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Upward Fire Spread Rate over Real-Scale EPS ETICS Façades

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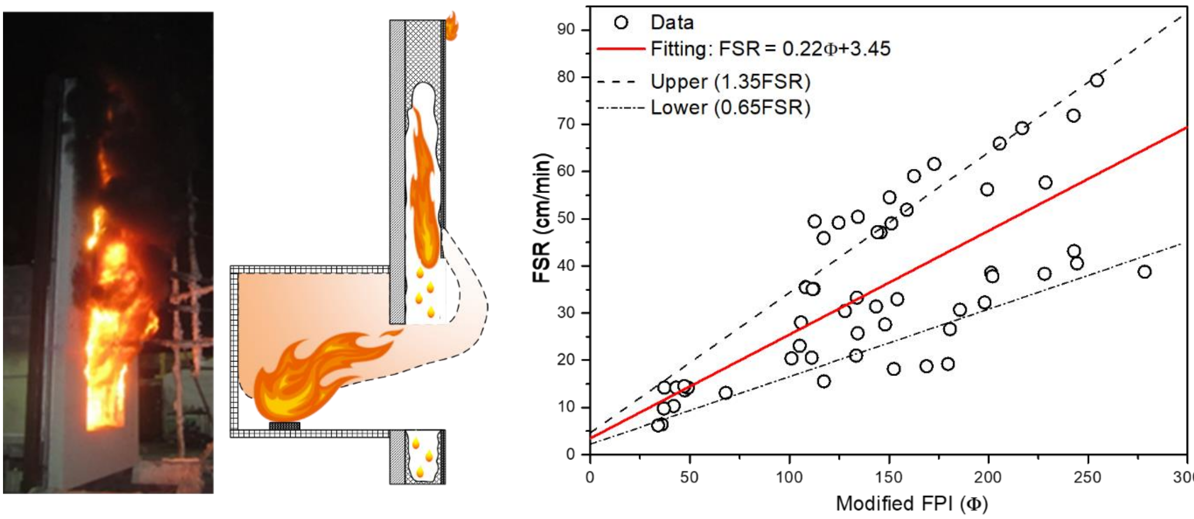
Abstract: The expanded polystyrene (EPS) façade has been widely used to save building energy, but it has also caused many severe facade fire accidents worldwide. Especially for aged buildings, the naturally weathered exterior surface layer can further increase the facade fire risk and the fire spread rate (FSR). In this work, a series of real-scale EPS External Thermal Insulation Composite System (ETICS) façades are tested via the JIS A 1310 standard. The EPS thickness varies from 100 mm to 300 mm, density changes from 15 kg/m^3 to 30 kg/m^3, and heat release rate (HRR) of window spilled flame ranges from 600 kW to 1,100 kW. Tests showed that the surface cement layer was quickly damaged by a spilled flame that provided negligible fire resistance for the internal flammable EPS panel. The measured upward FSR increases with the rising of HRR and with the decreasing EPS thickness like the thermally thin material. An empirical correlation of instantaneous upward FRS is proposed, FSR= 0.22Φ + 3.45 [cm/min], where Φ is a modified fire propagation index derived from the experimental temperature distribution. In addition, a simple prediction method for FSR is proposed for the façade fire and verified by the experimental data. This work provides a useful method to quantify the upward façade fire propagation, which also helps evaluate the fire risk and hazard of EPS ETICS façade prior to the costly large-scale tests and installation.

Keywords: *Vertical flame spread; window spilled flame; empirical correlation; JIS A 1310 standard.*

Graphic Abstract



Nomenclature

Symbols		***Abbreviations***	
A	window opening area [m^2]	*CM*	cement mortar
A_T	inner surface area of chamber [m^2]	*EPS*	expanded polystyrene foam
c_p	specific heat [J/(kg·K)]	*ETICS*	external Thermal Insulation Composite System
H	The height of window opening [m]	*FPI*	fire propagation index [(m/s$^{1/2}$)/(kW/m)$^{2/3}$]
k	thermal conductivity [W/(m·K)]	*FSR*	fire spread rate [cm/min]
L_{EPS}	EPS thickness [mm]	*HRR*	heat release rate [kW]
$\dot{Q}_0$	critical HRR for post-flashover [kW]	*IHFFS*	incident heat flux on facade surface [kW/m^2]
$\dot{Q}'_{ch}$	heat release rate per unit width [kW/m]	*PCM*	polymer cement mortar
T_0	ambient temperature [°C]	*PE*	polyethylene
T_{ig}	surface ignition temperature [°C]	*SBR*	styrene-butadiene rubbers-latex
T_g	steady gas temperature [°C]	*TRP*	thermal Response Parameter [kW·s$^{1/2}$/m^2]
T_z	maximum surface temperature [°C]	$\overline{FSR}$	averaged FSR of different positions [cm/min]

1. Introduction

Today large fires associated with façade systems in tall buildings are currently occurring at a rate of more than once a month globally [1]. These façade fires are and are responsible for many deaths and billions of dollars in losses, such as the tragic event of the Grenfell Tower fire in 2017, and the facade flammability are still a major building fire safety concern. One the most common façade system, External Thermal Insulation Composite Systems (ETICS), has been widely used in buildings due to their thermal advantages, low cost, and ease of application [2, 3] . A typical ETICS is consisted of the wall construction, insulation material, cement bound mortar with reinforcement, and rendering and is fixed by dowels and mortar [4]. The flammable insulation materials, like expanded polystyrene (EPS) and polyurethane (PU) foams, are often used. In China, many façade fires have happened in EPS ETICS in different regions from the north to south, such as the 2009 TVCC fire and 2010 Shanghai fire.

It is well known that EPS ETICS is quite flammable, which consists of adhesive, EPS insulation material, cement, reinforcing mesh, finishing coat [5]. For the aged EPS ETICS façade, the fire resistance of polymer cement mortar (PCM) layer becomes weak after it is deteriorated by the environment, so that fire risk of EPS ETICS may increase as time goes by. A complex fire behavior, including EPS melt-flow and dripping has been reported when EPS ETICS specimens exposed to a fire [6]. The fire spread rate (FSR) of EPS ETICS has been observed to be fast, but the measurements and data of FSR on building façade still lack today.

