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Alternative fire performance screening method of cladding system using cone calorimeter

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ABSTRACT

Small-scale cone calorimeter tests are commonly used to evaluate the flammability properties of building materials used in cladding systems. However, the combined effect of aluminium composite cladding panels (ACPs) and insulations used in cladding systems has rarely been investigated in the field of small-scale fire assessment. This could be due to a lack of device adaptation for testing multi-component materials, as well as difficulties in translating the results to real-world scenarios. In this study, an alternative fire performance screening method based on a cone calorimeter is developed to evaluate the flammability properties of the cladding system. Two types of assemblies were tested to highlight the interaction between panel and insulation in cladding systems: i) layer-by-layer and ii) side-by-side. The results showed that the more flammable insulation accelerated the global combustion kinetics in side-by-side assemblies. The presence of insulation to the back of the cladding panel in layer-by-layer assemblies caused a thermal thickening, which slowed the combustion of the front cladding panel. Finally, acceptance criteria are developed to assess the fire risk of cladding systems.

1. Introduction

The lightweight cladding systems frequently used in high-rise buildings are composed of organic polymeric materials, which creates a high fuel load in a fire, increasing the fire hazard. Aluminium composite panels (ACPs) have received much attention in the cladding fire issue, and mitigation efforts have been largely focused on fire testing protocols and consistent risk ranking [1–3]. The ACP cladding system is a combination of cladding panels (ACP-PE, ACP-FR and ACP-NC/ACP-A2) and insulation foams, including polyisocyanurate (PIR), phenolic foam (PF), extruded polystyrene (XPS) and glass wools (GW) (see Fig. 1). ACP-PE consists of two sheets of aluminium (thickness-0.5 mm) sandwiching a core layer of 100% polyethylene (PE). The other varieties are PE (30%) filled with mineral filler (70%) as a fire retardant (FR) and non-combustibles (NC) of 93 to 100% inorganic composite or mineral filler (see Fig. 2) [1–3]. ACP cladding system is a cost-effective option for thermal insulation, weatherproofing (e.g., heavy rain), and building aesthetic appeal [3]. However, different combustibles, including core materials of panels and insulation in such systems, have become routes for rapid fire spread through the building exterior during fire incidents [1,4,5]. The incidents at Lacrosse Building in Melbourne (2014), Dwelling Building in Baku (2015), Grenfell Tower in London (2017), and Neo Tower in Melbourne (2019) underscored the grave risks associated with the inappropriate utilisation of flammable cladding materials in the construction of building exteriors [6]. While the Lacrosse and Neo towers did not result in any fatalities, the Baku fire claimed the lives of 16 individuals, and the Grenfell Tower fire led to a staggering 72 fatalities [6]. These tragic outcomes highlight the serious consequences of fire incidents caused by the use of combustible ACP cladding systems in buildings. Furthermore, toxic smoke can make people unconscious during a cladding fire, resulting in death without rescue [1,7]. The resultant fire behaviour of various combustibles during combustion must be recognised to estimate fire risk.

McKenna et al.[1] studied different cladding panels and insulation for flammability and toxicity analysis under small-scale fire testing. The major components like ACPs, insulations and sarking or waterproof

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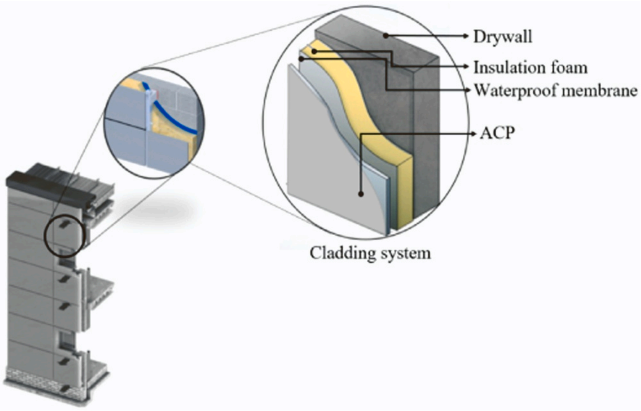


Fig. 1. Details of cladding system.

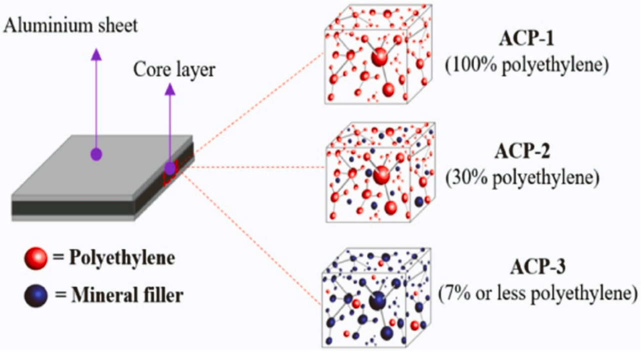


Fig. 2. Different types of ACP cladding.

membranes in cladding systems have been used to develop an assessment framework for analysing fire behaviour [4]. The thermal and flame behaviour test database was developed using small-scale test apparatus like thermogravimetric analysis (TGA), bomb calorimeter and cone calorimeter [4]. Recently, Khan et al.[5] also studied the fire retardant ACPs (ACP-FR and ACP-NC) under cone calorimeter fire testing. However, most fire studies suggested that the crisis of cladding fire is a resultant effect of all materials in the system and is not limited to ACPs only.

Building codes in Australia, New Zealand, and Japan allow the use of cone calorimeters to assess the fire risk rating of lining and insulation materials in buildings [8–10]. Most likely, only the reaction–to–fire properties of individual cladding materials or single components are available under small-scale test protocol. Reaction-to-fire behaviour such as time to ignition (t_{ign}), peak heat release rate (pHRR), total heat release (THR), mass loss rate and smoke production can be measured by a cone calorimeter [1,11,12]. Most papers deal with the additive method for fire assessment ranking of the complete assembly using individual component values of the multi-component assemblies. The behaviour of assemblies is hardly ever investigated in reaction-to-fire attributes, possibly due to a lack of equipment designed for testing multi-component materials and the difficulties in translating the results to real-world scenarios [13,14].

This study explores the resultant flammability properties of combined assemblies of the ACP cladding system under a small-scale cone calorimeter. The objective is to characterise the flammability properties of the cladding assemblies and to evidence and understand the potential interactions between ACPs and insulations. Tests were performed with ACP claddings (ACP-1, ACP-2 and ACP-3) and insulation (extruded polystyrene-XPS and glass wool-GW). Two combined assembly configurations were considered: i) layer-by-layer and ii) side-by-side.

2. Experimental materials and methods

The current study examines the reaction-to-fire properties of single and the combined effects of cladding panels and insulation. It is also used to predict the combined behaviour of cladding panels and insulation as part of a cladding system. Based on the test data of pHRR and THR, a risk assessment classification is developed. In Fig. 3, the detailed flow process of analysing the flammability of test samples and the related prediction method is shown.

