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# Experimental study of expanded polystyrene (EPS) External Thermal Insulation Composite Systems (ETICS) masonery façade reaction-to-fire performance

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ABSTRACT

External Thermal Insulation Composite Systems (ETICS) consisting of insulation core and decoration surface materials, are quite common in new constructions and refurbishment buildings with design-oriented goals of sustainability and energy efficiency. However, combustible insulation core has caused serious result due to the ravages of fire disasters. Thermoplastic expanded polystyrene (EPS) acting as an insulation core is widely and vertically installed in ETICS. Presently, with an aim to evaluate EPS ETICS fire performance, a series of EPS ETICS specimen varying EPS thickness from 50 mm to 300 mm, polymer mortar type including SBR polymer mortar and acrylic resin mortar, reinforcement including one layer and two layer's glass fiber mesh, and opening edge treatment method differs from back-wrapping method to fire barrier method are tested by a large-scale Japanese façade fire propagation method JIS A 1310 with heating intensity from 100 kW to 1100 kW. A comprehensive fire risk evaluation **INDEX** method of EPS ETICS based on EPS burn area and façade surface temperature profiles of JIS A 1310 tests is proposed. It could easily classify the effects of mortar, reinforcement, EPS thickness and opening edge treatment method on EPS ETICS fire performance. It is concluded that in JIS A 1310 method, the fire risk of EPS ETICS could be classified by **INDEX** method as the followings: the **INDEX** ≤ 0.825 is an acceptable level; the **INDEX** ≥ 0.836 is the unacceptable level; 0.825 ≤ **INDEX** ≤ 0.836 is the critical level. The fire propagation index (**FPI**) is believed to be a potential prediction method for EPS ETICS fire risk evaluation before JIS A 1310 tests. The **FPI** is classified as the followings: the **FPI** ≤ 17.3 is an acceptable level; the **FPI** ≥ 21.4 is the unacceptable level; 17.3 ≤ **FPI** ≤ 21.4 is the critical level.

## 1. Introduction

External thermal insulation composite systems (ETICS) have been used in buildings for several decades due to their thermal advantages, low cost and ease of application [1]. The principal design of an ETICS includes wall construction, insulation material, cement bound mortar with reinforcement, rendering, and fixation by dowels and mortar [2]. In China, several ETICS fire cases involving extreme fire spread upon exterior combustible claddings have occurred in recent years, and caused serious property damage and life loss [3]. The Television Cultural Center (TVCC) ETICS fire (core material: Extruded Polystyrene (XPS) foam) burned at night on February 9, 2009. Residential Building ETICS Fire (core material: polyurethane (PU) foam) happened on November 15, 2010, killed 58 residents and injured 71. The attention on ETICS fire was increased sharply after the serious exterior cladding (core material: polyethylene foam) Grenfell Tower fire happened in London on June 14th, 2017 [4]. EPS is believed to be one of common thermal insulation thermoplastic materials used on external walls of buildings. When EPS foam exposed to heat, melt-drip results in a serious fire in both upward and downward direction. Furthermore, the previous experiments in our group showed that HRR was hard to distinguish the fire risk of EPS ETICS specimens with different EPS thickness because that unburnt EPS molten was observed in the bottom of facade. Therefore, a suitable evaluation method for EPS ETICS reaction-to-fire performance is necessary and urgent.

The main emphasis of available EPS ETICS researches are focused on probabilities of fire spread assessment [5], fire safety of EPS ETICS during transport, construction and end use conditions [6], fire rescue analysis of EPS ETICS [7], fire barrier influence on EPS ETICS reaction-to-fire performance [8] and incident heat flux upon the facade's surface (IHFFS) and damage of the facade's render effects on the EPS ETICS fire performance [9]. Although these studies could be useful for EPS ETICS

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**Nomenclature**

| | |
|---|---|
| ETICS | External Thermal Insulation Composite System |
| EPS | Expanded polystyrene foam |
| FPI | Fire propagation index |
| HRR | Heat release rate |
| IHFFS | Incident heat flux upon the facade's surface |
| OC | Oxygen Consumption Calorimetry |
| PE | Polyethylene foam |
| THR | Total heat release rate |
| TRP | Thermal Response Parameter |
| XPS | Extruded Polystyrene foam |
| $\Delta T_{ig}$ | The ignition temperature of the polymeric material above ambient in K |
| k | Thermal conductivity in kW/m/K |
| ρ | Density in $kg/m^3$ |
| $c_p$ | Specific heat in kJ/kg/K of the solid |
| u | The upward fire propagation rate in mm/s |
| $\delta$ | The characteristic forward heat transfer distance and is generally assumed to be constant in m |
| $\dot{Q}'_{rad}$ | The radiative heat release rate per unit sample width in kW/m |
| $X_f$ | The flame height for upward fire propagation in m |
| $\dot{Q}'_{ch}$ | Chemical heat release rate per unit width (kW/m) |
| $\chi_{rad}$ | The radiative fraction of the combustion efficiency |
| $T_{ig}$ | The surface ignition temperature (K) |
| $T_0$ | Ambient temperature (K) |
| $\dot{q}''_e$ | The incident heat flux ($kW/m^2$) |
| $\dot{q}_{cr}$ | Critical heat flux for ignition (CHF) ($kW/m^2$) |
| $\chi$ | Average heat loss as a fraction of the critical heat flux and takes into account the fact that heat losses are initially zero and increase as the solid is heated to its ignition temperature |

fire performance investigation, little knowledge of influence mortar, reinforcement, EPS thickness and opening edge treatment method on the EPS ETICS reaction-to-fire performance is available. In addition, it is widely acknowledged that EPS ETICS consist of adhesive, EPS insulation material, cement, reinforcing mesh and finishing coat. However, most of investigations are only concentrated on the fire characteristics of single component, such as EPS [10–12], adhesive [13], polymer-modified concrete [14–15] and finishing coat reaction-to-fire performance [16–19]. It seems impossible to use the fire performance of a single component to evaluate EPS ETICS fire performance, which are very complicated. In our past researches, it was found that the medium scale façade tests (ISO 13785-1) is difficult to confirm the property of downward fire propagation. Furthermore, the sand-burner installed under the test specimen was found to be blocked up because of droplets in case of foamed plastics installed within the façade specimen [20–22]. Considering the defects of ISO 13785-1 and the lacking of clear standards in Japan, the JIS A 1310: 2015 façade fire test method had been set up and issued. Although it is clear that EPS ETICS would exhibit a complex fire performance in a fire, little knowledge of a quantitative fire risk evaluation method of EPS ETICS is available.

In this work, a series of EPS ETICS specimens varied opening edge treatment and EPS thickness are tested according to JIS A 1310 façade fire test method by using different heating intensity from 300 kW to 1100 kW. Before each façade fire test, calibration test was firstly carried out. A quantitative evaluation method for EPS ETICS fire risk based on JIS A 1310 test results is proposed and discussed.