The EPS ETICS fire has been one of the hot and challenging topics in building facade fire. Nevertheless, the high cost of large-scale fire tests and the strong influence of scale effect have limited the deeper understanding of EPS ETICS fire research. Fire characteristics of a single component have been reported, such as EPS [7-10], adhesive [11], polymer-modified concrete [12, 13], and finishing coat reaction-to-fire performance [14, 15]. However, it is not sufficient to use the reaction-to-fire performance of a single component to evaluate fire hazards of any façade system [16]. Regarding the whole ETICS, its fire behavior has been discussed in the aspects of fire spread assessment [17-20], fire safety during different process stages [21], fire rescue analysis [22], fire barrier influence on reaction-to-fire performance [23], and incident heat flux upon the facade's surface (IHFFS) and damage of the facade's render [20, 24], vertical temperature distribution [25, 26], EPS thickness [27-29], fire evaluation methods after test [30] and so on. However, more fundamental knowledge of vertical FSR of EPS ETICS masonry façade fire over the exterior building wall is urgently needed.

In this work, a series of real-scale EPS ETICS façade specimens differing parameters are tested under various HRR of window spilled flame, EPS thickness, and thermal parameters of ETICS according to the JIS A1310 method. We investigate the temperature history of façade fire exposed to a window spilled fire and propose an empirical method to predict the FSR of a façade fire.

2. Experiment and method

2.1. JIS A 1310 façade fire test

The experiment method adopted the Japanese Industrial Standards JIS A 1310 façade fire test method [31]. The test setup and EPS ETICS specimens are illustrated in **Fig. 1**. The experimental layout is shown in **Fig. 1(a)**, and a simple sketch of the experiment is detailed in **Fig. 1(b)**. The facade fire test facility consisted of a propane gas combustion chamber (size in L × W × H = 1,350 mm × 1,350 mm × 1,350 mm), window opening (size in L × W= 910 mm × 910 mm), gas burner (size in L × W= 600 mm × 600 mm), specimen substrate and specimen support frame. The opening size and opening aspect n (n=2W/H) were W × H = 910 mm × 910 mm and n=2, respectively. The chamber had an inner surface area of 10.1 m^2.

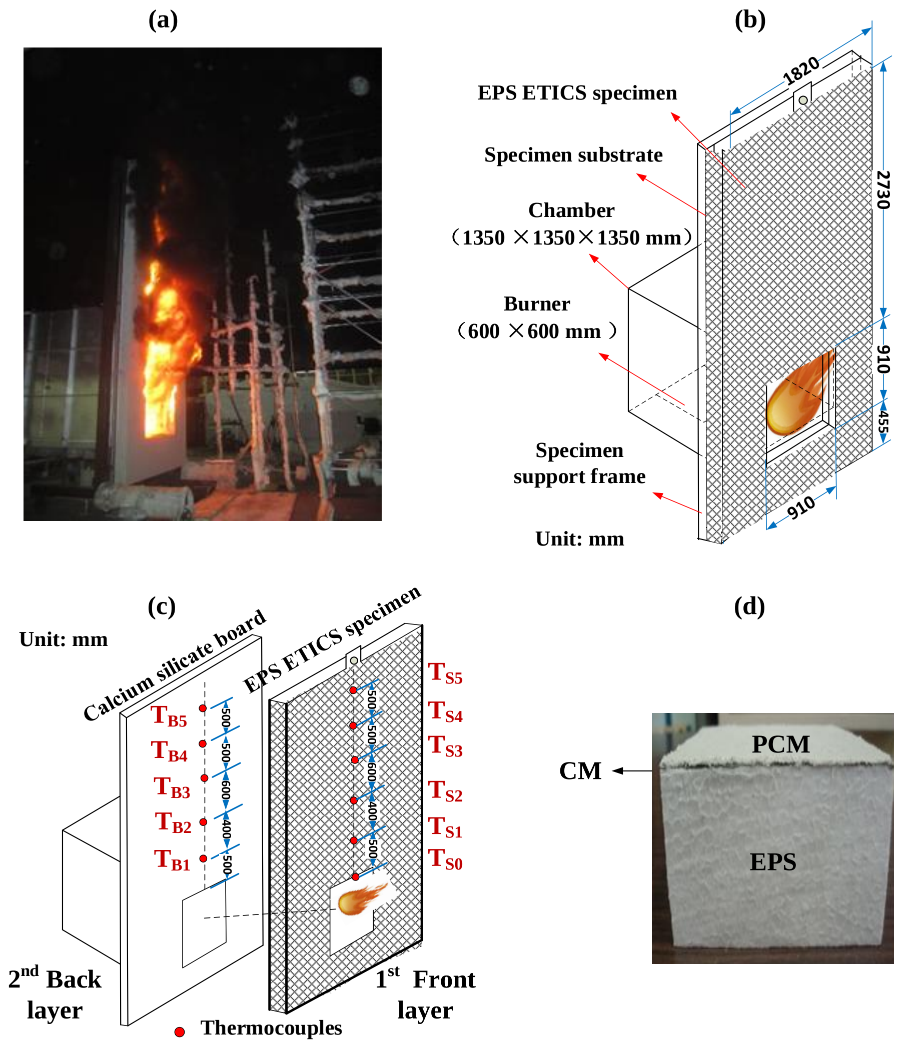


Fig. 1. The description of the experiment (a) The layout of test configurations (b) a sketch model of experiment layout (c) thermocouple configuration (d) the details of EPS ETICS configuration

The various propane window spilled flames were produced by a gas burner. The gas burner was filled with ceramic beads to ensure the propane gas with a uniform speed. The specimen substrate was made by laying 2 pieces of 12-mm thick calcium silicate board, and the joint of the first layer was not overlapped with the joint of the second layer. The specimen support frame made of stainless steel was employed to support the specimen and its substrate. The interior surface of the chamber was coated by a 25-mm thick ceramic fiber blanket. The temperature histories of both façade surface (1st front layer, T_S) and calcium silicate board (2nd back layer, T_B) were recorded by a series of K-type thermocouples on the finishing coat surface in the height of 0 m (T0 for temperature), 0.50 m (T1), 0.90 m (T2), 1.50 m (T3), 2,000 mm (T4) and 2,500 mm (T5) above the top of the opening, respectively. The K-type thermocouple with a 3-mm bead has an accuracy of ± 2.2 °C. The arrangement and locations of thermocouples are shown in **Fig. 1(c)**.