2.1. Test specimens

Table 1 provides a summary of the test specimens investigated in this study. The research focuses on cladding systems shown in Fig. 1, incorporating cladding panels and insulations. Three distinct types of commonly used cladding were employed, namely ACP-1, ACP-2, and ACP-3 (Fig. 2). Notably, ACP-1, consisting of 100% PE cladding, was found in the Grenfell Tower fire disaster [1,5]. ACP-2 and ACP-3 were selected to showcase variations in fire performance attributed to

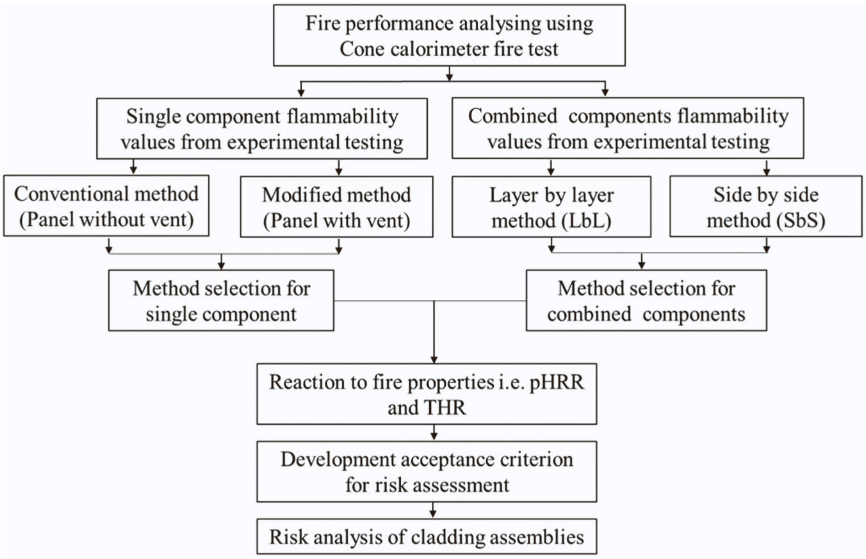


Fig. 3. Flow chart for developing a prediction method to evaluate flammability properties of combined components of cladding systems.

Table 1
List of materials used in a typical cladding system.

Sl.No	Sample code	Materials	Thickness (mm)	Density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat (Jg^{-1}K^{-1})
01	ACP-1	100% PE	4 (3*)	917	0.29	2.16
02	ACP-2	30% PE	4 (3*)	1617	0.33	1.53
03	ACP-3	7% PE	4 (3*)	1650	1.00	1.05
04	XPS	Polystyrene**	25	28	0.02	1.71
05	GW	Glass wool	25	45	0.03	0.85

[*] only core,* *extruded polystyrene, PE= polyethyelene

Table 2
Test assemblies of different samples.

Test No.	Sample code	Configuration	Assemblies*	Description
1	SC-1	Panel core only	Single	100% LDPE
2	SC-2		Single	30% LDPE
3	SC-3		Single	7% LDPE
4	SC-4	Insulation	Single	Extruded polystyrene (XPS)
5	SC-5		Single	Glass wool (GW)
6	SP-1	Panel only	Single	100% LDPE panel (ACP-1)
7	SP-2		Single	30% LDPE panel (ACP-2)
8	SP-3		Single	7% LDPE panel (ACP-3)
9	SPV-1	Panel with vent	Single	100% LDPE panel (ACP-1)
10	SPV-2		Single	30% LDPE panel (ACP-2)
11	SPV-3		Single	7% LDPE panel (ACP-3)
12	SJ-1	Panel + insulation	Combined (SbS)	ACP-1 + Extruded polystyrene
13	SJ-2		Combined (SbS)	ACP-2 + Extruded polystyrene
14	SJ-3		Combined (SbS)	ACP-3 + Extruded polystyrene
15	SJ-4		Combined (SbS)	ACP-1 + Glass wool
16	SJ-5		Combined (SbS)	ACP-2 + Glass wool
17	SJ-6		Combined (SbS)	ACP-3 + Glass wool
18	SS-1	Panel + insulation	Combined (LbL)	ACP-1 + Extruded polystyrene
19	SS-2		Combined (LbL)	ACP-2 + Extruded polystyrene
20	SS-3		Combined (LbL)	ACP-3 + Extruded polystyrene
21	SS-4		Combined (LbL)	ACP-1 + Glass wool
22	SS-5		Combined (LbL)	ACP-2 + Glass wool
23	SS-6		Combined (LbL)	ACP-3 + Glass wool

[*] LbL= layer-by-layer (superimposed); SbS= side-by-side (Juxtaposed).

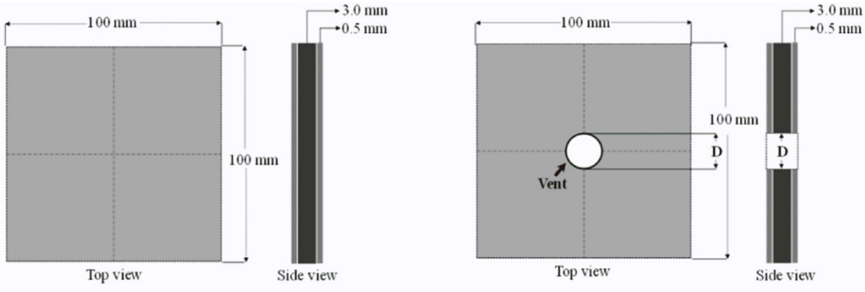
different core materials, representing widely used commercial cladding in the current market [1,5]. The core materials of ACP-2 and ACP-3 comprised a blend of polymer (PE) with varying levels of fire-retardant mineral fillers (Aluminium trihydrate and Calcite). ACP-2 and ACP-3 contained approximately 30% and 7% of the polymer in the total core composites, respectively. Density and thermal conductivity data were sourced from materials suppliers, revealing ACP-1 with a density of 917 kg/m^3 and thermal conductivity of 0.28 W/m·K, ACP-2 with a density of 1617 kg/m^3 and thermal conductivity of 0.33 W/m·K, and ACP-3 with a density of 1650 kg/m^3 and thermal conductivity of 1.00 W/m·K. Specific heat values (C_p) were determined through Differential Scanning Calorimetry (DSC), yielding 2.16 J/g·K for ACP-1, 1.53 J/g·K for ACP-2, and 1.05 J/g·K for ACP-3. The chemical compositions of core materials were confirmed through morphological analysis in a previous study [15]. Additionally, two commonly used insulation materials, XPS and GW, were used, each with specific characteristics [16,17]. XPS insulation is favored for cladding in high-rise buildings due to its thermal performance, moisture resistance, durability, and easy installation [16]. However, its flammability remains a concern. Meanwhile, GW is gaining popularity for its low combustibility and efficient thermal insulation, reducing energy consumption in tall structures [17]. XPS, commonly derived from oil-based polystyrene with expanding gas agents, demonstrated a density of 28 kg/m^3 and a specific heat of 1.71 J/g·K. GW, composed of SiO_2 (63.4%), Na_2O (16.1%), CaO (8.3%), MgO (2.5%), Al_2O_3 (1.9%), and others (7.8%), exhibited a density of 45 kg/m^3 and a specific heat of 0.85 J/g·K [18,19]. The thermal conductivity values for both insulation materials were obtained from literature sources [18]. All of the ACPs were 3 mm core material sandwiched between two 0.5-mm thick aluminium layers. The insulations were tested with 25 mm thickness. A total of 23 samples were tested. Repeatability was analysed according to test standards [20]. The test assemblies can be seen in Table 2.