## 2. Experiment and materials

### 2.1. JIS A 1310 façade fire test method [23]

In JIS A 1310 façade fire test, the test specimen was vertically installed, just as shown in Fig. 1 (a) and (b). Façade fire test facility consisted of propane gas combustion chamber (size in L × W × H = 1350 mm × 1350 mm × 1350 mm), fire spreading 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. Chamber was used to produce different heating intensity fire, which was conducted by the controlled high purity propane combustion. The specimen substrate is made by laying two pieces of 12 mm thickness calcium silicate board and the joint of the first layer was not overlapped with joint of second layer. Specimen support frame made of stainless steel was employed to support specimen substrate and the specimen tested. The interior surface of chamber was coated by a thickness of 25 mm ceramic fiber blanket. The k-type thermocouples information varying test time was recorded by utilization of a series of thermocouples on finishing coat surface of façade test specimen in the height of 0 mm (T0 for temperature), 500 mm (T1 for temperature), 900 mm (T2), 1500 mm (T3), 2000 mm (T4) and 2500 mm (T5) away from the upper of the opening, respectively. The installations of thermocouple positions are given in Fig. 1(c). Heat release rate (HRR) and total heat release rate (THR) was calculated by the common methodology Oxygen Consumption Calorimetry (OC). During OC measurement, the gas-analysis equipment was used to record oxygen concentration ranged from 0.009% to 20.9% in every two seconds. K-type thermocouple has an accuracy of ± 2.2 °C. The gas-analysis has an accuracy of ± 0.02% $O_2$, ± 0.02% CO and ± 0.02% $CO_2$.

Before façade fire test, the 4 L alcohol combustion was used to calibrate the whole equipment condition. Then chamber heating intensity in kW was determined by controlling the mass flow of high purity propane. Before each façade fire test, the calibration test was carried out by laying a thickness of 25 mm ceramic fiber façade. After 20 min façade specimen test, time averaged temperature of each thermocouple position $T_{0\text{-}3}$ (0–3 min), $T_{0\text{-}10}$ (0–10 min) and $T_{0\text{-}20}$ (0–20 min) were calculated respectively. The outlook of an EPS ETICS specimen after JIS A 1310 test is shown in Fig. 1 (d). EPS burn area S was obtained by a statistic method, just as shown in Fig. 1 (e).

### 2.2. Preparation of EPS ETICS specimen

The horizontal section of EPS ETICS specimen is shown in Fig. 2 (a). It consisted of four layers from top to down, finishing coat made of polymer cement mortar, cement, reinforcing mesh made of fire glass fiber and EPS. In this study, polymer cement mortar varied thickness and composition. EPS thickness varied from 50 mm to 300 mm. Cement thickness differed from 1 mm to 3 mm and the reinforcing mesh differed from 1 layer to 2 layers. All the specimens are provided by Cinqvit Corporation and Nohara Holdings, Inc.. The preparation of EPS ETICS specimen is described in the followings. Firstly, specimen support frame made of stainless steel was made in size of W × L = 1820 mm × 4100 mm. There was an opening (size in L × W = 910 mm × 910 mm) in the middle of support frame, just as shown in Fig. 2 (b). Two pieces of calcium silicate board with a thickness of 12 mm was laid and fixed on the specimen support frame (See Fig. 2(c)). Then EPS panel was laid and fixed on it, which is shown in Fig. 2 (d). After EPS coating with a layer of glass fiber reinforcing mesh, the cement was used to fix the reinforcing mesh, just as shown in Fig. 2 (e). Finally, the finishing coat made of polymer cement mortar was laid on the surface of cement, which is described in Fig. 2 (f).

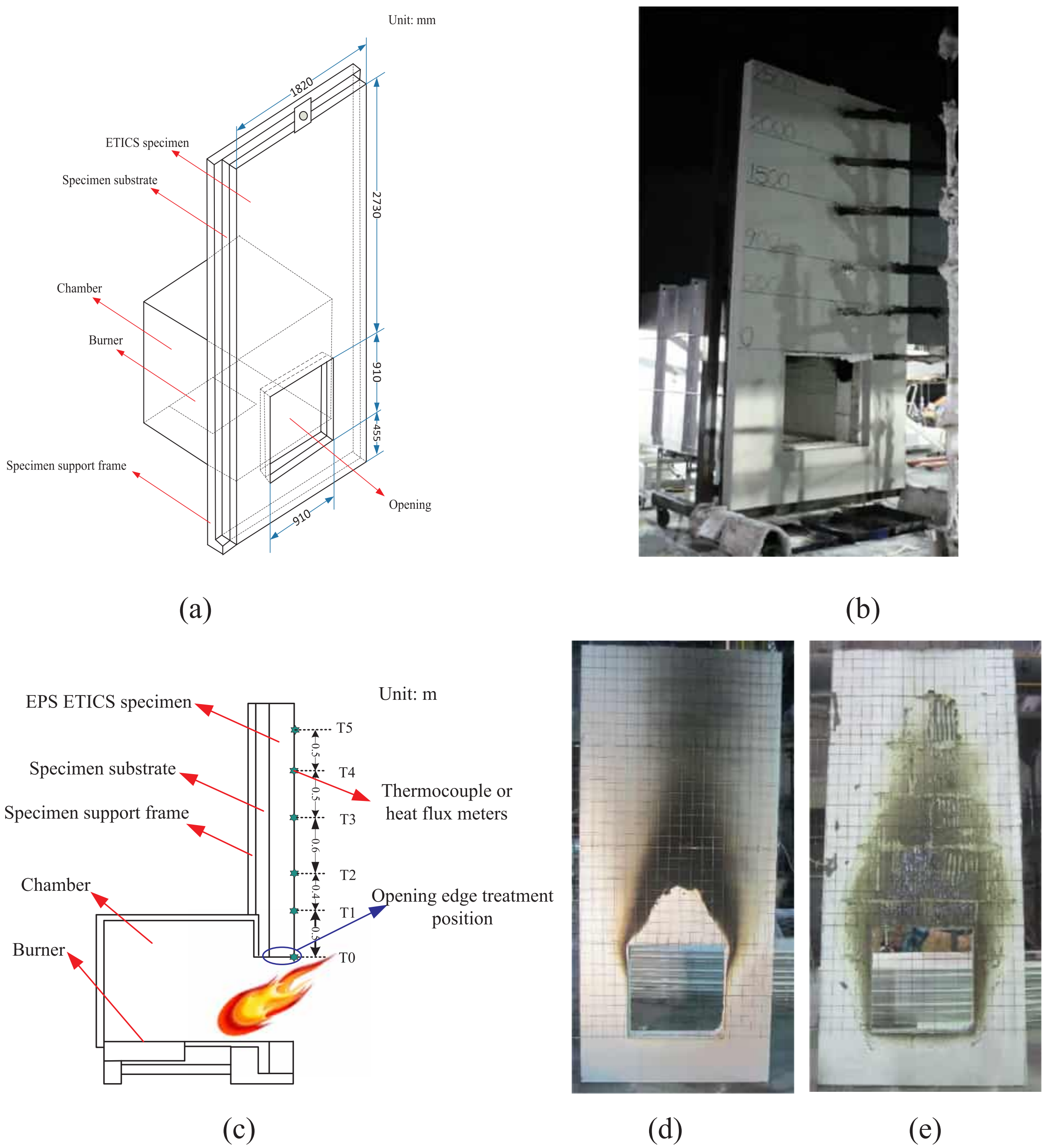


**Fig. 1.** Experiment layout (a) a simple model of experiment (b) the experimental layout (c) thermocouples installation position description.