The heat release rate (HRR) was calculated by the common methodology of Oxygen Consumption Calorimetry. A gas-analysis equipment was used to record oxygen concentration ranged from 0.009% to 20.9% every 2 s. The gas analyzer had an accuracy of ±0.02 %. Before the façade fire test, 4-L alcohol was burnt to calibrate the whole measuring system. Repeatability of the experimental setup had been verified previously [30]. Details of EPS ETICS specimens and testing conditions are listed in **Table 1**.

Table 1. Details of EPS ETICS specimens and testing conditions, where all specimens are performed with one layer of reinforcement mesh. The PCM layer is contained with SBR, and the opening treatment is back-wrapping.

Test No.	EPS thickness (mm)	EPS density (kg/m^3)	HRR (kW)
1	100	18	1000
2	100	15	1100
3	150	15	900
4	200	15	1100
5	200	18	1000
6	200	18	600
7	300	18	600
8	100	15	600
9	100	15	900
10	100	30	900
11	200	15	900

2.2. Test parameters

All EPS ETICS specimens were prepared by the same standard method, which were consisted of polymer cement mortar (PCM), cement mortar (CM), reinforcement mesh layer, and EPS foam. All experiments were conducted in the Building Research Institute of Japan, located in the Tsukuba of Japan. Four EPS thickness (L_{EPS}), 100 mm, 150 mm, 200 mm, and 300 mm, as well as two densities of EPS foam 15 kg/m^3 to 18 kg/m^3 were tested. Four HRR values from 600 kW to 1,100 kW were chosen for the propane gas burner (see **Table 1**). All opening edges of EPS ETICS specimens were treated by the back-wrapping method (see more details in reference [32]). A thermocouple was located in the ceiling of the chamber to monitor the inner temperature of the chamber.

Although the spilled flame attached to the façade surface and grew higher, initially, it imposed little influence on the EPS panel, since it was coated with a non-combustible CM layer. The upward fire spread occurred on the flammable EPS panel, but the location of the flame inception on the façade surface was difficult to identify. On the other hand, once the EPS foam is directly heated by the flame, it will quickly melt and shrink by the surface tension, and the backside can be almost instantaneously heated by the flame. Therefore, in this work, we define the arrival of the fire front at the moment when the EPS back temperature (T_B) had a sudden increase. Then, we can define FSR as

$$FSR = \frac{L_i}{t_i} \tag{1}$$

where L_i is the location of backside thermocouple (i) changing from 0.5 m to 2.5 m, and t_i is the preheating time for the façade at each position L_i in **Fig. 1(c)**.

3. Results and discussion

For all facade fire tests, it was found that when the HRR of window spilled flame increases from 600 kW to 1,100 kW, the ceiling temperature of the chamber (Inside chamber) approached a fixed value. In all cases, the spilled flame, as an indicator of flashover, was observed, so that the tested compartment fire was post-flashover or fully-developed fire.

3.1. Phenomena of EPS ETICS façade fire

Fig. 2 illustrates the development of the compartment fire, the ignition of the façade, and the upward spread of the façade fire, based on test No. 4 (1,100 kW fire with 200-mm thick EPS). The supplemental video shows a typical fire test process. With the development of the compartment fire (**Fig. 2a**), the flame spilled out through the window opening and attached to the ETICS surface wall (**Fig. 2b**). When the hot flame got in contact with on façade surface, the PCM layer would be ignited soon, because of the combustible nature of styrene-butadiene rubbers-latex (SBR). Soon after, the CM layer became damaged by window spilled flames (**Fig. 2c**). Then, flames came into the EPS layer to ignite a new fire, which started to spread both upward and downward [33] (**Fig. 2d**). The upward fire spread was dominant and much faster. The downward fire spread was accompanied by dripping ignition of molten EPS [6, 34]. Finally, most of the fuels were burnt out, so the fire became weak. After about 20 min, the flame disappeared, and a big hole was found above the opening (**Fig. 2e**). No remaining EPS was found when the residual surface was removed (**Fig. 2f**).

The corresponding front-surface and backside thermocouple temperatures of test No. 4 are detailed in **Fig. 3**. Taking T_{S5} (the uppermost one) in **Fig. 3a** as an example, it reaches the 1st peak at $t = 95$ s due to the initial ignition of the PCM layer and the following fire propagation. After the burnout of PCM, T_{S5} starts to decrease slightly. As the surface temperature quickly exceeded 800 °C that is hot enough to decompose the cement cover (or CM layer). Quickly afterward, a hole between 0.90 m (T_{S2}) and 1.50 m (T_{S3}) was formed as the CM layer was severely damaged by the direct impact of spilled flame, as illustrated in **Fig. 2c**. For T_{S5}, the 2nd peak appeared at $t = 326$ s was ascribed to the EPS fire or the combustion of styrene gas, that is, the main pyrolysis product of EPS [35]. The measured peak surface temperature, in general, decreased with the height from 1090 °C (T_{S0}) to 765 °C (T_{S5}).