2.2. Test procedures

The cone calorimeter (ISO 5660) [21] is used to evaluate the flammability of the samples. According to the standard, the samples were cut to the size of 100 × 100 mm^2. All specimens were evaluated at a typical heat flux of 50 kW/m^2. The chosen heat flux level of 50 kW/m^2 is indicative of a typical developed fire scenario [22]. Its purpose is to replicate the conditions that materials might encounter in real-world household fire situations. Standard test methods, such as ISO 5660, often recommend a heat flux of 50 kW/m^2 for cone calorimeter testing. This level of standardisation ensures consistency and comparability of test results across different laboratories and studies and is used by various fire risk rating and modelling applications [11,23–25]. The samples were mounted horizontally to avoid melting and dripping [21]. To further limit the melting and dripping of samples when horizontally oriented, the samples were mounted in the centre of an aluminium foil with the glossy side facing the specimen and the corner folded (aluminium boot or tray). The prepared samples were then put on a ceramic fibre backing pad and were ready for analysis. Since the samples appeared to swell, the sensitivity of the cone heater was reduced by testing them with a 60 mm gap between the radiant heater and the sample according to the standard ISO 5660 [21]. Tests were carried out with a piloted ignition under well ventilation condition and spark igniter located 48 mm above the sample. For repeatability analysis, each approach was tested three (03) times in accordance with the test standard [20]. Additionally, measurements of HRR were recorded at 5 s intervals.

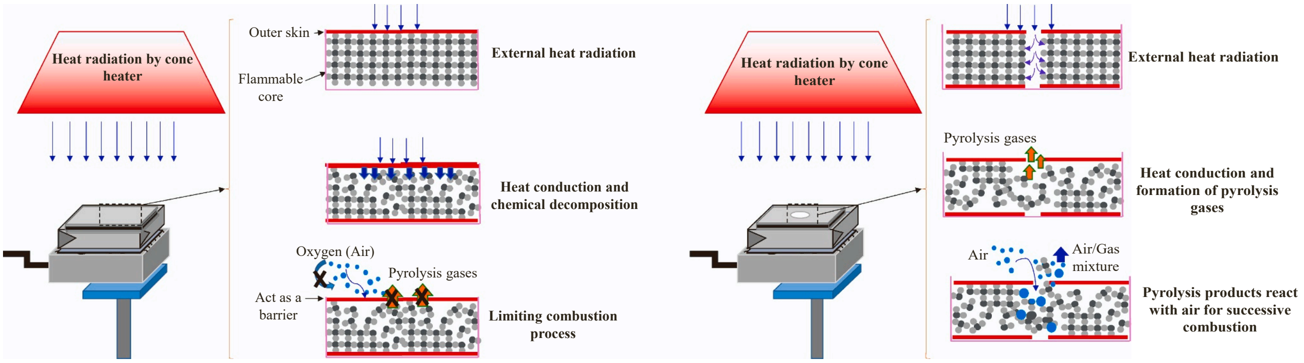
2.3. Test design conditions for single assemblies

In real scenarios, ACP panel was a main part of the total cladding system of a building [26]. During the real fire, ACP panels were directly exposed to heat, and the outer aluminium sheets served as a heat barrier for the cladding materials on both sides. For proper performance analysis, it was necessary to examine the core materials and the entire ACPs



a) Conventional sample **b)** Modified sample with vent

Fig. 4. Panel sample preparation for testing.



a) Conventional configuration **b)** Modified configuration with vent

Fig. 5. Combustion process of ACP.

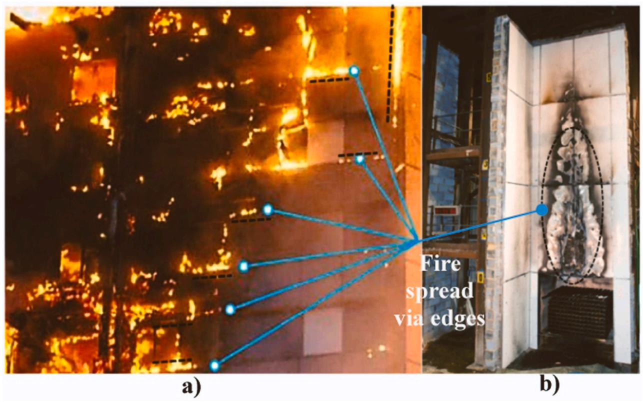


Fig. 6. Fire spread through panel edges; **a)** Grenfell tower fire [28] **b)** Full-scale fire test [29].

as a product. The sandwiched structure of ACPs makes it a complex product, and most current testing practises, including cone calorimeter fire test, were unable to establish mechanisms by which encapsulation fails and provide accurate fire performance ratings [26]. It was often difficult to analyse and differentiate the performance of combustible and non-combustible core composites under external heat exposure due to the non-combustible outer layer barriers. As a result, it was challenging to establish a test condition that could emulate the mechanism of ACP encapsulation failure. Because of this, the current study adopted a modified test sample (Fig. 4) approach (with vent), and the details were available elsewhere [27].

The primary challenge associated with ACP testing using a cone calorimeter revolves around the protective aluminium covering atop the core sample, as depicted in Fig. 5a. Typically, the radiant heat from the cone heater is insufficient to melt this protective outer shell and initiate the combustion process of the core components [28]. The ignition of the gaseous fuel phase necessitates prior production, and the dispersion of oxygen throughout the fuel is imperative before flame initiation can take place. Hence, this study adopted a modified sample configuration, introducing a 25 mm diameter vent at the center of the sample, as illustrated in Fig. 5b. This vent serves the purpose of ensuring uniform heat radiation exposure to all layers of the ACP composite, thereby facilitating the generation of flammable gases for an efficient and consistently repeatable combustion process.

In the context of real fire scenarios, the external combustion process commences with the melting of sealants and subsequently extends along the edges of the panels, as shown in Fig. 6a. A similar situation was also observed in full-scale testing, as depicted in Fig. 6b.

2.4. Test design conditions for combined assemblies

Under the common fire circumstance (Fig. 7a), when the fire reaches the flashover, the fire plume can spread through the exterior of the building in two ways, i.e. i) spread through cladding (Fig. 7b) and ii) spread between insulation and cladding (Fig. 7c). This experiment used two sample assemblies to analyse the fire performance under a cone calorimeter. At first, the cladding panels and insulations were tested individually as a single assembly. Finally, cladding with insulation was tested under two different combined assemblies, i.e. i) layer-by-layer and ii) side-by-side (Fig. 7d). Layer-by-layer assembly was used to determine the combined flammability effect of the cladding system when a fire spreads over a cladding panel. On the other hand, a side-by-side assembly was used to analyse the combined flammability effect of the cladding system when the fire spread between cladding and insulation.