### 2.3. Opening edge treatment methods

In our experiments, the opening edge treatment methods varied back-wrapping method, adhesion method, EPS exposed without treatment method, adhesion + rock wool (0.06 m) method and adhesion + rock wool (0 m) method. The details of opening edge treatment for each method are described in Fig. 3. The EPS used here is molten at about 85–110 °C and ignited at about 290 °C.

The traditional edge treatment method of EPS ETICS is adhesion. The section figure of it is disclosed in Fig. 3 (b). It is widely acknowledged that when EPS is exposed to a flame, EPS molten dropped down and caused downward fire spreading. Considering that EPS molten was easy to cause downward fire spread, the reinforcing mesh made of fire glass fiber is wrapped back to reduce EPS molten dropped down. This idea was realized by back-wrapping method. The difference between back-wrapping and adhesion lied in whether reinforcing mesh back wrapped, just as shown in Fig. 3 (a) and (b). The EPS exposed without treatment method was prohibited in current EPS ETICS building. Here, EPS exposed without treatment (Fig. 3 (c)) was being acted as a control group test to compare different opening edge treatment methods.

Fire barrier was one of effective methods to inhibit vertical flame spread, which had been widely used in EPS ETICS building. Presently, fire barrier made of rock wool was installed in the two methods. The difference between two methods lied in the vertical distance away from the top of opening. Installation of fire barrier made of rock wool on traditional edge treatment method was believed to be a good method for flame spread inhibition. In this study, adhesion + rock wool (0.06 m) indicated that the opening of specimen was treated by adhesion method and installing a fire barrier made of rock wool (size in H × L × W = 150 mm × 1820 mm × 50 mm) at 0.06 m away from the

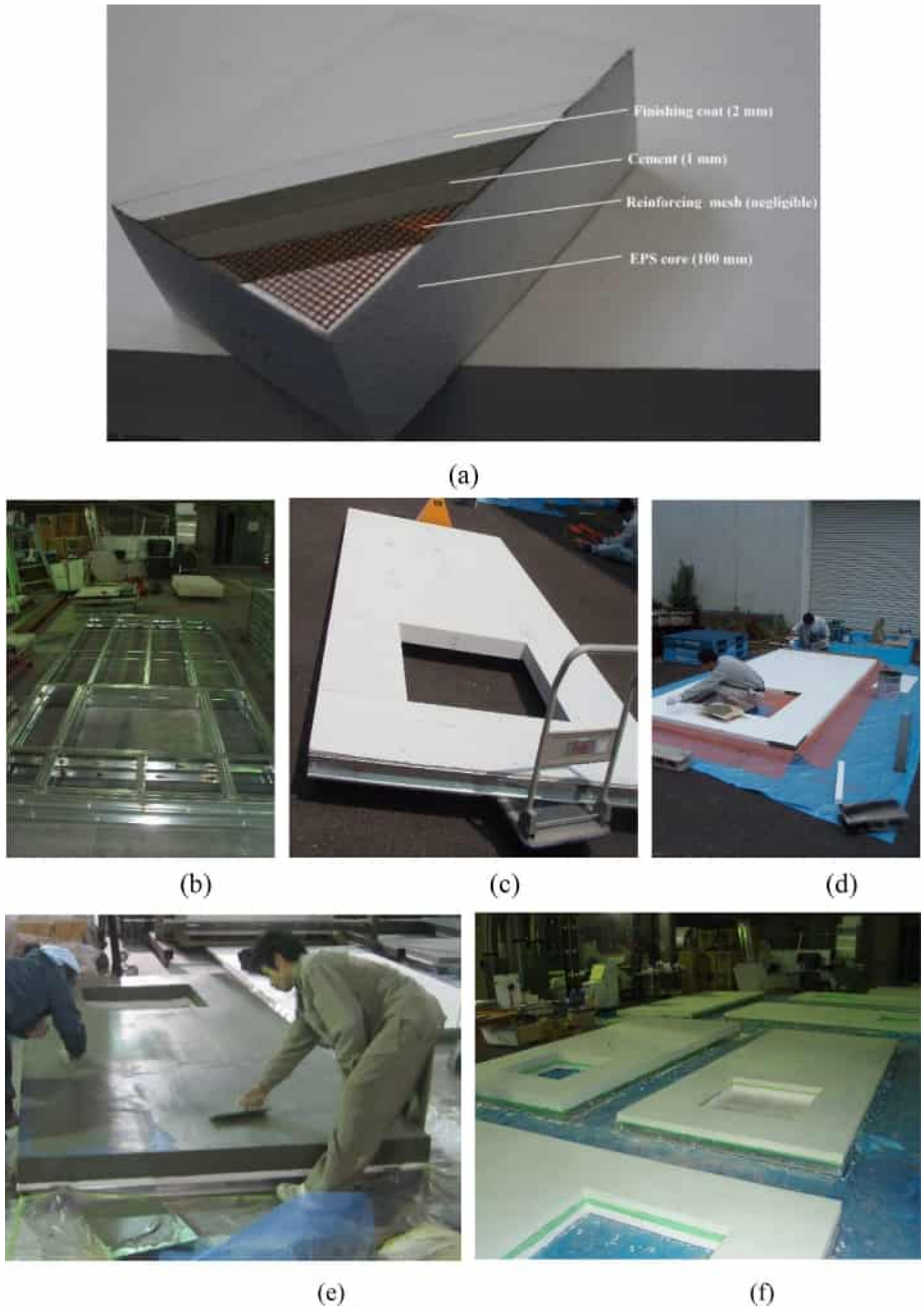


**Fig. 2.** The description of EPS ETICS specimen preparation (a) The horizontal section EPS ETICS specimen (b) specimen support frame (c) specimen substrate (d) EPS panel laying on specimen substrate (e) cement laying on reinforcing mesh (f) finishing coat laid on the cement.

top of the opening, just as shown in Fig. 3(d). Adhesion + rock wool (0 m) means that the opening of specimen was treated by adhesion method and directly installing a fire barrier made of rock wool (size in H × L × W = 150 mm × 1820 mm × 50 mm) at the top of opening (see Fig. 3(e)).