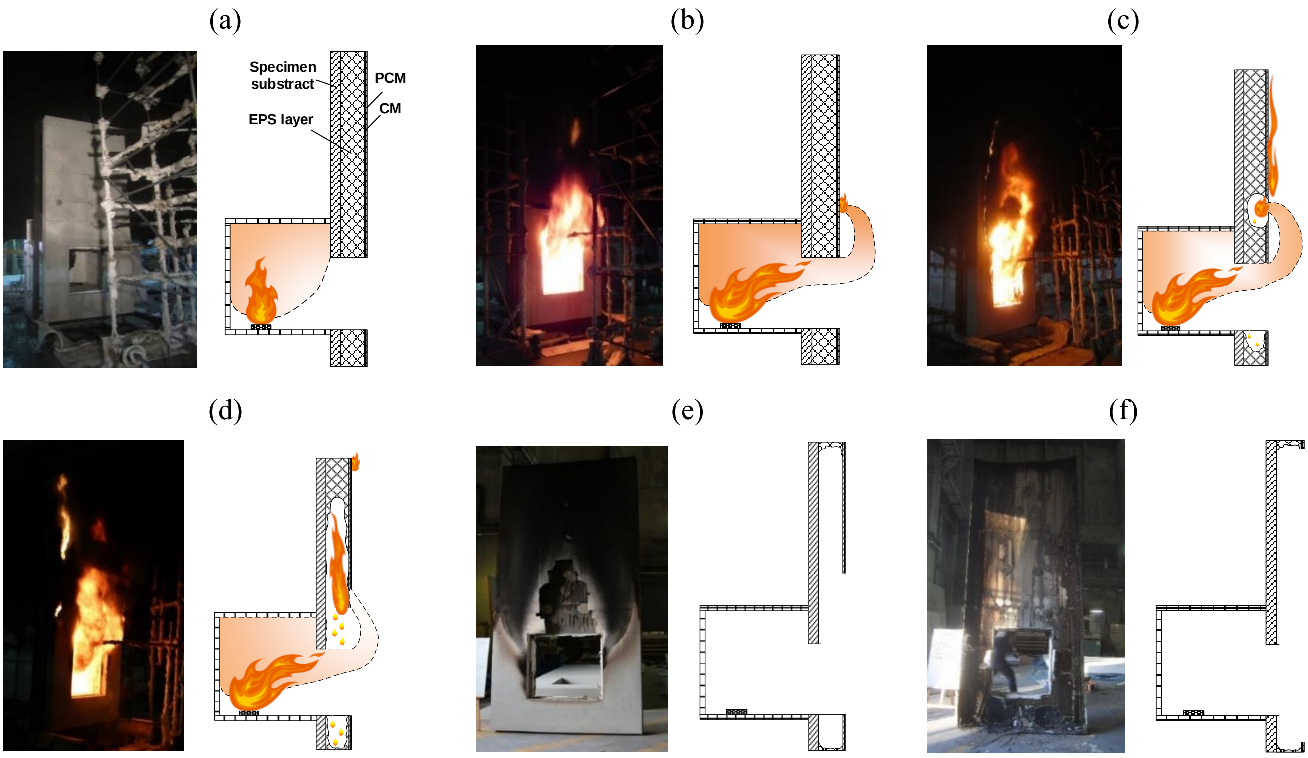


Fig. 2. The description of façade fire tests, (a) Early stage at t=1 s, (b) flame spilled out at t=24 s, (c) ignition of EPS and the formation of hole in CM layer at t = 95 s, (d) upward flame propagation at t=326 s, (e) EPS burnout outlook, and (f) removal of façade.

For the preheat time for the backside thermocouples in test No. 4 (**Fig. 3b**), they were 165 s (T_{B1} at 0.50 m), 172 s (T_{B2} at 0.90 m), 192 s (T_{B3} at 1.50 m), 220 s (T_{B4} at 2.00 m) and 254 s (T_{B5} at 2.50 m), respectively. Afterward, their temperatures started to rapidly increase above 200 °C without any drop, indicating the direct impact of the flame and the ignition of foam. These preheat time values will be used to calculate the transient and average upward FSR.

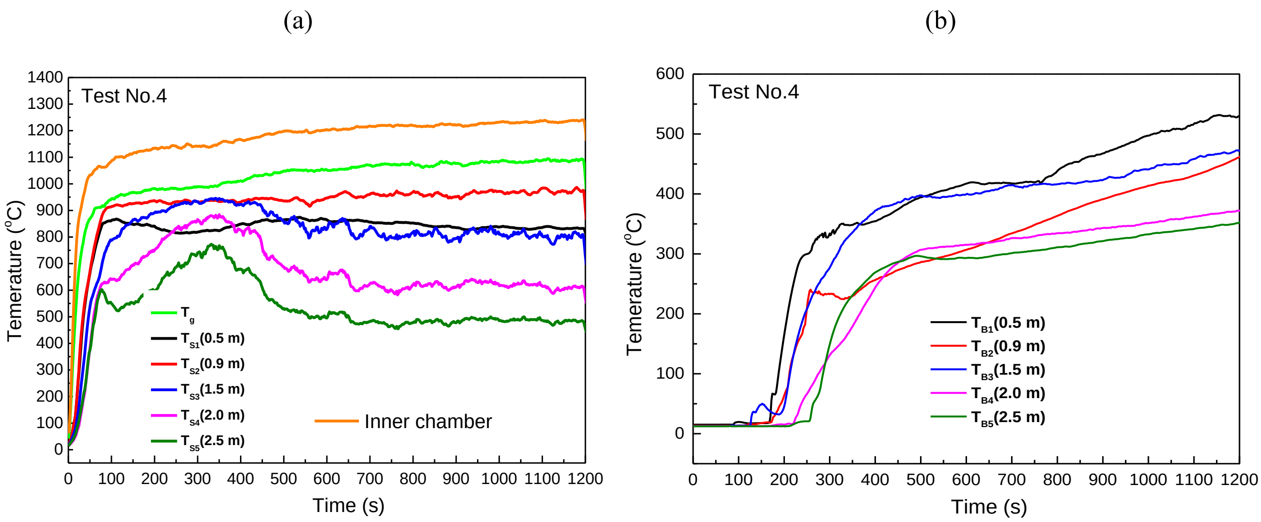


Fig. 3. The surface and back temperature histories of No.4 varying with test time, (a) surface temperature (T_S), and (b) back temperature (T_B).