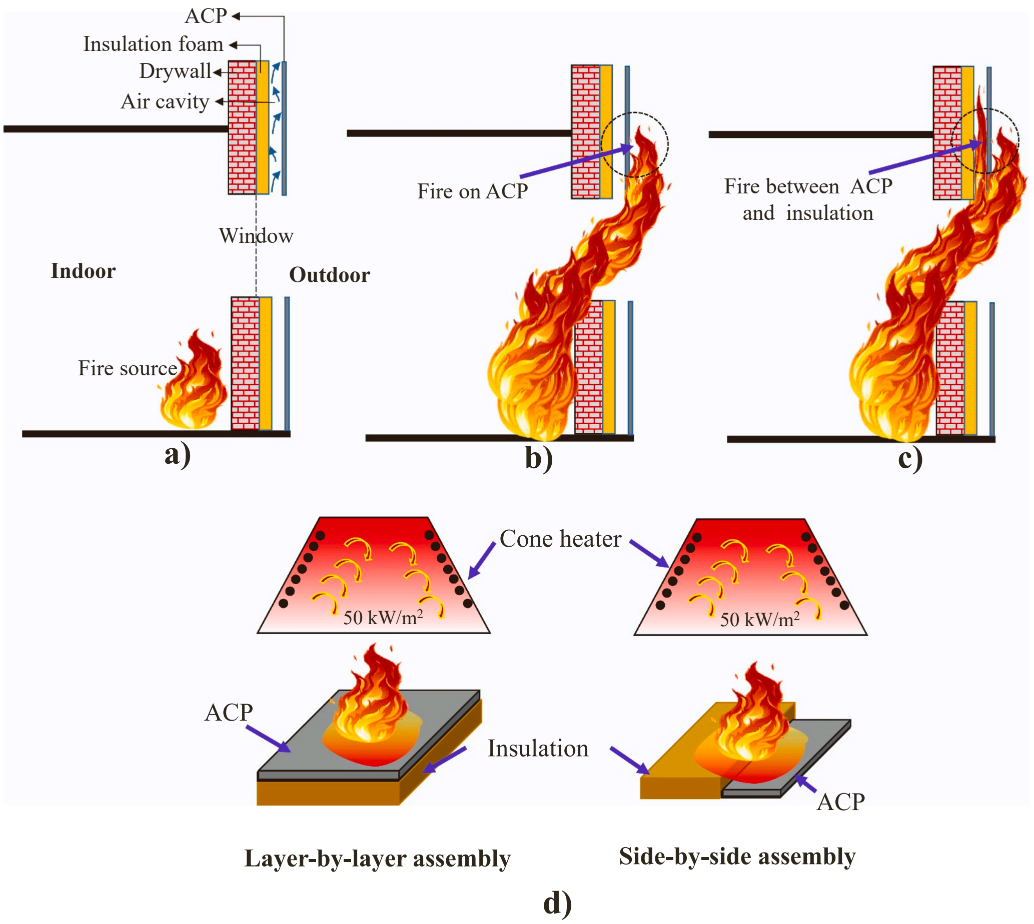


Fig. 7. Different fire scenarios in building cladding: a) Fire initiation in the building interior, b) Fire spread through the cladding, c) Fire spread between insulation and cladding, d) Test assemblies in cone calorimeter.

Table 3
Flammability properties of single assemblies.

Sample code	Flammability properties					
	TTI (s)	pHRR (kW/m^2)	Time to pHRR (s)	EHC (MJ/kg)	THR (MJ/m^2)	Specific MLR (g/s.m^2)
SC-1	35	1280	135	42.00	114	21.26
SC-2	40	247* 172**	97* 420**	23.21	55	5.64
SC-3	40	128* 200**	75* 152**	22.53	15	4.32
SC-4	02	504	26	27.74	27	11.36
SC-5	–	7	–	10.65	2	0.26
SP-1	202	950	333	41.50	113	16.30
SP-2	–	46	–	6.54	8	0.85
SP-3	–	5	–	–	–	0.43
SPV-1	136	1255	244	42	113	21
SPV-2	1013	365	1209	37	48	7
SPV-3	524	223	605	30	14	4.4

"—" = no ignition, * = 1st peak, * *= 2nd peak

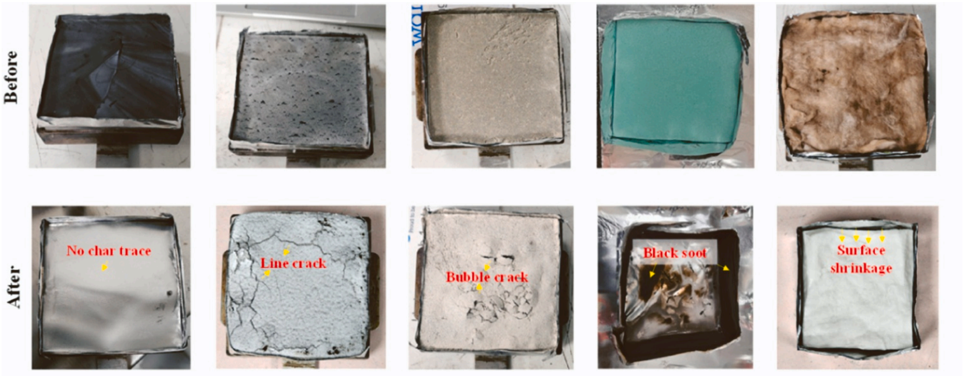
3. Results and discussion

3.1. *Flammability properties of single cladding materials*

Different flammability properties of single materials, like cores with and without panels and insulations, were tabulated in Table 3, and the details were illustrated in the below sections.

3.1.1. *Core materials of ACP panel and insulations*

Core materials of ACPs have a wide range of burning behaviour depending on their formulation (Table 3). Materials that were pure or nearly pure thermoplastics behaved as non-charring thermally thin solids, such as SC-1 and were characterised by very rapid ignition time (35 s), no residue (Fig. 8a), and high heat release rate (1280 kW/m^2) in Fig. 9. However, ACP cores containing inorganic filler tend to have lower heat release (200–247 kW/m^2) but nearly the same ignition time (Fig. 9). The presence of similar types of organic polymer (LDPE) in all of the tested samples may be the cause of the nearly identical ignition time. The percentage of polymer present in each sample strongly influenced the THR, EHC, and MLR values of the tested samples. Such as SC-1 with 100% organic polymer showed a maximum total heat release of 114 MJ/m^2, whereas SC-2 and SC-3 with 30% and 7% polymer have a total heat release of 55 MJ/m^2 and 15 MJ/m^{2,} respectively (Table 3). When comparing samples with 100% polymer to samples with organic fillers (7%), the effective heat of combustion nearly doubled. Also, the same trends have been found for the results of the mass loss rate of the samples. Sample SC-2 and SC-3 behave similarly to charring materials as a char layer builds up and insulates the underlying virgin material from external heat. The line cracks were shown in SC-2 char surface (Fig. 8b), whereas SC-3 showed cracks in the form of bubbles (Fig. 8c). Sample SC-2 and SC-3 both showed two peaks during the burning (Fig. 9). The first peak was coming from the surface ignition, and the later peak was responsible for the burning of interfacial polymer presents in the composite matrix. Both peaks were higher for SC-2 compared to SC-3. In the case of burning duration, SC-2 showed a higher burning duration (535 s) than SC-3 (203 s). Note that in real cladding fire scenarios, the difference in ignition time becomes less important under the heat flux above



a) SC-1 (100 % PE) **b)** SC-2 (30 % PE) **c)** SC-3 (30 % PE) **d)** SC-4 (XPS) **e)** SC-5 (GW)

Fig. 8. Visual observation of different materials of cladding system before and after test.

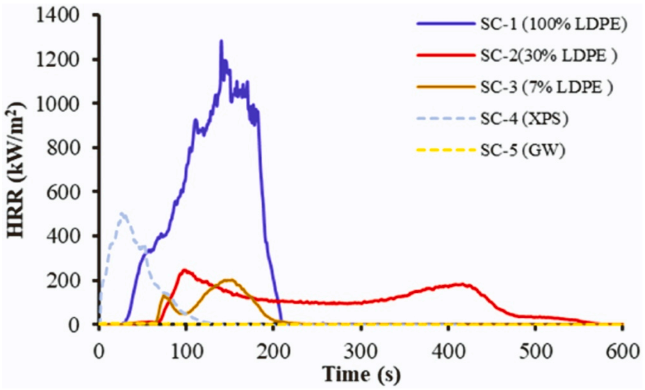


Fig. 9. Heat release rate of different materials used in cladding system.

Table 4
Flammability properties of combined assemblies of panels and insulations.