## 3. Results and discussion

### *3.1. A fire risk evaluation method of EPS ETICS based on JIS A 1310 test results*

#### *3.1.1. Chamber burner combustion coefficient of calibration test*

Just as previous report shows that performance of facade cladding systems in case of a fire cannot be fully assessed by laboratory tests [24]. In Japan, JIS A 1310: 2015 façade fire test method was set up and issued. In this study, the calibration test was carried out firstly with a 25 mm thick ceramic fibers installing on a 50 mm calcium silicate panel. The 20 min calibration test was carried out by employing different heating intensity from 350 kW to 1100 kW. The THR and HRR are calculated by oxygen-consuming method during 20 min façade fire test. Chamber burner combustion coefficient of calibration test was described in Table 1. In it, theoretical THR was calculated by gas volume (L/min)/60(s)/22.4 × 2217.8 kJ/mol. The averaged complete combustion coefficient from 350 kW to 1100 kW is 86.3%. Although incombustible propane gas may have an effect on façade fire performance, in this study its influence is ignored because all the specimens are under the same test condition.

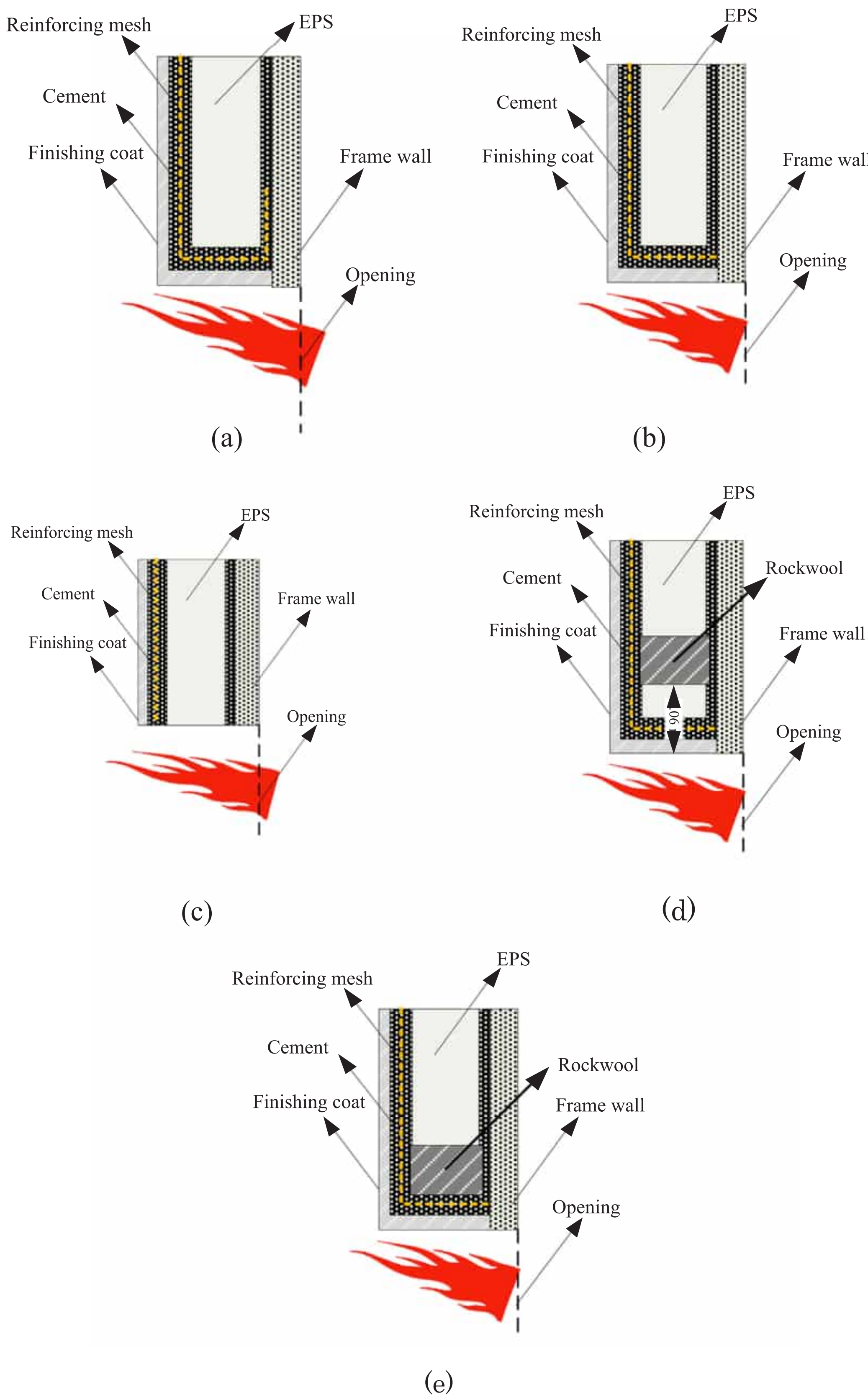


**Fig. 3.** The description of opening edge treatment methods of test NO.11 to NO.15 (a) Back-wrapping section figure (b) Adhesion section figure (c) EPS exposed without treatment section figure (d) Adhesion + rock wool (0.06 m) section figure (e) Adhesion + rock wool (0 m) section figure.

**Table 1**
Chamber burner combustion coefficient of calibration test.

| Heating intensity/kW | THR/MJ | pHRR/kW | Theoretical THR/MJ | Complete combustion coefficient/% |
|---|---|---|---|---|
| 350 | 378.0 | 372.8 | 397.6 | 95.1 |
| 600 | 670.1 | 662.3 | 775.8 | 86.4 |
| 650 | 754.4 | 703.9 | 855.4 | 88.2 |
| 850 | 959.6 | 956.0 | 1174.4 | 81.7 |
| 900 | 1056.4 | 1021.4 | 1333.8 | 79.2 |
| 950 | 1111.4 | 1057.3 | 1254.0 | 88.6 |
| 1100 | 1334.8 | 1242.7 | 1572.9 | 84.9 |

### *3.1.2. Fire risk evaluation of EPS ETICS based on JIS A 1310 façade fire test*

In our previous research, the HRR was found to be hard to distinguish the fire risk of EPS ETICS varying EPS thickness because that most unburnt EPS molten was observed in the bottom of the facade. Considering that the downward and upward fire spreading was observed during JIS A 1310 façade fire test, the fire risk evaluation based on EPS burn area and façade surface temperature profiles is proposed by the following:

$$\textbf{INDEX} = \frac{S_{EPS}}{6.64} \times 0.2 + T_1 \times 0.3 + T_2 \times 0.2 + T_3 \times 0.1 + T_4 \times 0.1 + T_5 \times 0.1 \tag{1}$$

Where $T_n = \left(\frac{T_{0-3}}{800} + \frac{T_{0-10}}{700} + \frac{T_{0-20}}{600}\right)/3$; $T_{0-3}$ means the average temperature from 0 min to 3 min during 20 min façade fire test; $T_{0-10}$ means the average temperature from 0 min to 10 min during 20 min façade fire test; $T_{0-20}$ means the average temperature from 0 min to 20 min during 20 min façade fire test. $S_{EPS}$ is the EPS burnt out area.