3.2. Upward fire spread rate (FSR)

The dependence of FSR with various test parameters are summarized in **Fig. 4**, and the experimental data are listed in **Table 2.** As expected, the upward FSR is not constant, but increases almost linearly with the time or the development of fire, as shown in **Fig.4 (a)**. In other words, the acceleration of FSR in each case is almost a fixed value. To simplify the comparison, the average value ($\overline{FSR}$) is used to study the influence of other fire and material parameters.

Fig. 4(b) shows that the averaged FSR decreases greatly as the thickness of EPS increases. Specifically, as the thickness increases from 100 mm to 200 mm, the value of $\overline{FSR}$ almost decreases half. This behavior is the same as the "thermally-thin material," although the thicknesses of EPS are several orders of magnitude greater than the conventional limit of thermally thin (about 2 mm). This is attributed to the quick shrinkage of EPS foam in contact with the flame, as well as the serious melt-flow or melt-drip phenomena that happened inside the ETICS.

In addition, the averaged FSR increases with the HRR rising of window spilled flame (see **Fig.4 (c)**). A greater HRR indicates a stronger flame heating, and the spilled flame length, which is attached to the ETICS surface, also increases with HRR. Compared to the effect of thickness, $\overline{FSR}$ is almost insensitive to the density of EPS, as shown in **Fig.4 (d)**. It is probably because the density of EPS is quite small, and the density variation does not affect the quick melting and shrinkage behaviors. Some study in the literature has also showed that density has a minimal effect on the ignition of low-density EPS foam [9].

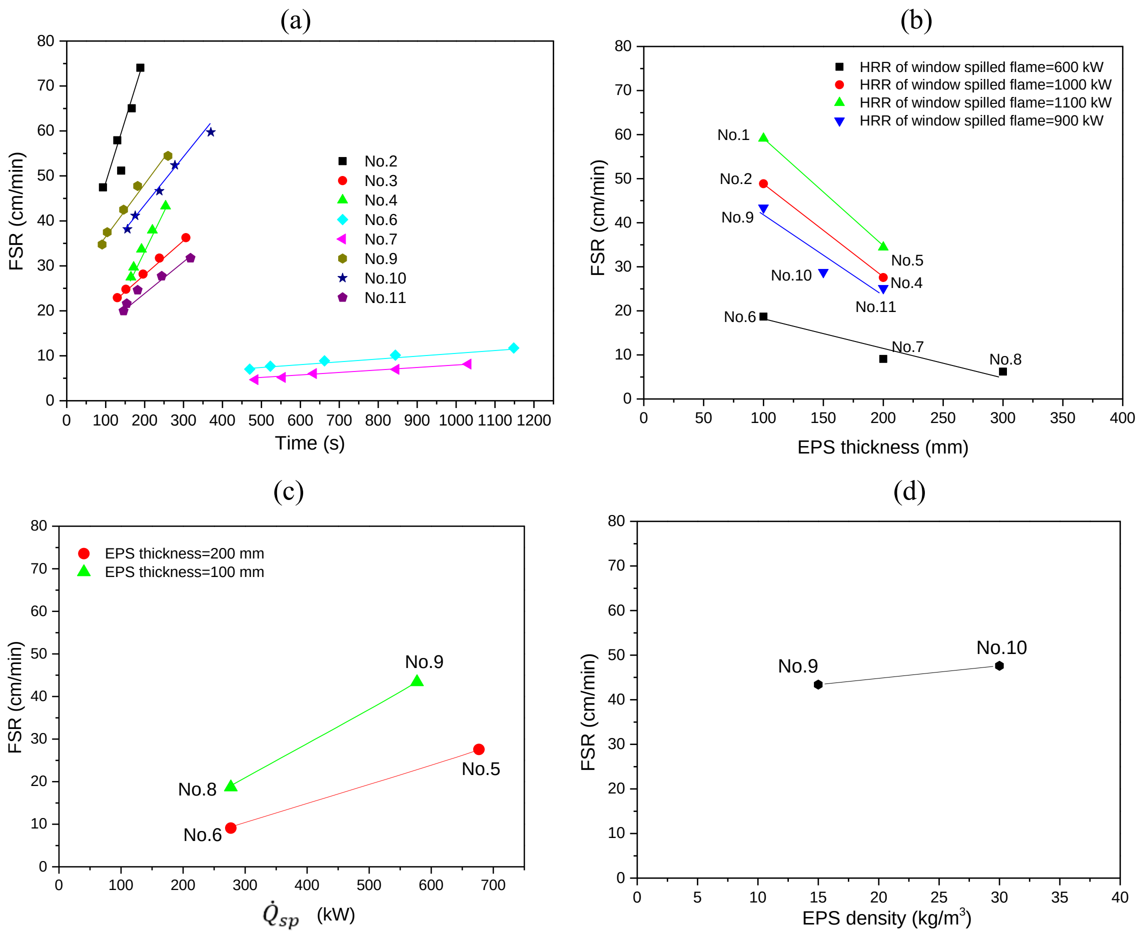


Fig. 4. The description of FSR varying test time, EPS thickness, HRR and EPS density, (a) FSR vs. test time (b) $\overline{\mathrm{FSR}}$ vs. $\mathrm{L_{EPS}}$ (c) $\overline{\mathrm{FSR}}$ vs. $\dot{Q}_{sp}$ (d) $\overline{\mathrm{FSR}}$ vs. ρ_{EPS}

Table 2. Temperature over calcium silicate board and the heat penetration time for each position during façade fire tests

Test No.	T_{B1} (°C)	T_{B2} (°C)	T_{B3} (°C)	T_{B4} (°C)	T_{B5} (°C)	t_1 (s)	t_2 (s)	t_3 (s)	t_4 (s)	t_5 (s)	$\overline{FSR}$ (cm/min)
1	436	352	262	212	196	160	203	160	313	387	48.86
2	520	472	533	374	364	93	140	130	167	189	59.13
3	438	387	454	283	262	130	152	196	238	306	28.78
4	531	462	471	370	350	165	172	192	220	254	34.42
5	477	377	331	251	273	107	257	256	394	451	27.56
6	236	267	220	88	18	470	523	662	844	1148	9.09
7	234	220	177	115	80	484	554	634	846	1031	6.21
8	231	158	147	30	157	147	348	350	435	/	18.68
9	422	313	266	287	165	91	104	146	182	260	43.39
10	559	555	546	327	244	156	176	238	278	370	47.62
11	514	436	331	283	227	146	154	182	244	318	25.13

3.3. Correlation of instantaneous FSR versus modified FPI (Φ)

The EPS ETICS façade fire is a comprehensive phenomenon that is greatly affected by fire intensity of compartment fire (e.g., HRR), spilled flame, opening treatment method, EPS thickness, material properties and so on [35-37]. Thereby, not a single parameter can determine the instantaneous FSR in the early stage of the façade fire, as well as the fire performance of the EPS ETICS.

