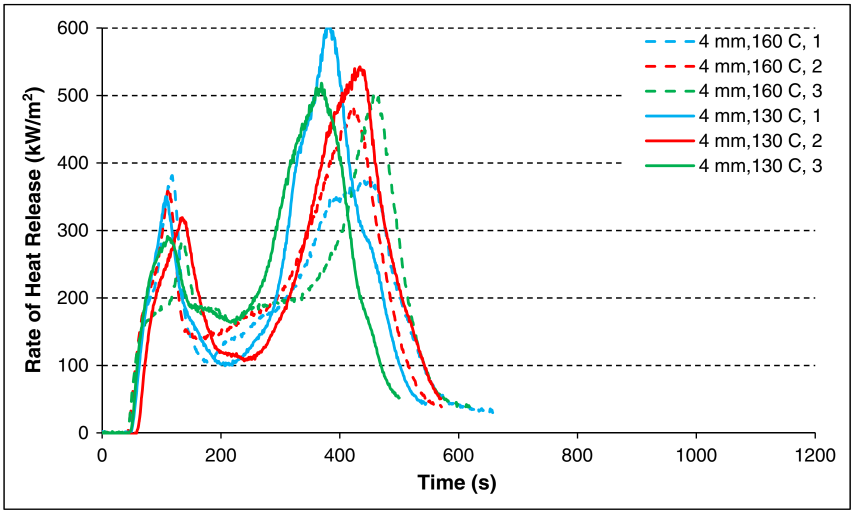

FIGURE 3 HRR of foam particle boards of type E and B in Figure 1 with no veneer as exposed to 50 kWm^{-2} [Colour figure can be viewed at wileyonlinelibrary.com]

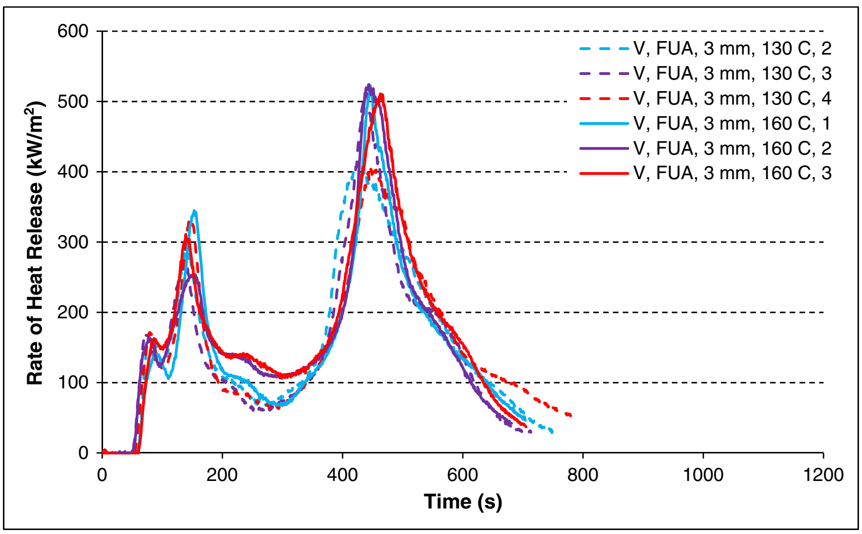

FIGURE 4 HRR profile of foam particle boards of type A and D with beech veneer adhered with FUA as exposed to 50 kWm^{-2} [Colour figure can be viewed at wileyonlinelibrary.com]

because there is a second, backside surface layer of particleboard, eventually the EPS will have fully melted and the charred remains of the exposed surface layer heats the backside surface layer by contact or radiation. Further volatilization occurs when the backside particleboard reaches the volatilization temperatures after a period of heating. The surface oxidation from the infusion of air takes over