### *3.1.3. Repeatability of calibration test with heating intensity 600 kW*

Repeatability of measurements refers to the variation in repeat measurements made on the same subject under identical conditions [25]. It means that variability in large scale measurements made on the same subject in a repeatability study can then be ascribed only to errors due to the measurement process itself. In fire research, the repeatability and reproducibility of fire tests are important [26]. For example, it has reported that a cone calorimeter round robin resulted in estimates for the peak heat release rate repeatability and reproducibility of 17% and 23%, respectively [27]. With an aim to clarify the repeatability of the calibration test, the calibration tests are carried out in four different time with the same test condition within two years. The repeatability test NO.1, NO.2, NO.3 and NO.4 were conducted in the January of first year, August of first year, January of second year, August of second year, respectively. Detailed experimental condition is shown in the table 2, which includes atmosphere pressure, ambient temperature, humidity, and vapor partial pressure. The **INDEX** value in Table 2 was calculated by the method proposed in 3.1.2. The standard deviation error of repeatability test was calculated by the following equation:

$$\sigma_{repeatability} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \tag{2}$$

Where $\sigma_{repeatability}$ is the standard deviation error of repeatability test; $x_i$ is value of each sample; $\bar{x}$ is the average value of all the samples; n is number of sample. By calculation, $\sigma$ is 0.017. Furthermore, it was also found that high humidity has a decrease effect on the **INDEX** value, just as comparison of NO.2 and NO.3 with NO.1 and NO.4. When the humidity is high, **INDEX** value of NO.2 (humidity 71%) and NO.3 (humidity 60%) are 3.9% and 4.4% lower than average value.

### *3.1.4. Effects of opening edge treatment on **INDEX***

A series of EPS ETICS specimens were tested with JIS A 1310 façade fire test method. The tests differed from heating intensity, mortar component, EPS thickness, cement thickness, reinforcement and opening edge treatment method. The **INDEX** values based on test results are shown in Table 3. The **INDEX** value varying a series of different specimens and heating intensities is described in Fig. 4. Before testing specimen, calibration tests varying with heating intensity from 100 kW to 1100 kW were carried out firstly, just as described from NO.1 to NO.10 of table 3. Opening edge treatment method effects on the **INDEX** values was discussed by conducting test from NO.11to NO.19. Test NO.23, NO.16, NO.24, NO.26, NO.11, NO.22, NO.20, NO.18, NO.25 and NO.27 are used to disclose influence of heating intensity on the **INDEX** values. Test NO.32, NO.33, NO.34, NO.36, NO.35, NO.11, NO.20, NO.21, NO.23, NO.22, NO.16, NO.18, NO.24, NO.25, NO.26 and NO.27 are employed to clarify the EPS thickness effects on the **INDEX** values. Test NO.16, NO.28, NO.18, NO.29, NO.26, NO.34, NO.27 and NO.36 are used to describe the influence of mortar types on the **INDEX** values. The reinforcement method is shown by compared NO.30 with NO.22.

Comparison of different opening edge treatment methods is shown in Fig. 5. It is well known that opening edge treatment method plays an important role in the prevention of façade fire caused by window fire. There are four types of opening edge treatment methods used widely in EPS ETICS façade. The test NO.13 was used as a control group. With respect to EPS thickness = 50 mm and heating intensity = 300 kW, the lowest **INDEX** value 0.400 is from test NO.13. During test NO.13, it was observed that EPS was ignited at 104 s and the substantial EPS molten accompanying with combustion and pyrolysis dropped down at 162 s. The serious combustion is ascribed to EPS molten dropping out from a space created by reinforcing mesh departed from specimen substrate panel. It could make a contribution for a low **INDEX** value. The traditional edge treatment method of EPS ETICS is adhesion (Test NO.12). Considering that EPS molten is easy to cause downward fire spread, the reinforcing mesh made of fire glass fiber is wrapped back to reduce EPS molten dropped down. This idea is realized by the back-wrapping method. It is found that back-wrapping method (Test NO.11) could reduce 7.9% of **INDEX** value than it from adhesion method (Test NO.12). Regarding test NO.12 performed adhesion method, the serious combustion appeared at t = 177 s and lasts for nearly 655 s. When test time approaching 1185 s, the combustion become weak. Furthermore, a weak combustion was observed during test NO.11 performed back-wrapping method. It is verified by low peak temperature and time (20 min) averaged temperature during façade fire test. The weak combustion started from t = 120 s and lasted for nearly all the test time. Compared with **INDEX** value of test NO.11, installing of fire barrier is believed to increase 10.1% and 5.6% of **INDEX** value, which are shown in test NO.14 and test NO.15. During test NO.14, a serious combustion started from 180 s and became weak at 960 s. In test NO.15, the serious combustion formed at about 480 s then became weak at 960 s. Regarding EPS ETICS performed with 100 mm EPS, the **INDEX** of test NO.17 (adhesion method) is 14.5% higher than **INDEX** of test NO.16 (back-wrapping method). With respect to EPS ETICS performed with 200 mm EPS, the **INDEX** of test NO.19 (adhesion method) is 1.3% higher than **INDEX** of test NO.18 (back-wrapping method). Based on the above discussion, EPS ETICS specimen test performed back-wrapping method has the low **INDEX** value.

**Table 2**
Repeatability test results of heating intensity 600 kW.

| Test | **INDEX** value | Atmosphere pressure/hpa | Ambient temperature/°C | Humidity/% | Vapor partial pressure/hpa |
|---|---|---|---|---|---|
| NO.1 | 0.346 | 1021.8 | 10.1 | 57 | 7.0 |
| NO.2 | 0.324 | 1011.6 | 28.2 | 71 | 28.0 |
| NO.3 | 0.322 | 1017.2 | 6.9 | 60 | 6.0 |
| NO.4 | 0.357 | 1012.5 | 22.9 | 49 | 7.3 |

