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Heat release and flame spread assessment of insulation in External Thermal Insulation Composite System (ETICS) façades

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ABSTRACT

External Thermal Insulation Composite Systems (ETICS) represent a popular modern façade for reducing energy consumption, particularly in retrofit applications. Insulation – typically in the form of either EPS (expanded polystyrene) or mineral wool – is applied to the exterior of buildings using mortar adhesive, and then coated with a final layer of sand-cement render and glass fibre reinforcement. The materials are relatively cheap, and the labour can be easy and inexpensive compared to other solutions.

The system does however mean that highly flammable EPS insulation is protected by only a thin layer of render, normally 3–8mm. The addition of this combustible material to the façade of the building represents a change in the fire risk, as the typical fire safety strategy involving compartmentation does not anticipate vertical fire spread on the exterior of a building. It is therefore necessary to characterise the fire risk, and ensure that an optimal fire barrier – namely, the render layer – is defined adequately.

In this work, the insulation component of an EPS ETICS façade is tested using micro- to small-scale methodologies. The objective of this is to characterise some of the fundamental thermal material properties, ignitability, heat release, and flame spread of the specific components. The aim is to then extend this to a larger-scale methodology for testing of complete systems, which will be complemented by numerical modelling to enable scaling. Previous attempts at testing ETICS in a small-scale have been largely unsuccessful, and efforts have pointed to large-scale apparatuses – generally 4–8m high – as the only viable solution at present. These are however expensive and time consuming, and deliver little information on how the façade performs. Testing is especially problematic for EPS, which melts and shrinks at low temperatures, leading to difficulties in attempting to extract global flammability properties.

MCC (Microscale Combustion Calorimeter) testing has been performed to benchmark the different EPS insulation that can be used in buildings. It is found that black EPS containing expanded graphite used in façades has substantially improved performance compared to ordinary white EPS used as building insulation. The peak heat release was reduced from 1160 W g^{-1} down to 490–740 W g^{-1}, occurring at a temperature of 430–440 °C. An extra additive to improve the moisture performance of the system also enhances the fire performance slightly by reducing the heat release further.

Previous attempts of testing ETICS and EPS using LIFT (Lateral Ignition and Flame spread Test) have in many cases been unproductive. For this experimental series, a sheet of paper has been applied to the surface of the first 100 mm of EPS in order to force ignition. Results for the flame spread velocity near to ignition have then been discarded to minimise the influence of this method. Flame spread results for the white EPS were not satisfactory due to the fact that the flame spread velocity had a weak dependence on the incident heat flux, and that that minimum critical heat flux for flame spread was 0.0 kW m^{-2}, that is, no external energy was required to sustain burning. For black EPS specimens, the addition of the expanded graphite was effective in improving the flame spread performance. The minimum heat flux for flame spread was increased to 0.75–1.09 kW m^{-2}, and the velocity was sufficiently moderate that a reasonable value for the flame spread modulus could be obtained.

In future, attempts will be made to correlate the flame spread results of these individual EPS products to the flame spread as part of a complete ETICS façade. This would then provide a more meaningful method to compare different ETICS solutions as a first step without the need for expensive large-scale testing during the main development phase of systems.

KEYWORDS:

Keywords: ignition, heat release, flammability, flame spread, facades; performance-based design, ETICS.

INTRODUCTION

ETICS (External Thermal Insulation Composite Systems) are a façade kit where insulation is attached to a solid wall, such as concrete or masonry, using mortar adhesive. An additional layer of mortar is applied to the insulation, before a sheet of glass fibre reinforcement and a thin finishing layer of render and paint. The system requires time to dry and cure due to the presence of the sand-cement render/mortar, but the application of the kit is otherwise rapid and relatively straightforward compared to other façade solutions [1].

The two most common insulation materials used in ETICS are either mineral wool or polystyrene in the form of EPS (expanded polystyrene) or XPS (extruded polystyrene). In some cases PUR/PIR (polyurethane/polyisocyanurate) or phenolic foam are used but at present these are less popular. EPS has good insulation properties at low cost, and is light and easily workable. However, its flammability is extremely poor. The material has a low thermal inertia which causes rapid surface heating leading to short ignition times [2]. In addition, the material melts and drips prior to its pyrolysis temperature which enhances flame spread. Upon ignition, the material releases very large amounts of energy owing to its high heat of combustion. Its use in buildings therefore requires careful consideration and proper fire risk mitigation strategies to be in place to enable its safe usage. Furthermore, the scaling up of results in the field of fire science is difficult, especially in the case of façades where the interaction between components is highly relevant [3]. In many cases the use of the material can be limited, which acts as a barrier to innovation. This overall aim of this work seeks to optimise the insulation to achieve maximum energy savings for quantified fire performance. This is a first step a complicated process, but utilises performance-based methods to rank material formulations to predict their behaviour in large-scale tests, with later applicability to predicting the performance of actual buildings.