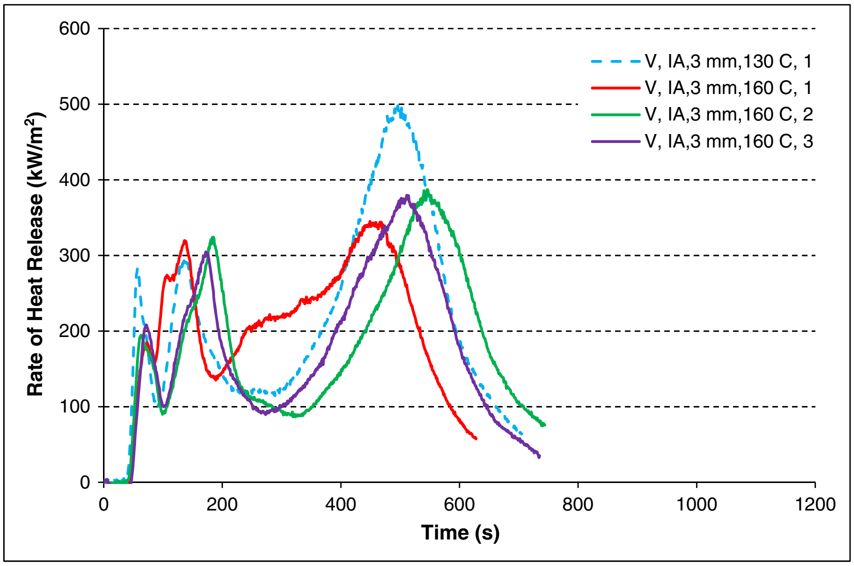

FIGURE 5 HRR profile of foam particle boards of type A and D with beech veneer adhered with IA as exposed to 50 kWm^{-2} [Colour figure can be viewed at wileyonlinelibrary.com]

at some point at a PHRR, and as the material is consumed, the HRR will decrease once again. Results illustrated in Figures 4 and 5 show that no improvements in HRR profiles have been achieved by using the beech veneer with either FUA or IA adhesives.

3.1.3 | Fire-retarded surface layer

Because detailed temperature measurements in an earlier study[12] showed that the foam core easily reached degradation temperatures, even with ordinary veneers, it was suggested to use a commercial veneer with an intumescent layer to protect the panel during fire exposures. The EnviroGraf Intumescent cloth with a 1-mm-thick veneer was used, although other similar products can be used. Results of using fire-retardant veneer with intumescent paper underneath the veneer (FRV) with various panel constructions are shown in Figures 6 to 9. All tests had the similar first and narrow PHRR of about 220 kWm^{-2} because of FRV degradation occurring at 50 seconds. The presence of the second PHRRs of various magnitudes at 200 to 300 seconds is due to the surface layer degrading and emitting combustible volatiles through the degraded FRV. The third HRR peak for all tests occurred after 600 seconds, indicating that the FRV resulted in HRR reduction compared with the unprotected panels. This is a conservative result as greater foam thickness with associated lower foam density due to the intumescent process would have been achieved without the wire grid restraint to provide even better protection to the panel and EPS from the heat source.

To compare the effects of adhesives, surface layer thickness, and processing temperatures, the second PHRR is worth further examination. The least improvement was obtained with FRV adhered with FUA and processing temperature of 160°C (Figure 6). Our microscopic observation of the surface layer densification revealed a relatively low compacted surface layer (in panels produced with a processing temperature of 160°C) in which some of the adhesive can penetrate into the surface layers, resulting in a relatively weak bond as well as in higher porosity for the volatiles to flow.[22] Additionally, the FUA is described in the EnviroGraf literature as to not give adhesive strength at high temperatures during cone test. As Figure 6 shows, even though the second PHRR is reduced and somewhat delayed compared with that in Figure 4, the HRR improvement overall now is somewhat comparable to Figure 2 for particleboard.