**Table 3**
Test results varying a series of specimens.

| NO. | Heating intensity/kW | EPS density/ $kg/m^3$ | EPS thickness/ mm | Mortar component (2 mm) | Cement thickness/mm | reinforcement | Opening edge treatment method | **FPI**/$(m/s^{1/2})/(kW/m)^{2/3}$ | **INDEX** value | Pass or fail |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 100 | Calibration test without combustible façade | | | | | | | 0.109 | — |
| 2 | 200 | | | | | | | | 0.15 | — |
| 3 | 300 | | | | | | | | 0.173 | — |
| 4 | 400 | | | | | | | | 0.194 | — |
| 5 | 500 | | | | | | | | 0.250 | — |
| 6 | 600 | | | | | | | | 0.337 | — |
| 7 | 650 | | | | | | | | 0.36 | — |
| 8 | 700 | | | | | | | | 0.363 | — |
| 9 | 1000 | | | | | | | | 0.561 | — |
| 10 | 1100 | | | | | | | | 0.651 | — |
| 11 | 300 | 15 | 50 | SBR | 1 | One layer | Back-wrapping method | 13.5 | 0.404 | — |
| 12 | 300 | 15 | 50 | SBR | 1 | One layer | Stick method | 13.5 | 0.436 | — |
| 13 | 300 | 15 | 50 | SBR | 1 | One layer | EPS exposed without treatment method | 13.5 | 0.400 | — |
| 14 | 300 | 15 | 50 | SBR | 1 | One layer | Stick + rock wool (0.06 m) method | 13.5 | 0.445 | — |
| 15 | 300 | 15 | 50 | SBR | 1 | One layer | Stick + rock wool (0 m) method | 13.5 | 0.427 | — |
| 16 | 600 | 15 | 100 | SBR | 1 | One layer | Back-wrapping method | 17.3 | 0.667 | — |
| 17 | 600 | 15 | 100 | SBR | 1 | One layer | Stick method | 17.3 | 0.764 | — |
| 18 | 600 | 15 | 200 | SBR | 1 | One layer | Back-wrapping method | 20.9 | 0.741 | — |
| 19 | 600 | 15 | 200 | SBR | 1 | One layer | Stick method | 20.9 | 0.751 | — |
| 20 | 300 | 15 | 200 | SBR | 1 | One layer | Back-wrapping method | 20.9 | 0.574 | — |
| 21 | 300 | 15 | 300 | SBR | 1 | One layer | Back-wrapping method | 17.4 | 0.596 | — |
| 22 | 600 | 15 | 50 | SBR | 1 | One layer | Back-wrapping method | 13.5 | 0.664 | — |
| 23 | 300 | 15 | 100 | SBR | 1 | One layer | Back-wrapping method | 17.3 | 0.476 | — |
| 24 | 900 | 15 | 100 | SBR | 1 | One layer | Back-wrapping method | 17.3 | 0.714 | Pass |
| 25 | 900 | 15 | 200 | SBR | 1 | One layer | Back-wrapping method | 20.9 | 0.886 | Fail |
| 26 | 1100 | 15 | 100 | SBR | 1 | One layer | Back-wrapping method | 17.3 | 0.774 | — |
| 27 | 1100 | 15 | 200 | SBR | 1 | One layer | Back-wrapping method | 20.9 | 0.886 | — |
| 28 | 600 | 15 | 100 | Acrylic resin | 1 | One layer | Back-wrapping method | 18.5 | 0.375 | — |
| 29 | 600 | 15 | 200 | Acrylic resin | 1 | One layer | Stick + rock wool (0 m) method | 22.4 | 0.487 | — |
| 30 | 600 | 15 | 50 | SBR,(4 mm) | 2 | Two layer | Back-wrapping method | 11.5 | 0.373 | — |
| 31 | 600 | 18 | 200 | Acrylic resin | 1 | One layer | Back-wrapping method | 21.4 | 0.678 | — |
| 32 | 1000 | 18 | 100 | Acrylic resin | 1 | One layer | Back-wrapping method | 20.0 | 0.825 | Pass |
| 33 | 1000 | 18 | 200 | Acrylic resin | 1 | One layer | Back-wrapping method | 21.4 | 0.836 | Fail |
| 34 | 1100 | 15 | 100 | Acrylic resin | 1 | One layer | Back-wrapping method | 18.5 | 0.764 | — |
| 35 | 1100 | 15 | 150 | Acrylic resin | 1 | One layer | Back-wrapping method | 20.9 | 0.802 | — |
| 36 | 1100 | 15 | 200 | Acrylic resin | 1 | One layer | Back-wrapping method | 22.4 | 0.781 | — |

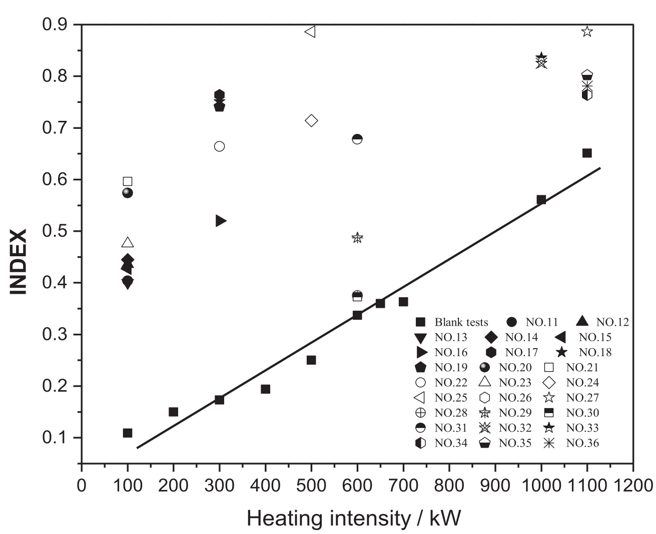


**Fig. 4. INDEX** value varying a series of different specimens and heating intensities.

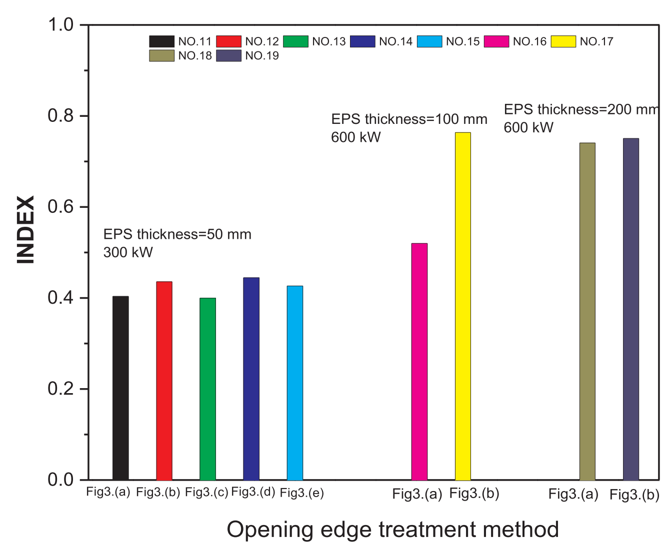


**Fig. 5. INDEX** value varying different opening edge treatment methods.

#### 3.1.5. Effects of heating intensity, EPS thickness, mortar and reinforcement on INDEX calculation

The influence of heating intensity on **INDEX** value is described in Fig. 6. The heating intensity varies from 300 kW to 1100 kW and EPS thickness differs from 50 mm to 200 mm. As for ETICS performed with the same EPS thickness, the **INDEX** value increases as the heating intensity changes from 300 kW to 1100 kW. The relationship between EPS