The window spilled flame is a common ignition source of the exterior building wall [38]. The HRR of the compartment fire ($\dot{Q}$) includes the part confined inside the chamber and the residue released out of chamber. The critical HRR confined in the chamber ($\dot{Q}_{v,crt}$ in kW) could be calculated as [39]

$$\dot{Q}_{v,crt} = 150\left(\frac{A_T}{A\sqrt{H}}\right)^{\frac{2}{5}} A\sqrt{H} \tag{2}$$

which only depends on the compartment configuration and is 323 kW for the current chamber. Then, the HRR of window spilled flame ($\dot{Q}_{sp}$ in kW) is

$$\dot{Q}_{sp} = \dot{Q} - \dot{Q}_{v,crt} \tag{3}$$

which is a key index for the evaluation of the reaction-to-fire performance of façade specimens. Specifically, for the $\dot{Q}$ of 600 kW, 900 kW the $\dot{Q}_{sp}$ is

The upward FSR at the initial stage should be related to the HRR of the window spilled fire as

$$FSR \sim \dot{Q}_{sp} \sim \left(\dot{Q} - \dot{Q}_{v,crt}\right) \tag{4}$$

which is most valid when the spilled flame is small.

Previously, the fire propagation index (FPI) was used to evaluate the potential of vertical fire propagation by using the following equation [40]:

$$FSR \sim FPI = 750\frac{(\dot{Q}'_{ch})^{\frac{1}{3}}}{TRP} \tag{5}$$

The thermal response parameter (TRP) is

$$TRP = \left(\frac{\pi}{4} k\rho c_p\right)^{\frac{1}{2}} (T_{ig} - T_0) \tag{6}$$

where $T_{ig} - T_0 = 220$ °C for the PCM contained SBR latex. However, this FPI may not be valid for the EPS ETICS. For example, **Fig. 4(d)** shows that the density has a negligible effect on the FSR.

Thus, based on the analysis above and our previous work [41], we proposed a modified FPI (Φ) to evaluate the upward fire propagation potential of EPS ETICS as

$$\Phi = FPI\left(\frac{\dot{Q} - \dot{Q}_{v,crt}}{L_{EPS}}\right)\left(\frac{T_z}{T_g}\right)^{\frac{2}{3}}\left(\frac{T_g - T_0}{T_z - T_0}\right) \tag{7}$$

where T_z is the real-time surface temperature $T_S(t)$, and T_g is the real-time window gas temperature. In this work, the value of Φ ranges from 30 to 280 for the HRR of from 600 kW to 1,100 kW.

Table 3. Peak surface temperature varying test time during façade fire tests

Test No.	T_g (°C)	T_{S1} (°C)	T_{S2} (°C)	T_{S3} (°C)	T_{S4} (°C)	T_{S5} (°C)
1	1122	882	775	648	514	376
2	1044	1023	990	856	693	637
3	1068	942	893	766	598	491
4	1090	865	973	943	888	765
5	1078	1004	647	895	699	644
6	992	905	678	547	517	313
7	1045	670	580	573	450	391
8	946	498	394	323	282	245
9	1126	938	883	754	554	465
10	1089	985	923	785	564	558
11	1066	902	893	878	725	561

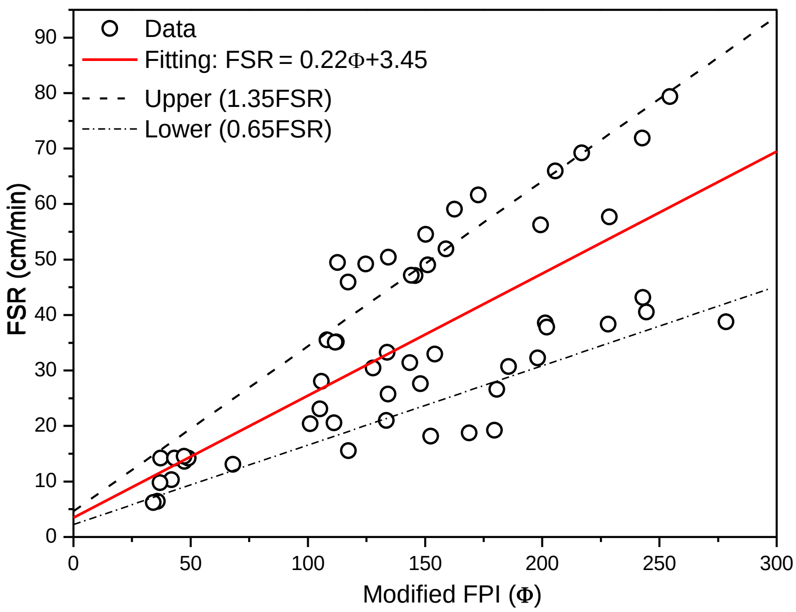


Fig. 5. The relationship between FSR of each position and modified FPI ().

The correlation between the instantaneous FSR and Φ is shown in **Fig. 5**. The best-fitting correlation for all FSR data is

$$FSR = 0.22\Phi + 3.45 \tag{8}$$

where most of the experimental data are within ±35% of this correlation. To predict the FSR, , and should be estimated first.