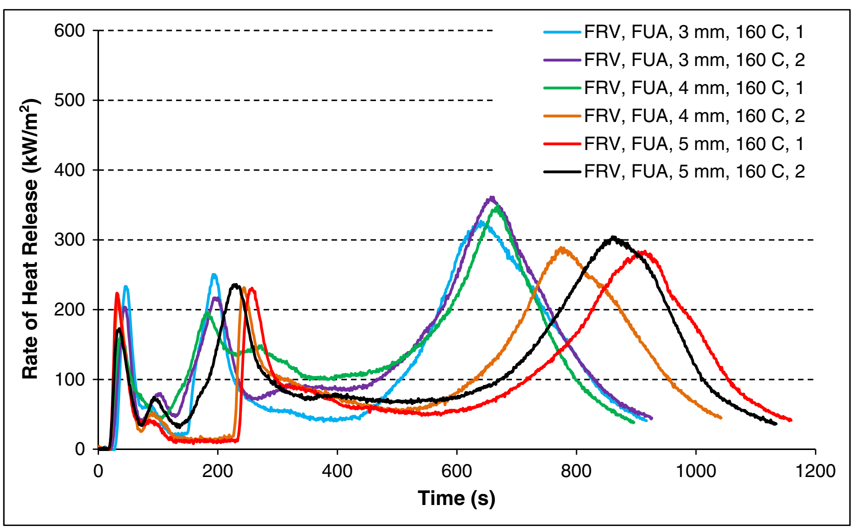

FIGURE 6 HRR of foam particle boards for types D, E, and F of FRV adhered with FUA and processing temperature of 160°C [Colour figure can be viewed at wileyonlinelibrary.com]

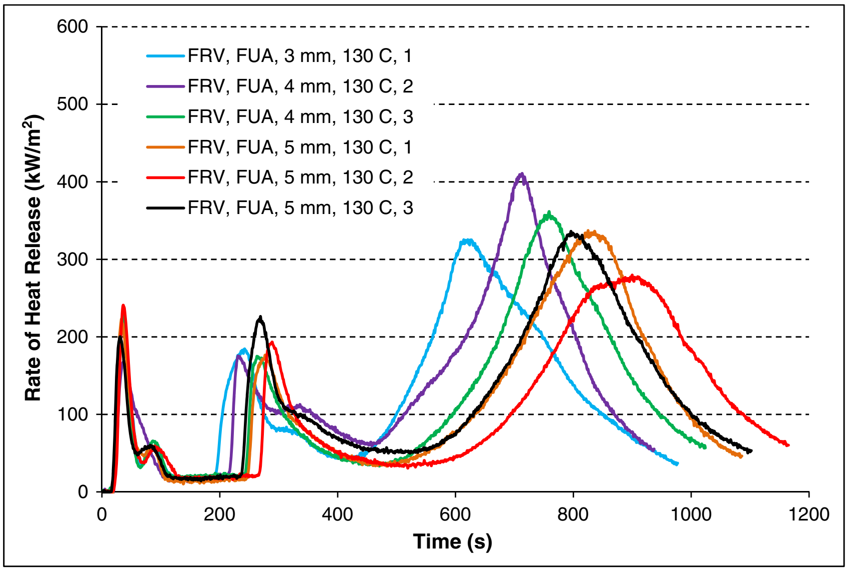

FIGURE 7 HRR of foam particle boards for types A, B, and C of FRV adhered with FUA and processing temperature of 130°C [Colour figure can be viewed at wileyonlinelibrary.com]

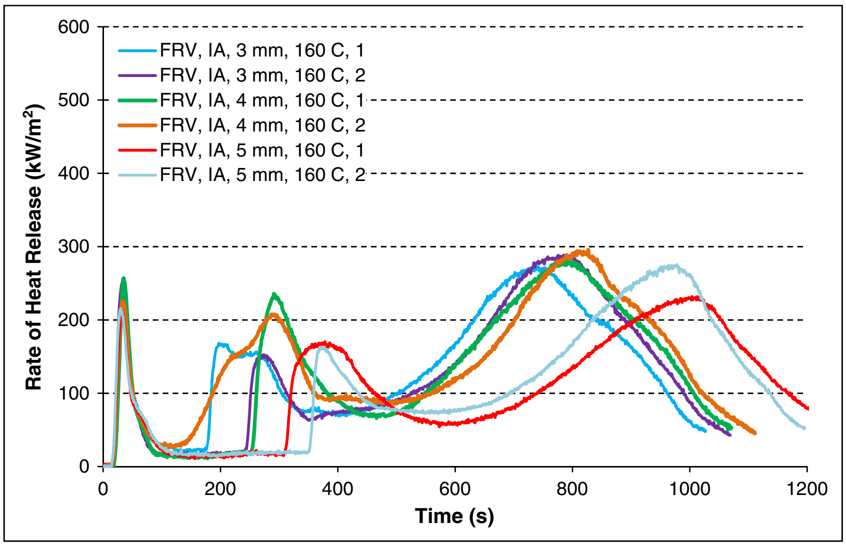

FIGURE 8 HRR of foam particle boards for types D, E, and F of FRV adhered with IA and processing temperature of 160°C [Colour figure can be viewed at wileyonlinelibrary.com]