MATERIALS

There were three types of EPS chosen for study. The first was a typical white EPS product used for insulation in walls and can be easily purchased on the market. This type of insulation is not typically used in façades, but acts as a useful benchmark for comparing results to literature. The other two products were both black EPS materials as used in ETICS façades. The blackened nature of the EPS indicates that it includes expanded graphite in order to improve its thermal performance but also results in a slight increase in cost. Both of these products were also available on the market. The second of the two black EPS products further contains an extra additive to improve the hygrothermal performance of a façade. This is due to the fact that EPS ETICS tend to suffer the effects of high moisture [4]. A crude estimation based on visual observation is that approximately one in 400 beads contain the additive – indicated by yellow beads – for the latter EPS product.

IGNITABILITY AND HEAT RELEASE METHODOLOGY

Microscale Combustion Calorimeter (MCC)

The microscale measurements were performed in an MCC produced by the FAA (Federal Aviation Authority, New Jersey). The methodology follows the standard defined in ASTM D7309 [5]. Experiments for all materials were performed in nitrogen and some additional experiments were performed in air. The flow rate of gas was 0.1 L min^{-1} and the heating rate in all cases was 1.0 $^\circ$K s^{-1}. Sample weight across all experiments was within the range of 2.1–2.5 mg, and each specimen was prepared using a scalpel.

Bench-scale calorimetry

Flammability and flame spread assessments generally require accurate determination of the critical heat flux of the material, which in turn necessitates a large number of tests. Previous work on the flammability of EPS has identified the difficulties in obtaining a representative value of the critical heat flux [6,7]. This is due to the fact that the material softens at a temperature much lower than its pyrolysis and exothermic oxidation reactions. As a result, the surface of the material rapidly regresses and ignition in many cases either does not occur or is delayed. Additionally, the incident heat flux upon ignition will be lower due to the greater distance from the cone heater. For these reasons, the bench-scale ignitability and heat release results are instead taken from the highly detailed studies by Hidalgo *et al.* [6] and Cleary & Quintiere [7]. In future, it will be necessary to obtain specific and accurate critical heat fluxes for the actual materials tested in this project.

FLAME SPREAD METHODOLOGY

The LIFT (Lateral Ignition and Flame spread Test) apparatus is designed to extract an experimentally determined empirical correlation for the flame spread of materials. It was developed over a number of years by Quintiere and colleagues [8–10] using a radiant panel positioned at a set angle from a 155 mm high by 800 mm long specimen. Flame spread is evaluated in opposed flow conditions but using dimensionless parameters

it can be adapted for upward, wind-aided or forward flow conditions [11]. The apparatus in this study was in the ISO 5658 configuration [12], where a strong pilot is positioned vertically and partially impinges on the surface of the sample. Calculations of the heat release based on oxygen depletion [13] in the hood indicated that the pilot flame released 1.0–2.0 kW of energy. This provides additional heat flux to the surface which reduces the time to ignition. Other difficulties of this pilot position have been noted in the literature [14].

Radiant panel gas

The burner as specified by the standard should be fuelled by methane and provide a standardised heat flux distribution across the length of the specimen. However, practicalities in the laboratory at Lund University dictated that propane was a more convenient gas to use.

Peak heat flux modification

In the original development of the LIFT apparatus there was a methodology which outlined a different peak heat flux. In current standards there is only a single heat flux specified which is intended to reasonably ignite all materials, which is 50 kW m^{-2}. This is done for the sake of simplicity, especially for complex materials, and so that it is not necessary to perform ignitability tests before running LIFT. The original method set the peak heat flux to instead be approximately 5 kW m^{-2} above the critical heat flux of the material This value could be obtained either through bench-scale testing in the cone calorimeter or by using the LIFT apparatus in its ignition configuration. A range of 15.5–70 kW m^{-2} was also specified based on the limitations of the radiant panel [9].