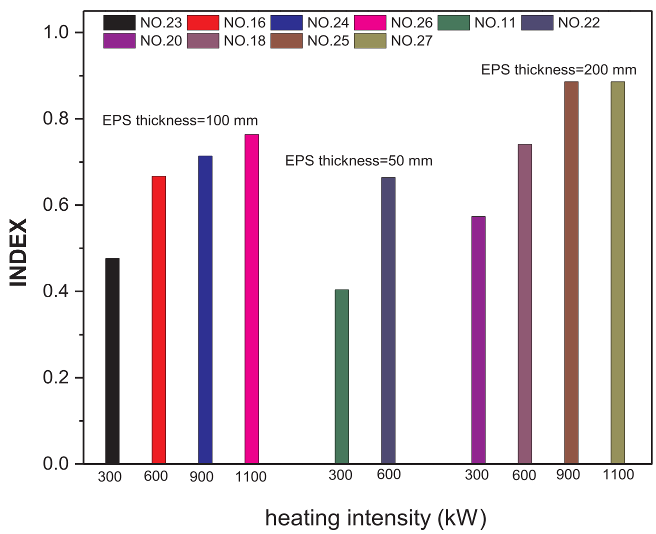


**Fig. 6. INDEX** value varying different heating intensity with the same specimen.

thickness, heating intensity and **INDEX** values is disclosed in Fig. 7. It is found that the **INDEX** value versus EPS thickness used in EPS ETICS is linear with the same heating intensity. Currently, two types of mortars are widely used in the EPS ETICS of Japan. The **INDEX** values varying with two different mortars with the same specimen are shown in Fig. 8. Compared with EPS ETICS performed SBR polymer mortar, performance of Acrylic resin mortar could easily reduce the **INDEX** value. With respect to heating intensity 600 kW, the **INDEX** of EPS ETICS performed acrylic resin mortar is 43.8% (EPS thickness = 100 mm) and 34.3% (EPS thickness = 200 mm) lower than **INDEX** values of EPS ETICS performed with SBR mortar. As for high heating intensity 1100 kW, the **INDEX** of EPS ETICS performed acrylic resin mortar is 1.3% (EPS thickness = 100 mm) and 11.9% (EPS thickness = 200 mm) lower than **INDEX** values of EPS ETICS performed with SBR mortar. The reinforcement method including one layer glass fiber mesh and two layer glass fiber mesh is discussed in Fig. 9. It clearly indicates that two layer's fiber mesh reinforcement method is superior to one layer's mesh since the lower **INDEX** value from the EPS ETICS performed two layer's glass fiber mesh. In summary, the **INDEX** evaluation method could be used to clarify different heating intensity, EPS thickness, polymer mortar type, and reinforcement method.

### *3.2. A potential fire risk prediction method for EPS ETICS before facade fire test*

Fire propagation index (**FPI**) describes the fire propagation behavior of materials under flame-radiating conditions prevalent in large-scale fires. Small- and large-scale fire propagation test data of various materials along with understanding of fire propagation phenomena suggest that the **FPI** values can be used to classify materials as either propagating (fire propagates rapidly beyond ignition zone) and non-propagating (there is no fire propagation beyond the ignition zone) [28]. The flame propagation rate in the small-scale and large-scale apparatus showed good correlation and satisfied the engineering relationships derived from the fundamental flame propagation theories. The following relationship was found for the flame propagation rate [29].

$$v^{1/2} = \frac{\delta^{1/2}\dot{q}_{fs}''}{\Delta T_{ig}\left(\frac{\pi}{4}k\rho c_p\right)^{\frac{1}{2}}} \tag{3}$$

Where $\Delta T_{ig}$, k, ρ and $c_p$ are is the ignition temperature of the polymeric material above ambient in K, thermal conductivity in kW/m/K, density in kg/m$^3$, specific heat in kJ/kg/K of the solid, respectively. u is the upward "re propagation rate in mm/s. $\delta$is the characteristic forward heat transfer distance and is generally assumed to be constant in m.

The flame heat flux transferred ahead of the pyrolysis front can be expressed as [30]:

$$\dot{q}_{fs}'' \propto \frac{\dot{Q}_{rad}'}{X_f} \tag{4}$$

Where $\dot{Q}_{rad}'$ is the radiative heat release rate per unit sample width in kW/m and $X_f$is the flame height for upward fire propagation in m. $\dot{Q}_{rad}'$ is expressed as:

$$\dot{Q}_{rad}' = \frac{\chi_{rad}}{\chi_{ch}}\dot{Q}_{ch}' \tag{5}$$

Where $\dot{Q}_{ch}'$ stands for chemical heat release rate per unit width (kW/m); $\chi_{rad}$ is the radiative fraction of the combustion efficiency, $\chi_{ch}$.

In general, the term $\frac{\chi_{rad}}{\chi_{ch}}$ does not vary much between fuels and can be considered approximately constant. The flame height, $X_f$, is expressed as:

$$X_f \propto (\dot{Q}_{ch}')^{2/3} \tag{6}$$

From Eqs. (4), (5), (6):

$$\dot{q}_{fs}'' = \left(\frac{\chi_{rad}}{\chi_{ch}}\dot{Q}_{ch}'\right)^{1/3} \tag{7}$$

And with Eq. (3),

$$v^{1/2} = \frac{\delta^{1/2}\left(\frac{\chi_{rad}}{\chi_{ch}}\dot{Q}_{ch}'\right)^{1/3}}{\Delta T_{ig}\left(\frac{\pi}{4}k\rho c_p\right)^{\frac{1}{2}}} \tag{8}$$

A simplified form of Eq. (8) is used in the 4910 Test Protocol where right hand side is identified as the fire propagation index (**FPI**) and Thermal Response Parameter (TRP). Thermal Response Parameter (TRP) is defined as:

$$\mathrm{TRP} = \left(\frac{\pi}{4}k\rho c_p\right)^{\frac{1}{2}}(T_{ig}-T_0) \tag{9}$$

Where, k, ρ and $c_p$ are thermal conductivity in kW/m/K, density in kg/m$^3$, specific heat in kJ/kg/K of the solid, respectively. $T_{ig}$ and $T_0$ are the surface ignition temperature (K) and ambient temperature (K).