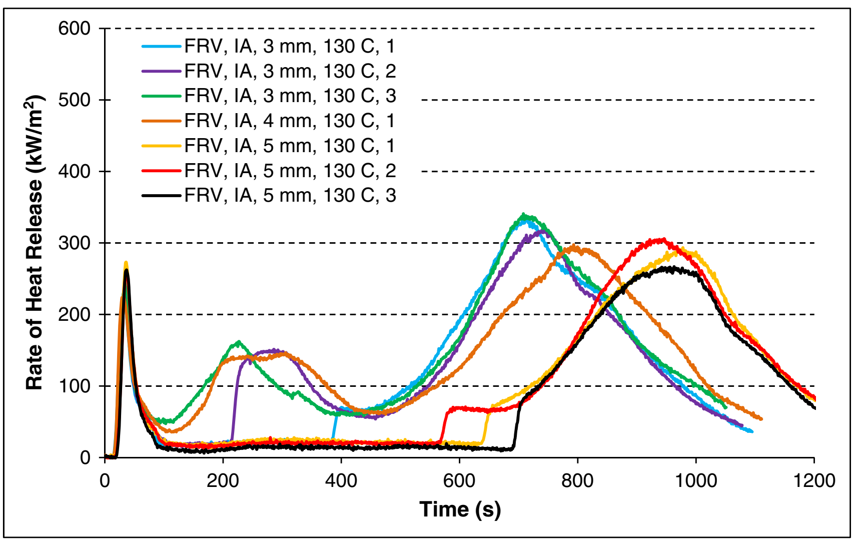

FIGURE 9 HRR of foam particle boards for types A, B, and C of FRV adhered with IA and processing temperature of 130°C [Colour figure can be viewed at wileyonlinelibrary.com]

The next level of improvement is shown in Figure 7, where a lower processing temperature of 130°C for panel production resulted in a denser surface layer. This increases the thermal inertia of the layer that prolong the temperature rise to ignition as predicted with Equation 3, to permit more rapid transition from ablation to charring to lower the pyrolysis MLR. In the use of FUA adhesive similar to that of panels produced by processing temperature of 160°C, there is a further delay in the second PHRR by about 100 seconds, and the improvement in the overall HRR is somewhat better than that of the particleboard in Figure 2. Because the second and third PHRRs are around 200 kWm^{-2} or higher, it would still have a predicted fire classification of Euro Class D, conservatively.[23] A somewhat better improvement in reducing HRR is shown in Figure 8, where the FRV is adhered with IA on the less dense surface layer with processing temperature of 160°C. Envirograf literature describes this adhesive as adhering wood joints for a long period of high temperature exposure time, for at least 60 minutes. It appears the greater volatile blocking provided by the IA has similar effects on the initial HRR profile as the higher density surface layer effects on enhanced charring. The thickest surface layer of 5 mm has the longest delay for the second PHRR at approximately 400 seconds. The thicker surface layer takes advantage of the thermal wave process that lowers the pyrolysis rate with time. With the HRR tending to hover around 100 kWm^{-2}, the maximum HRR less than 180 kWm^{-2}, and if the initial PHRR of FRV can be lowered with FRT coating, an Euro Class C can be possibly predicted according to Tsantaridis et al[23] criterion.

The best performance in reducing the HRR is shown in Figure 9, in which the second PHRR has been eliminated by using FRV adhered with IA to the thickest and densest surface layer tested. This is due to a combination of 4 enhancing physical effects that are working together: first with intumenscent to reduce heat flux levels below it, second with IA to block volatiles better, third with thicker surface layer to promote thermally thick behavior, and finally, higher surface layer density to slow the temperature rise rate to promote charring associated with the lower degrading temperatures. This low HRR lasted over 600 seconds until the back surface layer began oxidizing. If the narrow PHRR due to the initial FRV degradation is also reduced sufficiently with an FRT paint, it can even be expected that a North America Class A FSI and Euro Class B are attainable. It is likely that if FRV is adhered with FUA to conventional particleboard, a similar level of reduction of HRR will also occur, but with the third PHRR occuring at an even later time than 900 seconds.