In this research, the latter method has been used. The determination of an accurate critical heat flux in EPS proves difficult, as previously noted. Values in the literature indicate nonetheless that the range may be between 6–15 kW m^{-2}, and a maximum of 20 kW m^{-2}. Therefore the peak heat flux of the panel was set to be 25.0 kW m^{-2} and measured before every experiment.

Preliminary testing

A set of preliminary testing was performed to ensure the suitability of these changes and that the results were still in-line with standardised testing. Tests were performed on plywood, MDF (Medium Density Fibreboard) and particle board (Swedish spånskiva). A total of twenty tests were performed with the propane fuelled radiant panel, and four tests were performed with the reduced radiant peak heat flux. The calculated flame spread modulus agreed with those found in the literature. Additionally, testing of EPS in the traditional unaltered configuration was performed. In this case, the material failed to ignite and instead melted along the length of the material. This matches the conclusions reached in the literature [15].

RESULTS AND DISCUSSION

Ignitability and heat release

The heat release for both of the black FR (fire retarded) EPS materials (EPS-A and EPS-B) are both reduced when compared to white non-FR EPS-C (Table 1). The heat release capacity, η_c, is reduced from 1160 J g^{-1} K^{-1} for EPS-C down to 740 J g^{-1} K^{-1} for EPS-B and down to 490–640 J g^{-1} K^{-1} for EPS-A when pyrolysed in an inert atmosphere (Fig. 1, left). It is therefore clear that the addition of expanded graphite is effective in reducing the heat release of the polystyrene product. Additionally, the yellow beads of EPS-A had the lowest heat release capacity and overall had a slightly lower heat release (14–35 % reduction) when compared to EPS-B. However, the temperature for the peak heat release, T_p, was reduced from 430–440 °C to 405°C which indicates that the material would ignite earlier. The reduction in the heat release for the yellow beads may not be sufficient to offset the decreased onset of ignition. Nonetheless, there is still substantial improvement over the non-FR white EPS-C.

The apparent heat of combustion, ΔH_c, is substantially improved from 45 kJ g^{-1} for EPS-C down to a consistent value of 30 kJ g^{-1} for EPS-B and EPS-A. The calculation for heat of combustion uses the original mass, m_0, and so the presence of a char yield for the black EPS products will provide some improvement in the calculated heat of combustion. Even if corrected only for the mass lost, there is still some improvement in the heat of combustion. This may be due to the expanded graphite reacting and reducing heat transfer to the polystyrene. This however would violate some of the principles of microscale calorimetry, namely that there should not be temperature gradients within the specimen, and would therefore require slower heating rates to ensure the conclusions are correct.

The results of EPS-A in an oxidative environment indicate much lower onset and peak reaction rate temperatures (Fig. 1, right). The temperature for peak heat release is reduced from 435 and 405 °C down to

345 and 365 °C for black and yellow beads respectively. Additionally, the pyrolysis occurs over a much wider range (approximately 130 °C compared to 100 °C) which leads to a comparable value of apparent heat of combustion for the black EPS-A beads. In the oxidative environment, the yellow beads are found to be more reactive. Whilst there is a marginal increase in the pyrolysis onset temperature, this is offset by higher heat release and higher heat of combustion. This leads to a higher value of the heat release capacity, η_c, and would suggest that it has the poorest performance between the two EPS-A beads.

Table 1. Summary of micro-scale calorimetry results for each of the EPS materials tested.

ID	Colour	Gas	η_c	$\dot{q}_p$	ΔH_c	T_p	Y
-	-	-	J g^{-1} K^{-1}	W g^{-1}	kJ g^{-1}	°C	%
EPS-A	Black	N$_2$	639.60	639.78	30.81	432.98	26.09
		Air	1120.71	376.60	30.49	346.56	4.35
	Yellow	N$_2$	487.50	486.32	30.40	402.92	12.00
		Air	1438.89	479.05	38.37	363.32	4.17
EPS-B	Black	N$_2$	741.75	741.36	31.65	439.13	14.29
EPS-C	White	N$_2$	1163.22	1163.10	45.52	436.61	0.00

Some differences in the behaviour of the materials between the inert and oxidative environments reveal different reaction pathways. Whilst the char yields, Y, for the black and yellow beads of EPS-A are quite different in an inert atmosphere, 26 and 12% respectively, these are found to both be 4% in air. For black EPS-A, the heat of combustion between the two atmospheres is found to be the same. However, for yellow EPS-A the heat of combustion is higher in air which suggests that the oxidative pathway is more exothermic than the pathway in an inert atmosphere.