Sample code	Flammability properties					
	TTI (s)	pHRR (kW/m^2)	t_{pHRR} (s)	EHC (MJ/kg)	THR (MJ/m^2)	MLR (g/s.m^2)
SS-1	122	743	399	43	148	17.03
SS-2	1080	372	1145	31	61	6.84
SS-3	500	302	691	29	35	6.16
SS-4	200	755	269	38	113	6.51
SS-5	1046	359	1231	33	46	5.54
SS-6	430	213	489	32	13	1.17
SJ-1	16	293 * 776 * *	38 * 198 * *	38	69	8.77
SJ-2	16	348 * 115 * *	44 * 644 * *	24	43	2.19
SJ-3	16	335 * 123 * *	44 * 209 * *	24	20	3.15
SJ-4	203	496	319	41	56	8.58
SJ-5	900	156	1136	34	21	2.80
SJ-6	–	15	48	2	1	0.26

"—" = no ignition, * = 1st peak, * *= 2nd peak, t_{pHRR} = time to peak heat release rate.

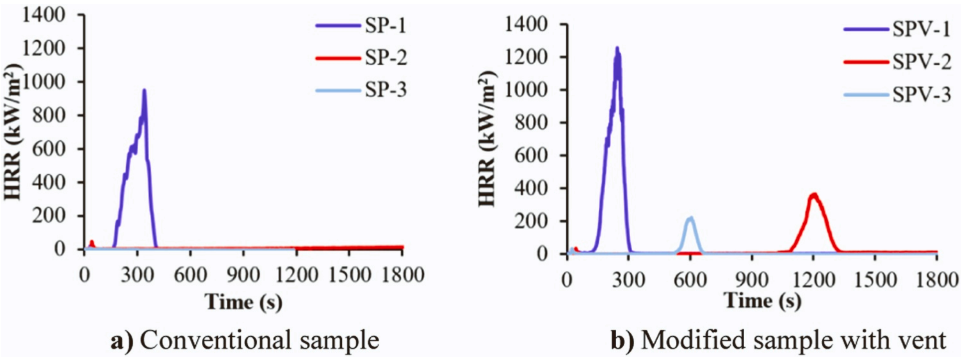
100 kW/m^2, like in a post-flashover fire, but the burning duration will be of higher relevance. Thus, a higher peak heat release rate and longer burning duration of SC-2 core materials show a more significant fire hazard compared to SC-3. Thus, from the viewpoint of HRR, the fire hazard of ACP core samples follows the polymer % fire hazard ranking. More importantly, the peak HRRPUA of SC-2 and SC-3 was also found to be higher than other common flammable materials such as timber wood (~150–200 kW/m^2) [30], polyisocyanurate foam (~139 kW/m^2) [31], PVC floor tile (~181 kW/m^2) [31], although lower than SC-1 (1280 kW/m^2).

Therefore, even under the small lab-test scale, the fire hazard of these ACPs core materials may still be a primary concern due to its fast-developed market. A number of key trends were noted for insulation materials. For XPS, low ignition time (2 s), shorter time to reach pHRR and hence limited burning period demonstrate high fire risk. The extremely low thermal inertia causes the surface to heat rapidly for cellular materials, and ignition was achieved quickly. The total energy released by this material, as indicated by the integral of the heat release, can be seen to be substantially lower than ACPs core samples. This was partially due to the low density of modern insulation materials leading to low sample mass. It was observed that, at the early stage of XPS combustion, the residue adheres to the surface of the unburned sample, restricting heat and mass transfer and decreasing the HRR over time. However, a small shoulder of HRR was formed during the gradual surface residue breakage, as seen in Fig. 9. No obvious ignition phenomenon was observed for GW. The colour of glass fibre will gradually fade from red to white over time (Fig. 8 e). The red colour was due to the presence of quinones, which were the oxidation products of phenols [17]. The red colour gradually fades as the substance decomposes and volatilises. The heat release rate was almost negligible because of its low value. The amount of mass loss was small, resulting in a small average mass loss rate. However, the sample shrinks to a state of smaller volume and greater hardness under external heat exposure (50 kW/m^2). In conclusion, changes in thickness will not change the non-flammable properties of glass fibre, but the thickness can affect the shape of the cladding assemblies by increasing the air cavity and chimney effect during fire incidents.

3.1.2. ACP panel samples tested using conventional and modified methods

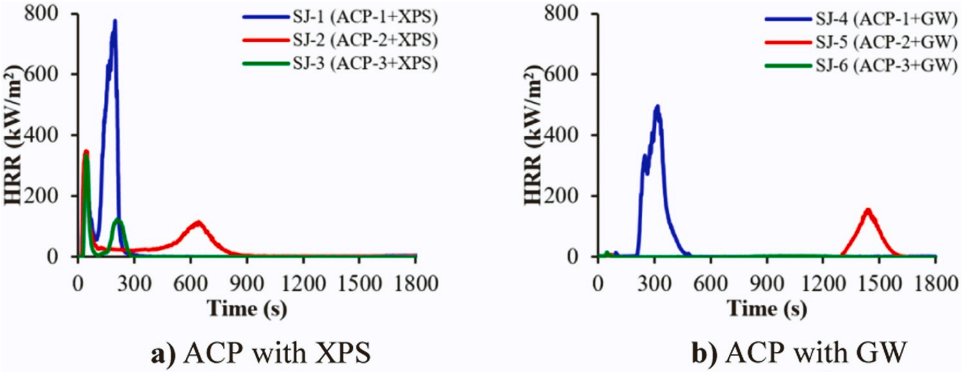
Fig. 8a shows the heat release results of the conventional panel samples, where SP-1 showed a combustion process with an ignition time of 202 s. However, no ignition was found for samples SP-2 and 3, and hence, no heat releases were observed for both samples, which makes it difficult to differentiate the fire performance of SP-2 and 3. Whereas in the modified approach, all samples achieved a successive combustion process with ignition (Fig. 8b).

When the panel was exposed to irradiation, the ACP paint ignited at 35–40 s and burned very quickly for a few seconds before flashing away. Although the brief flame aided the heating process and may pose some hazards in full-scale cladding systems, such a flash burning was not considered a successful ignition of the panel for this study. Table 4 shows the total summary of the flammability properties of the panel samples (conventional and modified). In contrast to core samples, each type of sample only showed one peak. The outer skin, which acts as a barrier and restricts the upper surface's exposure to direct heat, may be the



a) Conventional sample **b)** Modified sample with vent

Fig. 10. Heat release rate of different cladding panel samples.



a) ACP with XPS **b)** ACP with GW

Fig. 11. Heat release curve of cladding panel with insulation (side-by-side assemblies).