And the **FPI** calculation equation is shown in the following [31]:

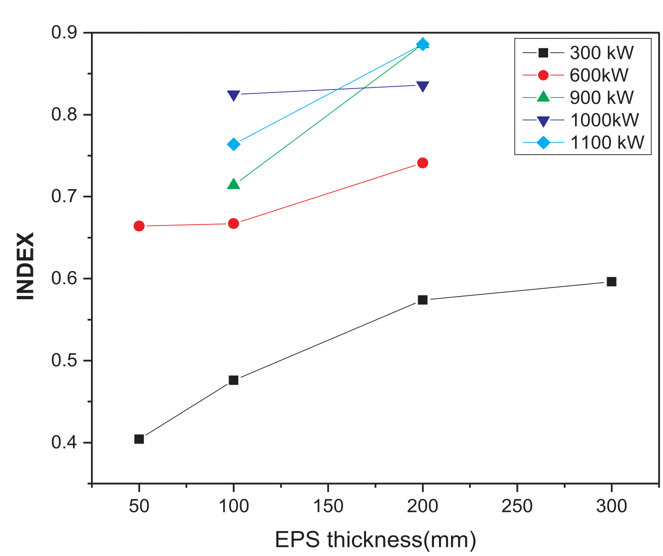


**Fig. 7. INDEX** value varying different EPS thickness and heating intensities.

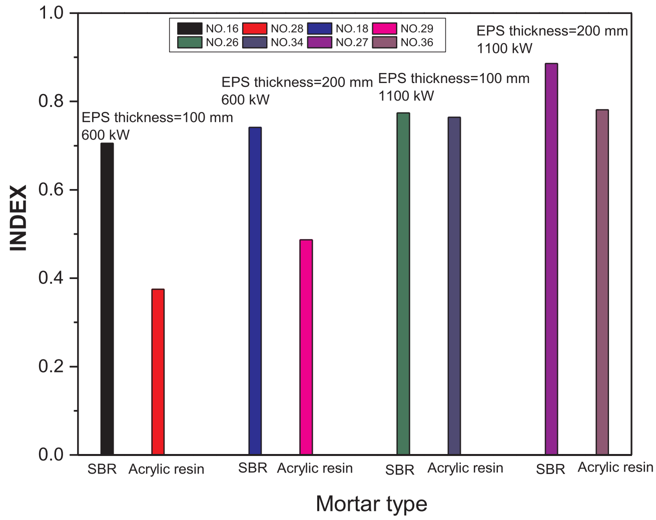


**Fig. 8. INDEX** value varying mortar types with the same specimen.

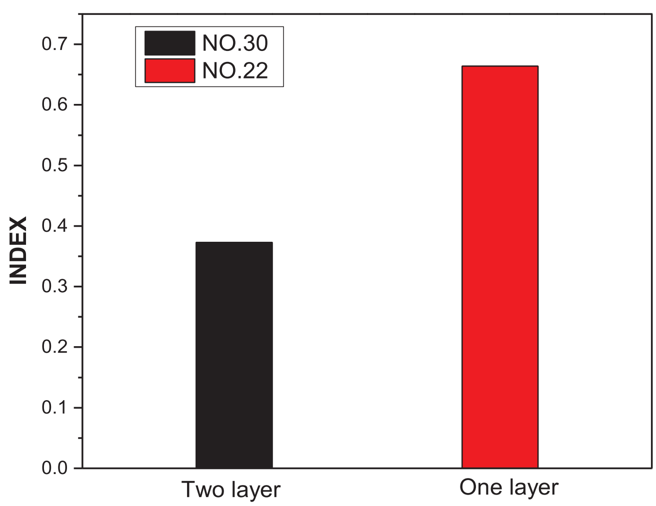


**Fig. 9. INDEX** value varying different reinforcement methods.

$$\mathbf{FPI} = 750\frac{\dot{Q}_{ch}^{'\ 1/3}}{TRP} \qquad (10)$$

Where, $\dot{Q}_{ch}^{'}$ stands for chemical heat release rate per unit width (kW/m).

### 3.3. *The acceptable* ***INDEX*** *level based on JIS A 1310 method*

In the JIS A 1310 method, it is ruled that under heating intensity 1000 kW or 900 kW, if the lasting time (T ≥ 500 °C) of T4 or T5 is over 120 s, it would fail in the JIS A 1310 test. Comparably, if the lasting time (T ≥ 500 °C) of T4 or T5 is less than 120 s, it would pass the JIS A 1310 test. According to the temperature histories of test NO.24, NO.25, NO.32 and NO.33, test NO.23 and test NO.32 passed JIS A 1310 method. Test NO.25 and test NO.33 failed in JIS A 1310 method. Therefore, it is concluded that EPS ETICS specimen for which the **INDEX** ≤ 0.825 passes JIS A 1310 method, and EPS ETICS specimen for which the **INDEX** ≥ 0.836 are judged to be unacceptable. The region where the **INDEX** values are greater than 0.825 but less than 0.836 is uncertain.

### 3.4. *The potential prediction method for EPS ETICS before JIS A 1310 methods*

As for **FPI**, it could be used to predict the fire propagation risk before JIS A 1310 test. It shows that EPS ETICS specimen for which the **FPI** ≤ 17.3 passes JIS A 1310 method, and EPS ETICS specimen for which the **FPI** ≥ 21.4 are judged to be unacceptable. The region where the **FPI** values are greater than 17.3 but less than 21.4 is uncertain.

## 4. Conclusions

In this work, the JIS A 1310 façade fire test method recently issued is employed to quantify fire risk of EPS ETICS specimen varying heating intensity from 100 kW to 1100 kW, EPS thickness from 50 mm to 300 mm, polymer mortar type including SBR polymer mortar and acrylic resin mortar, reinforcement including one layer and two layer's glass fiber mesh, and opening edge treatment method differs from back-wrapping method to fire barrier method. During EPS ETICS façade fire tests in JIS A 1310 method, the serious both downward and upward fire spreading was observed. Comparison of different opening edge treatment methods indicates back-wrapping method could reduce the **INDEX** value. As for ETICS performed with the same EPS thickness, the **INDEX** value increases as the heating intensity changes from 300 kW to 1100 kW. It was found that the **INDEX** value versus EPS thickness used in EPS ETICS is linear with the same heating intensity. Compared with EPS ETICS performed SBR polymer mortar, Acrylic resin mortar has a low **INDEX** value. And two layer's fiber mesh reinforcement method is superior to one layer's mesh since the low **INDEX** value obtained from the EPS ETICS performed two layer's glass fiber mesh. Furthermore, a quantitative fire risk of JIS A 1310 façade fire test method is proposed on the basis of EPS burn area and façade surface temperature profiles. By testing and analyzing a series of EPS ETICS specimens, it is concluded that the **INDEX** evaluation method could easily clarify the different heating intensity, EPS thickness, polymer mortar type, reinforcement, EPS thickness and opening edge treatment method. EPS ETICS specimen for which the **INDEX** ≤ 0.825 or **FPI** ≤ 17.3 passes JIS A 1310method, and EPS ETICS specimen for which the **INDEX** ≥ 0.836 or **FPI** ≥ 21.4 are judged to be unacceptable (i.e., Fail); 0.825 ≤ **INDEX** ≤ 0.836 or 17.3 ≤ **FPI** ≤ 21.4 is the critical level. Correlation between **FPI** and the **INDEX** value is needed to be further verified by various façade materials.

## 5. Conflict of interest

The authors declared that they have no conflicts of interest to this work.

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.tsep.2018.08.002.

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