3.2 | Further cone calorimeter results

Cone Calorimeter summary data (TTI, PHRR, EHC, MLR, and SEA), Beta and THR/TTI ratio reported in Table 2 are average of 3 replicates and standard deviation for the panels considered for this study. Despite the differences presented in Table 2, the tendency to flame spread indicated by the Beta calculation as predicted with Equation 7 are generally greater than 0.184 for all the panels, predicting for them a Class C FSI. Evidently, the narrow peak HRR due to burning of the FRV has biased the results of the summary data (Table 2). To correct this predictive problem, flame spread modeling could be revised to consider a narrow peak HRR instead of the more gradual exponential decay of the sample's HRR profile in the model formulation described by Equations 1 and 2. Of course, if the initial peak HRR is reduced with a brushed-on surface coating to where the exponential HRR decay can

TABLE 2 Cone calorimeter summary data for average of 3 replicates and standard deviation, Beta and THR/TII ratio

Code	TTI, s	PHRR, kWm^{-2}	THR, MJm^{-2}	AEHOC, MJ/kg	AMLR (10-90%), g/s	ASEA, m^2 kg^{-1}	Beta	THR/TTI, kWm^{-2}
B02	55.5 (6.6)	320.2 (29.6)	118.8 (4.9)	17.4 (0.3)	16.1 (0.2)	545 (56.2)	0.326	2141
A11	38.1 (1)	284 (1)	147.9 (1)	18.7 (1)	13.5 (1)	579 (1)	0.355	3877
A21	54.5 (0.6)	300.8 (43.7)	113 (6.7)	15.7 (0.1)	12.5 (0.2)	461.8 (25.5)	0.295	2071
AV1	17.6 (1.5)	234 (10.6)	138.9 (11)	16.9 (1.6)	9.1 (0.2)	624.1 (62.6)	0.317	7874
BV1	16.9 (2.3)	240.8 (17.1)	147.8 (7.4)	13.8 (4.4)	11 (2.1)	404 (123)	0.332	8741
CV1	18.9 (1.3)	265.5 (6.7)	117.9 (9.9)	11.6 (1.1)	9.5 (0.2)	347.7 (75.8)	0.360	6242
AV2	19.5 (1.6)	245.1 (25.1)	119.8 (7.4)	16 (1.4)	8.7 (0.3)	832 (59)	0.325	6143
BV2	19 (0.6)	201.9 (37.5)	120.7 (3.7)	14.2 (0.1)	10 (0.8)	971.5 (60)	0.254	6336
CV2	19.8 (2.4)	221.3 (20.4)	125.3 (3.8)	13.2 (0.7)	9.8 (0.4)	391.9 (15)	0.286	6319
E02	48.8 (2.9)	342.6 (52.2)	118.2 (2.5)	16.9 (0.3)	14.8 (0.4)	497.9 (43)	0.379	2421
D11	44 (2.9)	240.2 (68.9)	128 (3.9)	17 (0.6)	13 (0.6)	535 (104)	0.261	2912
D21	59.6 (4.6)	303 (46.1)	115.7 (6.9)	15.5 (0.9)	13.6 (0.1)	518.5 (60)	0.286	1940
DV1	16.9 (0.2)	238.7 (15.4)	134.2 (2.7)	16.3 (1.8)	8.9 (0.6)	554.3 (61)	0.325	7925
EV1	18.2 (2)	229 (26.4)	149.7 (9.2)	16.6 (1.1)	9.8 (0.3)	566.4 (18)	0.310	8240
FV1	15 (0.7)	215.4 (1.2)	135.3 (4.4)	13.2 (0.4)	9.6 (0.2)	391.3 (31)	0.289	8997
DV2	25.5 (1.9)	222.2 (16.2)	119 (7.9)	16.1 (0.6)	9.1 (0.4)	554.4 (39)	0.272	4669
EV2	18.9 (0.7)	179.8 (30.9)	118.6 (6.1)	14 (0.6)	10.4 (1)	454.1 (19)	0.216	6257
FV2	20.3 (2.1)	191.3 (27.9)	128.1 (8.9)	13.2 (0.8)	9.8 (0.5)	375.6 (23)	0.236	6295

Values in parentheses are standard deviations. Beta is defined in Equation 6.