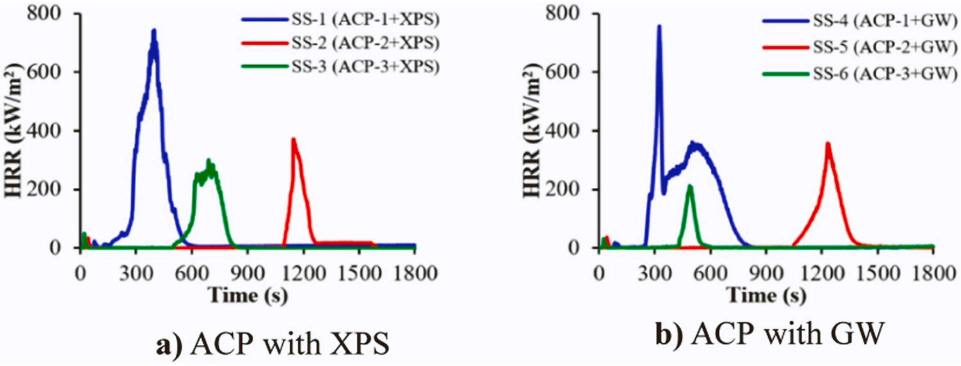
cause. However, ongoing heat transfer from the surface assists in getting the fuels in the entire composite matrix ready for combustion. Finally, the centre vent allows enough pyrolysis gas to ignite the subsequent combustion process. As a result, the ignition time for the panel sample is longer than for the core sample. However, the pHRR showed a higher value for all the panel samples compared to their core samples. Low-thickness aluminium was also good at reflecting radiant heat, i.e., electromagnetic 'infrared' radiation. "Free" electrons can pick up the forces in EM wave vibration (e.g., infrared) more easily, which was then re-radiated outwards [32]. This also results in a slightly higher peak in the panel samples' heat release rate than the core samples. In the case of HRR, the fire risk ranking can be SPV-1 >SPV-2 >SPV-3. In addition, the burning duration of SPV-2 (347 s) also showed more than two times higher value of SPV-3 (150 s). Overall, the modified approach with vent allowed us to differentiate the fire performance of the panel samples more effectively than the conventional testing approach. Fig. 10.

3.2. *Flammability properties of combined assemblies of panels and insulations*

A series of tests demonstrated the potential application of combining heat release rates of different items (cladding panel and insulation) in cladding systems and their fire hazard assessment. Table 4 shows the detailed flammability properties of the combined assemblies.

3.2.1. *Side-by-side assemblies method*

In order to improve energy efficiency, the ACP cladding system has an air cavity between the insulation and the cladding panel. In many instances, the most likely way a fire spreads through a cavity is through gaps created by the joining of the panes or holes created by the fire in the polymeric window framing boards. Due to the chimney effect, this air cavity acts as a chimney in a fire and promotes vertical fire spread. In the cavity fire, both cladding panels and insulations were exposed. With this connected condition, it was crucial to comprehend the fuel sources of



a) ACP with XPS **b)** ACP with GW

Fig. 12. Heat release curve of cladding panel with insulation (layer-by-layer assemblies).

the insulation and cladding panels. In order to comprehend how insulations and cladding panels affect the system's development of subsequent heat release, the current study employed side-by-side assemblies. A significant impact of the insulation panel was seen on the ignition time and pHRR of the samples. Similar ignition times for various cladding panels were observed in combined assemblies with XPS insulation.

Furthermore, the ignition time was assumed to be much quicker than for combined assemblies with GW. It suggests that flammable insulation may act as a catalyst for cladding systems to catch fire. ACP-1 and GW together demonstrated 1.5 times lower pHRR than ACP-1 and XPS. Comparing ACP-2 with GW to ACP-1 with XPS, pHRR for the combination was 2x times lower. Comparing ACP-3 with GW to ACP-3 with XPS, it showed a nearly 22x lower heat release rate. The HRR curves were shown in Fig. 11. The cladding panels with XPS illustrate two peaks in the HRR curve compared to cladding panels with GW. The first peak in Fig. 11a was caused by XPS burning, and the core materials of different panels mostly caused the second peak. In Fig. 11b, however, only a single peak was visible, which was the result of the panel's core only. Based on the flammability properties, it demonstrated the same ranking as previously mentioned for layer-by-layer assemblies. In addition, the ignition time of a single flammable material accelerates the total burning process in the side-by-side assemblies.

3.2.2. *Layer-by-layer assemblies method*

The cladding panel was directly exposed due to a flashover in a real fire, and the cladding panel protects the insulation. For the aforementioned phenomenon, layer-by-layer assemblies were used to analyse the fire behaviour of cladding panels and insulations. It's interesting to learn about the fundamental interaction of cladding panels and insulation during heat exposure. Fig. 12 depicts the burning curves of various cladding panels and insulation assemblies. The burning behaviour of various ACPs with flammable insulation (XPS) and non-flammable insulation (Glass wool) was depicted in Fig. 12a & b, respectively. The insulation types (combustible and non-combustible) had no effect on the pHRR and EHC values of the tested samples. However, the types of insulation used in the assemblies affected THR and MLR values. The MLR showed a 3x to 5x higher value of the samples SS-1 and SS-3 than SS-4 and SS-6 (Table 4), in which assemblies contained flammable insulations. Sample SS-1 in Fig. 12a displayed a single peak curve with a slight shoulder extent at the right side between 200–300 s. The shoulder could be a result of the fuel supply of XPS insulation. For SS-4, however, two peaks have been discovered (Fig. 12b). The first and sharp peaks could be attributed to the fuel supply of the ACP- 1 sample, whose core was made entirely of polymer. However, due to the conduction principle of heating, when the glass wool begins to receive heat, it attempts to absorb the heat for a period of time due to its high insulation properties. This action slows down the further heat release rate of the process. The second peak was caused by heat feedback from the GW and could be a smouldering process [33]. SS-2 showed a sharp peak with a shorter burning period (Fig. 12a), but SS-5 showed a sharp peak with a longer burning time, which could be due to GW and its smouldering phenomenon (Fig. 12b). In the case of the SS-3 sample, the curve was disciform in comparison to the SS-6 sample, which had a sharp peak (Fig. 12). The disciform shape may be the result of resultant heat release of XPS and ACP-3. However, there was a common trend in total flammability, and the fire performance of ACPs with XPS can be as SS-3 >SS-2 >SS-1. ACPs with GW fire performance can be ranked as SS-6 >SS-5 >SS-4. The ACP samples on the top surface of the assemblies as a shield to the backside flammable insulation and delayed the combustion process of the flammable insulation.

4. Acceptance criteria development for fire risk assessment

Building codes in Australia, New Zealand, and Japan allow the use of cone calorimeters to assess the fire risk rating of lining and insulation materials in buildings [8–10]. Acceptance criteria were developed in different countries and codes based on the cone calorimeter test data of different building materials. Those criteria were mainly established based on the peak heat release rate (pHRR) in kW/m^2 and total heat release (THR) in MJ/m^2, see Table 5.

Table 5
Acceptance criteria using cone calorimeter at 50 kW/m^2 for different countries and codes [8–10,34].

Country/Code	Acceptance criteria			Applications
	pHRR (kW/m^2)	THR (MJ/m^2)	Test time (min)	
Japan	200	8	20	Non-combustible products
Japan	200	8	10	Quasi Non-combustible products
Japan	200	8	5	Fire retardant products
Korea	200	8	10*	Semi Non-combustible products
Korea	200	8	5*	Fire retardant products
NFPA 5000 Building Code	150	20		Water resistive barriers
NFPA 1 Fire Code	300			Plastic rubbish containers
New Zealand	100	25	15	Exterior wall materials (building class AS 2, AS 4 and AS 5)
New Zealand	150	50	15	Exterior wall materials (building class AS 6)

* = no cracks allowed more than 20% of the thickness

Table 6
Proposed classification criteria of different combined assemblies using cone calorimeter at 50 kW/m^2.