Fig. 6 further shows the influence of EPS foam thickness under different compartment-fire HRRs; that is, FRS increases as the EPS thickness decreases. In addition, when the HRR of window spilled flame is low, the FSR trend agrees with the lower boundary. The influence of EPS thickness on FSR vs. is given in **Fig. 7**. A comparison of results indicates that EPS thickness imposes a serious effect on FSR. Considering the uncertainty of the real-scale façade fire test and the complexity of the reaction-to-fire performance of EPS ETICS, the FSR could be averaged approximately and adequately by the averaged trajectory.

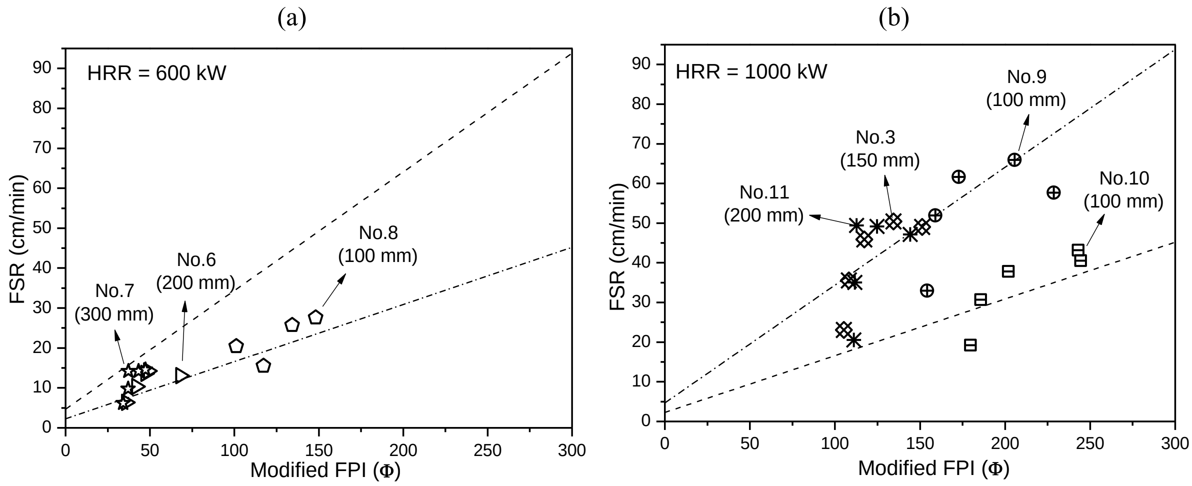


Fig. 6. The influence of HRR on FSR versus, (a) 600 kW, and (b) 1000 kW.

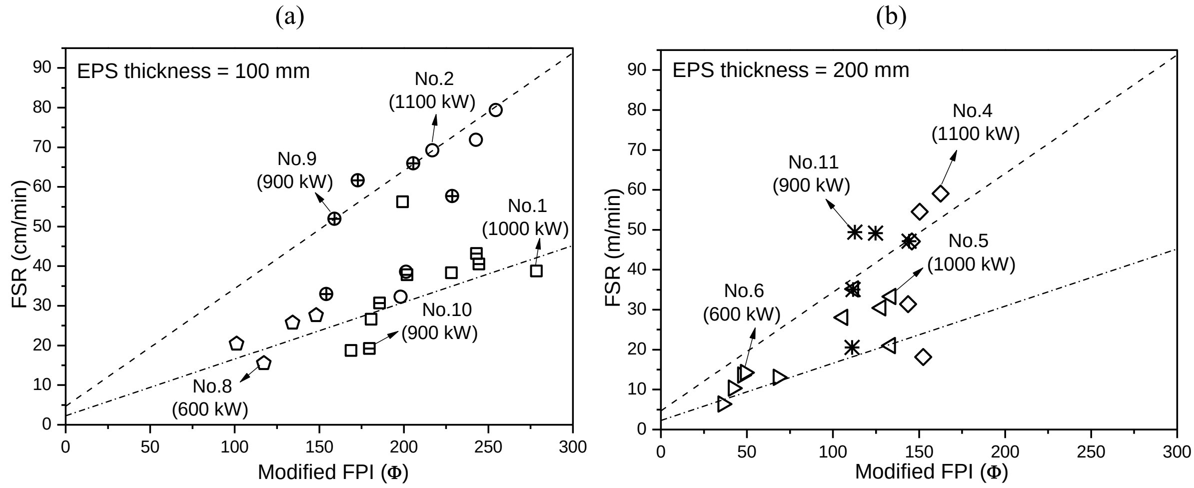


Fig.7 The influence of EPS thickness on FSR versus (a)100 mm (b) 200 mm

3.4. A prediction method for FSR prior to real-scale tests

3.4.1. A dimensionless temperature profile ($\boldsymbol{\Theta_c}$)

The vertical temperature distribution (Θ') over façade surface imposed by a window spilled flame has been proposed in our recent work [26] as

$$\Theta' = \frac{\Delta T_z r_0'^{\frac{5}{3}}}{\left(\frac{\dot{Q}^2 T_\infty}{\rho_z{}^2 c_p{}^2 g}\right)^{\frac{1}{3}} n^{\frac{1}{6}}} = \frac{0.45}{(1-x)^{\frac{1}{6}}}\left(\frac{T_g}{T_z}\right)^{\frac{2}{3}}\left(\frac{T_z - T_0}{T_g - T_0}\right) = F\left(\frac{z}{r_0'}\right) \tag{7}$$

where the neutral plane is calculated by the equation $x = \frac{z_0}{H} = \frac{1}{1+1.04(\frac{T_g}{T_0})^{1/3}}$. The new length scale r_0' was defined as $r_0' = \sqrt{\frac{W(1-x)H}{\pi}}$, where x is the ratio of neutral plane position z_0 to the window opening height H. Without this assumption, the location of the neutral plane is a constant at $0.5H$.