Abbreviations: AEHOC, average of effective heat of combustion; AMLR 10-90, average mass loss rate for 10%-90% of ultimate mass loss; ASEA: average specific extinction area; PHRR: initial peak of heat release rate; TSI: time to sustained ignition.

be approximated, then the associated coating PHRR can be used in the empirical formulation to predict Class A (with PHRR <46 kWm^{-2}) or Class B (with PHRR <143 kW/m^{-2}) instead of Class C. In any case the examination of the HRR profiles and comparing with reference HRR profiles provided a more useful flammability assessment than the cone calorimeter data summary shown in Table 2.

The best fire performance material, CV1, is the foam core particleboard created with processing panel temperature of 130°C forming a 5-mm surface layer thickness while using the IA adhesive with an intumescent veneer. It has the lowest EHC at 11.6 MJ/kg and the lowest smoke extinction area (SEA) at 348 m^2 kg^{-1} of all the materials tested, while its PHRR and MLR are comparatively low. No flammability consistency could be found for TTI only, except that it depends on surface type.

4 | CONCLUSION

It is noted that selections of physical attributes, which are material higher density, larger thicknesses, better flow blockage, and intumescent features rather than improving FRT chemistry were effective in the improved flammability properties of the foam core particleboard as measured with the cone calorimeter. The improvements to the surface layer were instrumental in protecting the EPS from degradation in mechanical properties when the panel was exposed to heat fluxes associated with relatively severe fires. We reaffirm the cone calorimetry as the bench-scale fire test of choice, particularly for devising multiple surface treatments to improve flammability.

The best fire performance for a foam core particleboard is offered by a processing panel temperature of 130°C, a 5-mm surface layer thickness, and IA adhesive with an intumescent veneer. This optimal panel is predicted to likely meet the Euro Class B (SBI) and North America Class A FSI (ASTM E 84) via the cone calorimetry HRR profile data at irradiance of 50 kWm^{-2} and with piloted ignition. This assessment was determined comparing the HRR profiles of the samples to some reference materials that have known HRR profiles with the associated flammability classifications. Other combinations of FRV with alternative adhesives, surface layer thicknesses, and processing temperature also resulted in much reduced HRR, to the point that they would be an equivalent replacement to conventional particleboard. The prediction of flammability ratings based on the summary data (Table 2) was ineffective for this particular panel product. This was attributed to the presence of a sharp and narrow peak HRR of the FRV material as not being accounted for in the flame spread model. However, removal of such a peak HRR with an added FRT paint coating would bring the flammability rating determined from the summary data to be in agreement with the process of comparing the HRR profiles to reference materials with well-established flammability ratings.

ACKNOWLEDGEMENTS

The authors thank Dr Robert White (deceased) and Carol Clausen of the Forest Products Laboratory for their support of this research and technician Ms Anne Fuller for collecting the data. We also thank Tarbiat Modares University and Thuenen Institute for financial support of this work. This work was performed by the US government employees on official time and is therefore in the public domain not subject to copyright in the United States.