Class	pHRR (kW/m^2)	THR (MJ/m^2)	Test time (min)
Class 0 (non-combustible)	< 10	< 5	30
Class 1(very limited combustible)	< 225	< 15	30
Class 2 (limited combustible)	< 225	< 25	30
Class 3 (moderate combustible)	< 350	< 50	30
Class 4 (highly combustible)	> 350	> 50	30

It can be seen from the acceptance criteria used in Japan that the value of pHRR (200 kW/m^2) of non-combustible products and fire retardant products were the same, although the combustibility level of those two materials was not the same. In addition, experimental data showed that fire retardant ACPs ignition to burnout time was beyond 20 mins, whereas 20 min was the test condition of the existing assessment classifications. The mentioned phenomenon indicates that the existing acceptance criteria were not suitable for fire risk assessment of the materials used in cladding systems. To address this gap, acceptance criteria for assessing fire risk of cladding systems (Table 6) were developed in this study based on the cone calorimeter test data of the combined assemblies and existing acceptance criteria used in various nations and codes. In this classification, there were five groups of classification which categorised different levels of combustibility. The proposed Class 0 will be assigned to non-combustible materials that were safe in the event of a fire and represent a class of materials that do not contribute to fire. Due to the flammable paint on the ACP, it was difficult to define the class 0 value from the assembly test data. So, the present study used the value of non-combustible GW as a base case for the non-combustibility. Class 1 and 2 were the assemblies in which both materials were quasi-non-combustible, or one material had non-combustibility with limited contribution to fire. For the class 2 criterion, the THR value was adapted from the classification criterion of exterior cladding [9]. Class 3 elements were fire retardant and tended to moderate fire spread. Finally, class 4 pertains to an assembly in which

Table 7
Correlation between the current work and full-scale test.

Combination of cladding system	Current test data			Assessment based on the acceptance criteria of proposed and BS 8414-1	
Assembly	pHRR (kW/m^2)	THR (MJ/m^2)	Class	Current study	BS-8414-1
ACP-1 +XPS (LbL)	743	148	Class 4	Fail	-
ACP-2 +XPS (LbL)	372	61	Class 4	Fail	-
ACP-3 +XPS (LbL)	302	35	Class 3	Fail	-
ACP-1 +GW (LbL)	755	113	Class 4	Fail	Fail
ACP-2 +GW (LbL)	359	46	Class 4	Fail	-
ACP-3 +GW (LbL)	213	13	Class 1	Pass	Pass
ACP-1 +XPS (SbS)	776	69.44	Class 4	Fail	-
ACP-2 +XPS (SbS)	348	43.27	Class 3	Fail	-
ACP-3 +XPS (SbS)	335	20.28	Class 3	Fail	-
ACP-1 +GW (SbS)	496	56.35	Class 4	Fail	-
ACP-2 +GW (SbS)	156	21.41	Class 1	Pass	-
ACP-3 +GW (SbS)	15	1.41	Class 0	Pass	-

*failing criterion = > Class 1, "-"= data not available.

one or both materials have a high tendency to spread fire. The present study found that either highly flammable insulation or cladding panels or the presence of both in the assemblies fall in this group.

Based on this proposed classification, the current test data were re-assessed to evaluate the level of combustibility of combined assemblies. It can be seen from Table 7 that ACPs with XPS insulation showed a consistent trend of combustibility ranking between SbS and LbL test assemblies.

However, discrepancies were found between the sample rankings of ACP with GW. As from the previous discussion, we know that glass wool can absorb heat and, at a certain level, start to heat feedback due to the smouldering phenomenon [33]. Due to the different test conditions (LbL and SbS), various ranking criteria were found even for the identical material assemblies, i.e., ACP-2 +GW. To restrict the material properties with very limited combustibility of cladding system, up to class 1 can be considered as an acceptance criterion. From the observations, it can be concluded that between the two assemblies' approaches, the LbL approach showed a more conservative nature for risk ranking assessment. It can be found that LbL assemblies data and acceptance criteria were consistent with existing full-scale tests.

Based on the above discussion, a fire performance assessment framework has been developed for a small-scale cone calorimeter (Fig. 13). Rather than directly analysing samples in full-scale tests, an initial screening of product assemblies can be done at a cone calorimeter in the laboratory. As a result, the cost and time associated with product development and regulatory legislation will be reduced. In such case, If the test failed to meet the threshold criterion (class 1) or the pHRR and THR were not less than 225 kW/m^2 and 15 MJ/m^2, respectively, the sample was classified as a combustible material, and no further analysis was needed. However, if the sample passes the test criterion, further analysis must be done for full-scale.

5. Conclusions

This paper assessed the fire behaviour of two typical arrangements (SbS and LbL) of cladding panels and insulations of the cladding system by small-scale cone calorimeter. The following conclusions were drawn from this study:

- The higher peak heat release was found for the SC- 1(100% LDPE). SC-2 (30% LDPE) and SC-3 (7% LDPE) showed relatively small differences in pHRR results. However, the higher burning duration makes the SC-2 vulnerable compared to SC-3 in the fire.
- The modified sampling approach with vent was more effective than the conventional testing procedure in differentiating the flammability properties of the sandwich cladding panels, especially for panels SP-2 and SP-3.
- In side-by-side (SbS) assemblies, results indicated that the more flammable insulation acted as an accelerator for the global combustion kinetics. Two (2) distinct phenomena were observed initially in layer-by-layer (LbL) assemblies: the front cladding panels acted as a shield, delaying the combustion of the rear insulation material, and the presence of a backside insulation material induced a thermal thickening, slowing the combustion process of the front cladding panels.

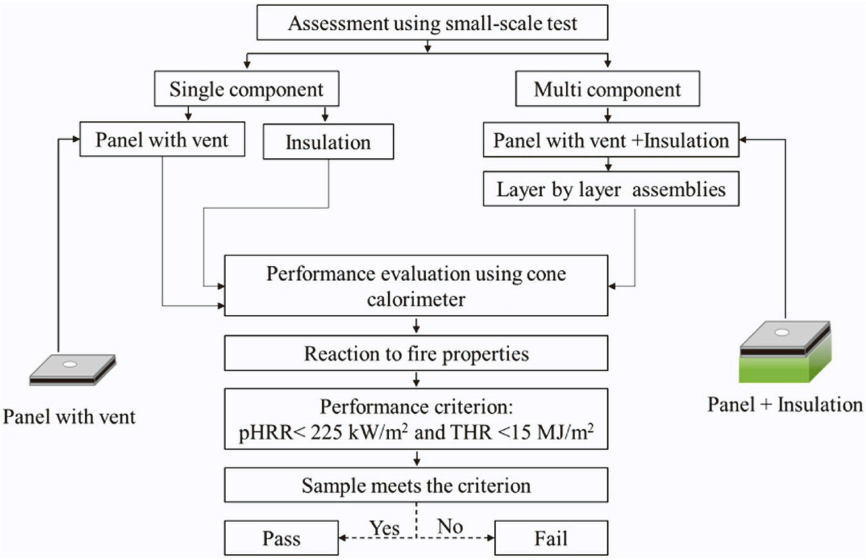


Fig. 13. Fire performance assessment steps of cladding materials using small-scale testing.

- The current study proposed a cladding system classification criterion using the reaction-to-fire characteristics of the combined assemblies, i.e. layer-by-layer (LbL) assemblies. It suggests that using the current assemblies and method, an initial screening of product assemblies can be performed with cone calorimeter in the lab rather than directly analysing samples in full-scale tests. As a result, there will be a decrease in the price and time needed to develop new products and pass new regulations.