The vertical temperature over the facade surface varies with the HRR of window spilled flames and the fire propagation potential of façade materials. Then, the correlation between dimensionless Θ_c and $\frac{z}{r_0'}$ is proposed by incorporating the FPI [30], as proposed and verified in our previous work [25]:

$$\Theta_c = \frac{\Theta'}{\sqrt{FPI}} = \frac{0.45}{(1-x)^{\frac{1}{6}}}\left(\frac{T_g}{T_z}\right)^{\frac{2}{3}}\left(\frac{T_z - T_0}{T_g - T_0}\right) FPI^{-\frac{1}{2}} = F\left(\frac{z}{r_0'}\right) \tag{8}$$

Regarding EPS ETICS façade, dimensionless Θ_c is approximated to be a nearly linear relationship with $\frac{z}{r_0'}$ based on test results. An adequate approximation is $\frac{z}{r_0'} = -180 \times \Theta_c + 17.3$.

3.4.2. Proposal of a prediction method for FSR

Based on the above discussion and Eq. (8), we have $\mathrm{FSR} \propto \Phi$ that can be further expressed as

$$FSR \propto FPI\left(\frac{Q - Q_{v,crt}}{L_{EPS}}\right)\left(\frac{T_z}{T_g}\right)^{\frac{2}{3}}\left(\frac{T_g - T_0}{T_z - T_0}\right) \tag{9}$$

According to Eq. (7), we have

$$\left(\frac{T_g}{T_z}\right)^{\frac{2}{3}}\left(\frac{T_z - T_0}{T_g - T_0}\right) = \frac{\Theta_c\sqrt{FPI}}{0.45}(1-x)^{\frac{1}{6}} \tag{10}$$

Then, Eq. (9) is changed as:

$$FSR \propto \sqrt{FPI}\left(\frac{Q - Q_{v,crt}}{L_{EPS}}\right)\frac{0.45}{\Theta_c(1-x)^{\frac{1}{6}}} \tag{11}$$

To propose a simple method for calculating the vertical FSR in the facade, $FSR = 0.22\Phi + 3.45$ is used. Finally, the FSR [cm/min] becomes

$$FSR = \frac{Q - Q_{v,crt}}{L_{EPS}(1-x)^{\frac{1}{6}}} \times \frac{39.6\sqrt{FPI}}{17.3 - \frac{z}{r_0'}} + 3.45 \tag{12}$$

which can predict the early-stage FSR of EPS ETICS prior to façade fire. The necessary parameters are z, r_0', FPI, x , Q, $Q_{v,crt}$ and L_{EPS}, which are easy to obtain with respect to a fixed test condition. For simplification, $x = 0.5$ can be used for calculation.

3.5. Comparison of prediction methods

In our previous work, a calculation method for FSR on the basis of test results from a series of tests is given [41]. When $L_{EPS} \leq 0.3$m,$Q \leq 1100$ kW, and $17.3 \leq FPI \leq 31.3$ (m/s$^{1/2}$)/(kW/m)$^{2/3}$, FSR in [cm/min] could be predicated by

$$FSR = 100\exp\left[\left(1.56FPI\frac{Q - Q_{v,crit}}{L_{EPS}} - 0.045\right)t - 2.2\right] \tag{13}$$

In this work, a new calculation method (current method) is proposed based on considering the HRR of window spilled flame and thermal parameters of EPS ETICS. We can predict FSR with t, FPI, Q, L_{EPS} by Eq. (12). The comparison of experimental and calculated data is shown in **Fig. 8**. It indicates the result performed by the current method shows a better agreement with experimental data. In general, the agreement is much increased by using the current method. Thus, the current method is adequately approximated for engineering applications.

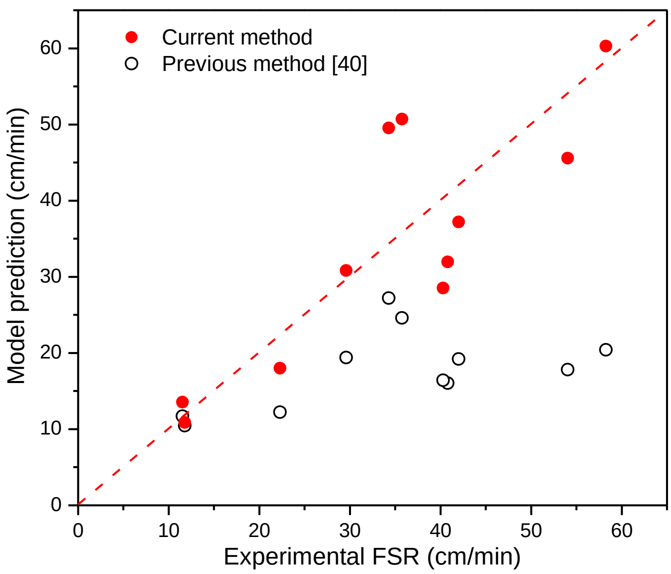


Fig. 8. The deviation between experimental and calculated FSR by using two methods.

4. Conclusions

In this work, FSR of EPS ETICS facades exposed to different window spilled fires are discussed on the basis of a series of real-scale fire tests according to the JIS A 1310 façade standard test method. Tests showed that the surface CM layer only provided a small fire resistance for the internal flammable EPS panel. Once the CM layer was damaged by spilled flame locally, the EPS panel would be quickly ignited. The measured upward FSR increases with the rising of HRR and with the decreasing EPS thickness like the thermally thin material.

A dimensionless parameter $\Phi = FPI\left(\frac{\dot{Q}-\dot{Q}_{v,crt}}{L_{EPS}}\right)\left(\frac{T_z}{T_g}\right)^{\frac{2}{3}}\left(\frac{T_g-T_0}{T_z-T_0}\right)$ is defined to quantify the instantaneous FSR, and all tests in this work satisfy $FSR = 0.22\Phi + 3.45$ [cm/min]. With the measured ETICS temperature profile, the FSR can be predicted as $FSR = \frac{Q-Q_{v,crt}}{L_{EPS}(1-x)^{\frac{1}{6}}} \times \frac{39.6\sqrt{FPI}}{17.3-\frac{z}{r_0'}} + 3.45$. This work provides a useful method to quantify the upward façade fire propagation, which also helps evaluate the fire risk and hazard of EPS ETICS façade prior to expensive tests.

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