ORCID

Ali Shalbafan http://orcid.org/0000-0002-7355-5977

REFERENCES

1. Shalbafan A, Luedtke J, Welling J, Fruehwald A. Physiomechanical properties of ultra-lightweight foam core particleboard: different core densities. *Holzforschung*. 2013;67:169-175.
2. Scudamore MJ, Briggs PJ, Prager FH. Cone calorimetry—a review of test carried out on plastics for the association of plastic manufacturers in Europe. *Fire Mater*. 1991;15(2):65-84.
3. Weil ED, Patel NG, Said MM. Oxygen index: correlations to other fire tests. *Fire Mater*. 1992;16(4):159-167.
4. Morgan AB, Galaska M. Microcombustion calorimetry as a tool for screening flame retardancy in epoxy. *Polymers for Advanced Technologies*. 2008;19(6):530-546.
5. Lee B-H, Kim H-S, Kim S, et al. Evaluating the flammability of wood-based panels and gypsum particleboard using a cone calorimeter. *Construct Build Mater*. 2011;25(7):3044-3050.
6. Dietenberger MA, White RH. Reaction-to-fire testing and modeling for wood products, 12th Annual BCC Conference on Flame Retardancy, Stamford, CT. Norwalk, CT, Business Communications Co, 2001; 54–69.
7. White RH, Dietenberger MA. Cone calorimeter evaluation of wood products. 15th Annual BCC conference on Flame Retardancy, Stamford, CT. Norwalk, CT, Business Communications Co, 2004.
8. Harada T, Uesugi S, Masuda H. Fire resistance of thick wood-based boards. *J Wood Sci*. 2006;52(6):544-551.
9. Cooke GME. Stability of lightweight structural sandwich panels exposed to fire. *Fire Mater*. 2004;28(24):299-308.
10. Albani AWG, Kluiver LLD, de Korte ACJ, van Herpen RAP, Weewer R, Brouwers HJH. Mass loss and flammability of insulation materials used in sandwich panels during the pre-flashover phase of fire. *Fire Mater*. 2017;41(6):779-796. https://doi.org/10.1002/fam.2418
11. Luedtke J. Development and evaluation of a concept for the continuous production of lightweight panels comprising a polymer core and wood-based panel facings. (Dissertation), University of Hamburg, 2011.
12. Shalbafan A, Dietenberger MA, Welling J. Fire performances of foam core particleboards continuously produced in a one-step process. *European Journal of Wood and Wood Products*. 2013;71(1):49-59.
13. Levchik SV, Camino G, Costa L, Luda MP. Mechanistic study of thermal behaviour and combustion performance of-carbon fibre-epoxy resin composites fire retarded with a phosphorous-based curing system. *Polym Degrad Stab*. 1996;54(2-3):317-322.
14. Hshieh FY, Beeson HD. Flammability testing of flame-retarded epoxy composites and phenolic composites. *Fire Mater*. 1997;21(1):41-49.
15. Hirschler MM. Flame retardants and heat release: review of data on individual polymer. *Fire Mater*. 2015;39(3):232-258.
16. Eibl S. Reaction-to-fire properties of polymer matrix composites with integrated intumescent barriers. *Fire Mater*. 2014;39:658-674.
17. Kandola BK, Kandare E. Composites having improved fire resistance. In: Horrocks AR, Price D, eds. *Advances in Fire Retardant Materials*. Cambridge, U.K.: *Woodhead Publishers*; 2008:398-442.
18. Jimenez M, Duquesne S, Bourbigot S. Characterization of the performance of an intumescent fire protective coating. *Surf Coat Technol*. 2006;201(3-4):979-987.
19. Camino G, Costa L, Martinasso G. Intumescent Fire-retardant Systems. *Polym Degrad Stab*. 1989;23(4):359-376.
20. Kandola BK, Horrocks AR, Myler P, Blair D. The effect of intumescents on the burning behavior of polyester-resin-containing composites. *Composites: Part A*. 2002;33(6):805-817.

21. Dietenberger MA, Shalbafan A, Welling J, Boardman C. Treated and untreated foam core particleboards with intumescent veneer. *Journal of Thermal Analysis and Calorimetry*. 2013;114(3):979-987.

22. Shalbafan A, Welling J, Luedtke J. Effect of processing parameters on physical and structural properties of lightweight foam core sandwich panels. *Wood Material Science and Engineering*. 2012;8:1-12.

23. Tsantaridis L, Östman B, Hakkarainen T. Euroclass predictions for wood based products with improved fire performance – a rule of thumb, SP Technical Research Institute of Sweden, SP Report 2010.

24. Dietenberger MA. Update for combustion properties of wood components. *Fire Mater*. 2006;26:255-267.

25. White RH, Dietenberger MA. *Wood Handbook: Wood as an Engineering Material. Chapter 18: Fire Safety of Wood Construction*. 18-1 Madison, Wisconsin, USA: Forest Products Laboratory, Department of Agriculture Forest Service; 2010:18-22.

How to cite this article: Dietenberger MA, Shalbafan A, Welling J. Cone calorimeter testing of foam core sandwich panels treated with intumescent paper underneath the veneer (FRV). *Fire and Materials*. 2017;1–10. https://doi.org/10.1002/fam.2492