CRediT authorship contribution statement

Md Delwar Hossain: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anthony Chun Yin Yuen:** Writing – review & editing, Supervision. **Cheng Wang:** Writing – review & editing. **Hassan Md Kamrul:** Writing – review & editing, Supervision. **Swapan Saha:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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References

[1] S.T. McKenna, N. Jones, G. Peck, K. Dickens, W. Pawelec, S. Oradei, S. Harris, A. A. Stec, T.R. Hull, Fire behaviour of modern façade materials–Understanding the Grenfell Tower fire, J. Hazard. Mater. 368 (2019) 115–123.

[2] A.C.Y. Yuen, T.B.Y. Chen, A. Li, I.M. De Cachinho Cordeiro, L. Liu, H. Liu, A.L.P. Lo, Q.N. Chan, G.H. Yeoh, Evaluating the fire risk associated with cladding panels: An overview of fire incidents, policies, and future perspective in fire standards, Fire and Materials, 2021.

[3] M.D. Hossain, M.K. Hassan, A.C.Y. Yuen, Y. He, S. Saha, W. Hittini, Flame behaviour, fire hazard and fire testing approach for lightweight composite claddings – a review, J. Struct. Fire Eng. 12 (2021) 257–292.

[4] M.S. McLaggan, J.P. Hidalgo, J.C. Tirado, M. Heitzmann, A. Osorio, J.L. Torero, Flammability trends for a comprehensive array of cladding materials, Fire Saf. J. (2020) 103133.

[5] A.A. Khan, S. Lin, X. Huang, A. Usmani, Facade fire hazards of bench-scale aluminum composite panel with flame-retardant core, Fire Technol. (2021) 1–24.

[6] M.D. Hossain, M.K. Hassan, A.C.Y. Yuen, Y. He, S. Saha, W. Hittini, Influencing factors in small-scale fire testing of aluminium composite panels. In *Proceedings of the 12th Asia-Oceania Symposium on Fire Science and Technology (AOSFST 2021), Virtual* (pp. 7-9).

[7] G. Peck, N. Jones, S.T. McKenna, J.L. Glockling, J. Harbottle, A.A. Stec, T.R. Hull, Smoke toxicity of rainscreen façades, J. Hazard. Mater. 403 (2021) 123694.

[8] K. Sumathipala, R. White, Flammability tests for regulation of building and construction materials, Flammability testing of materials used in construction, transport and mining, Elsevier (2006) 217–230.

[9] N. White, M. Delichatsios, Regul., Fire Hazards Exter. Wall Assem. Contain. Combust. Compon., Springe (2015) 49–54.

[10] K. Nguyen, N.K. Kim, D. Bhattacharyya, A. Mouritz, Assessing the combustibility of claddings: A comparative study of the modified cone calorimeter method and cylindrical furnace test, Fire and Materials, 2021.

[11] A.S. Hansen, P.J. Hovde, Prediction of time to flashover in the ISO 9705 room corner test based on cone calorimeter test results, Fire Mater. 26 (2002) 77–86.

[12] B.A.L. Östman, L.D. Tsantaridis, Correlation between cone calorimeter data and time to flashover in the room fire test, Fire Mater. 18 (1994) 205–209.

[13] C. Vincent, L. Ferry, C. Longuet, L. Aprin, G. Rambaud, Method to characterize the fire behavior of materials assemblies, Fire Mater. 42 (2018) 627–637.

[14] W.K. Chow, S. Han, Superposition of heat release rate curves for combustibles with bench-scale tests, Polym. Test. 25 (2006) 75–82.

[15] M.D. Hossain, S. Saha, M.K. Hassan, A.C.Y. Yuen, C. Wang, Establishing pyrolysis kinetics for fire modelling and thermal analysis of polymeric cladding materials used in high-rise buildings, Case Stud. Constr. Mater. 19 (2023) e02535.

[16] M.D. Hossain, M.K. Hassan, M. Akl, S. Pathirana, P. Rahnamayiezekavat, G. Douglas, T. Bhat, S. Saha, Fire behaviour of insulation panels commonly used in high-rise buildings, Fire 5 (2022) 81.

[17] R. Yuan, Y. Zhang, T. Qiu, S. Lu, Research on the effect of pyrolysis and melting on thermal insulation of glass fiber at multiple scales, J. Therm. Anal. Calorim. 147 (2022) 8009–8018.

[18] M.D. Hossain, M.K. Hassan, S. Saha, A.C.Y. Yuen, C. Wang, L. George, R. Wuhrer, Thermal and Pyrolysis Kinetics Analysis of Glass Wool and XPS Insulation Materials Used in High-Rise, Build., Fire 6 (2023) 231.

[19] P.N. Lemougna, J. Yliniemi, H. Nguyen, E. Adesanya, P. Tanskanen, P. Kinnunen, J. Roning, M. Illikainen, Utilisation of glass wool waste and mine tailings in high performance building ceramics, J. Build. Eng. 31 (2020) 101383.

[20] D. Morrisset, G. Thorncroft, R. Hadden, A. Law, R. Emberley, Statistical uncertainty in bench-scale flammability tests, Fire Saf. J. 122 (2021) 103335.

[21] ISO 5660–1:2015, Reaction-to-fire tests — Heat release, smoke production and mass loss rate — Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement), 2015.

[22] B. Schartel, T.R. Hull, Development of fire-retarded materials—interpretation of cone calorimeter data, Fire Mater.: Int. J. 31 (2007) 327–354.

[23] W. Chow, Fire hazard assessment on polyurethane sandwich panels for temporary accommodation units, Polym. Test. 23 (2004) 973–977.

[24] R.A. Mensah, Q. Xu, S. Asante-Okyere, C. Jin, G. Bentum-Micah, Correlation analysis of cone calorimetry and microscale combustion calorimetry experiments, J. Therm. Anal. Calorim. 136 (2019) 589–599.

[25] S. Bakhtiyari, L. Taghi-Akbari, M.J. Ashtiani, Evaluation of thermal fire hazard of 10 polymeric building materials and proposing a classification method based on cone calorimeter results, Fire Mater. 39 (2015) 1–13.

[26] M. McLaggan, J. Hidalgo, A. Osorio, M. Heitzmann, J. Carrascal, D. Lange, C. Maluk, J. Torero, Towards a better understanding of fire performance assessment of façade systems: Current situation and a proposed new assessment framework, Constr. Build. Mater. 300 (2021) 124301.

[27] M.D. Hossain, S. Saha, M.K. Hassan, A.C.Y. Yuen, C. Wang, W. Hittini, L. George, R. Wuhrer, Testing of aluminium composite panels in a cone calorimeter: A new specimen preparation method, Polym. Test. 106 (2022) 107454.

[28] D.B. Lane, Routes for Vertical and Horizontal fire spread throughout the Building Envelope Phase 1 Report - Section 10, 2018.

[29] DCLG, BS 8414–1:2015 + A1:2017 test referred to as DCLG test 1., BRE global, 2017.

[30] Q. Xu, L. Chen, K.A. Harries, F. Zhang, Q. Liu, J. Feng, Combustion and charring properties of five common constructional wood species from cone calorimeter tests, Constr. Build. Mater. 96 (2015) 416–427.

[31] K. Carpenter, M. Janssens, Using heat release rate to assess combustibility of building products in the cone calorimeter, Fire Technol. 41 (2005) 79–92.

[32] S. Calatroni, Reflection of infrared radiation from thin aluminium layers, 2001.

[33] P. Leppänen, M. Malaska, Experimental study on the smouldering combustion of mineral wool insulation in chimney penetrations, Fire Technol. 55 (2019) 2171–2194.

[34] B. Östman, Acceptance criteria for products according to the cone calorimeter, Fire Mater. (2022).