Lyon *et al.* [16] has studied six white EPS products previously. Comparison with EPS-C shows that the temperature of peak reactions, T_p, is given as 445±1 °C which is within ±5 % of the results presented here. The ±5 % is the anticipated accuracy of the MCC apparatus, as detailed in the same report. The result for heat of combustion is however somewhat higher in this study; 46 kJ g^{-1} compared to 40 kJ g^{-1} in the results of Lyon *et al.* [16]. This is also higher than values quoted for styrene, 39.4–42.2 kJ g^{-1} [17], and so may require additional testing or modification to the calculation.
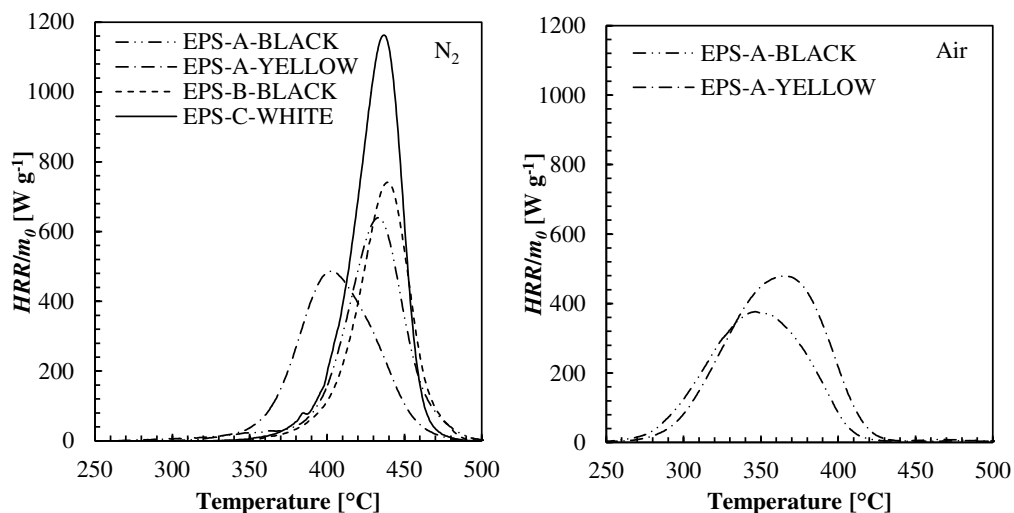

Fig. 1. Results from MCC testing for all three EPS materials in nitrogen (left) and only EPS-A in air (right).

Flame spread

In order to achieve ignition, a piece of standard 80 g m^{-2} paper (100 mm wide by 150 mm high) was attached to the surface of 47.5 mm thick EPS. This caused ignition after 4–8s for white EPS and 5s for black EPS. This is more rapid than the ignition times of EPS obtained from the literature in bench-scale calorimetry and so

reduces the preheating time of the upstream material before the flame front arrives. Analysis by Quintiere [8] indicates that a longer preheating time is preferable when testing a material for research purposes but for polystyrene this is not the case due to the rapid melting causing loss of material.

Despite the forced ignition, the results for non-FR white EPS-C are still somewhat inadequate and the scatter is large. The flame spread velocity is found to have a weak dependence on the incident heat flux (Fig. 2, left), and the minimum heat flux for flame spread, $\dot{q}_{0,s}''$, is found to be 0.0 kW m^{-2} due to the fact that all material was consumed. Nonetheless, a flame front was still established which spread along the length of the material. There was generally not significant generation of flaming droplets – although sufficient to still fail the standardised test – and molten styrene was instead contained within the holder.

A substantial improvement was found in the black EPS specimens containing expanded graphite. As indicated by the MCC results previously, the introduction of the graphite increases the char yield of the product. On exposure to heat, this rapidly expands and inhibits some heat transfer to the polystyrene. This in turn increases the time required to pyrolyse the EPS upstream and reduces the flame spread velocity. A stronger correlation between the incident heat flux and the flame spread velocity is then found (Fig. 2, right) and the minimum heat flux for flame spread in this case is found to be 0.75–1.09 kW m^{-2}. This value is still extremely low but the product would nonetheless require some external heat source to sustain burning. At present, four flame spread tests of EPS-A and three tests of EPS-C have been performed. Specimens of EPS-B are currently being tested, along with complete ETICS kits with the mortar render in place. Once the flame spread is understood to some extent then suitable experiments to evaluate the integrity of the render layer can be performed.
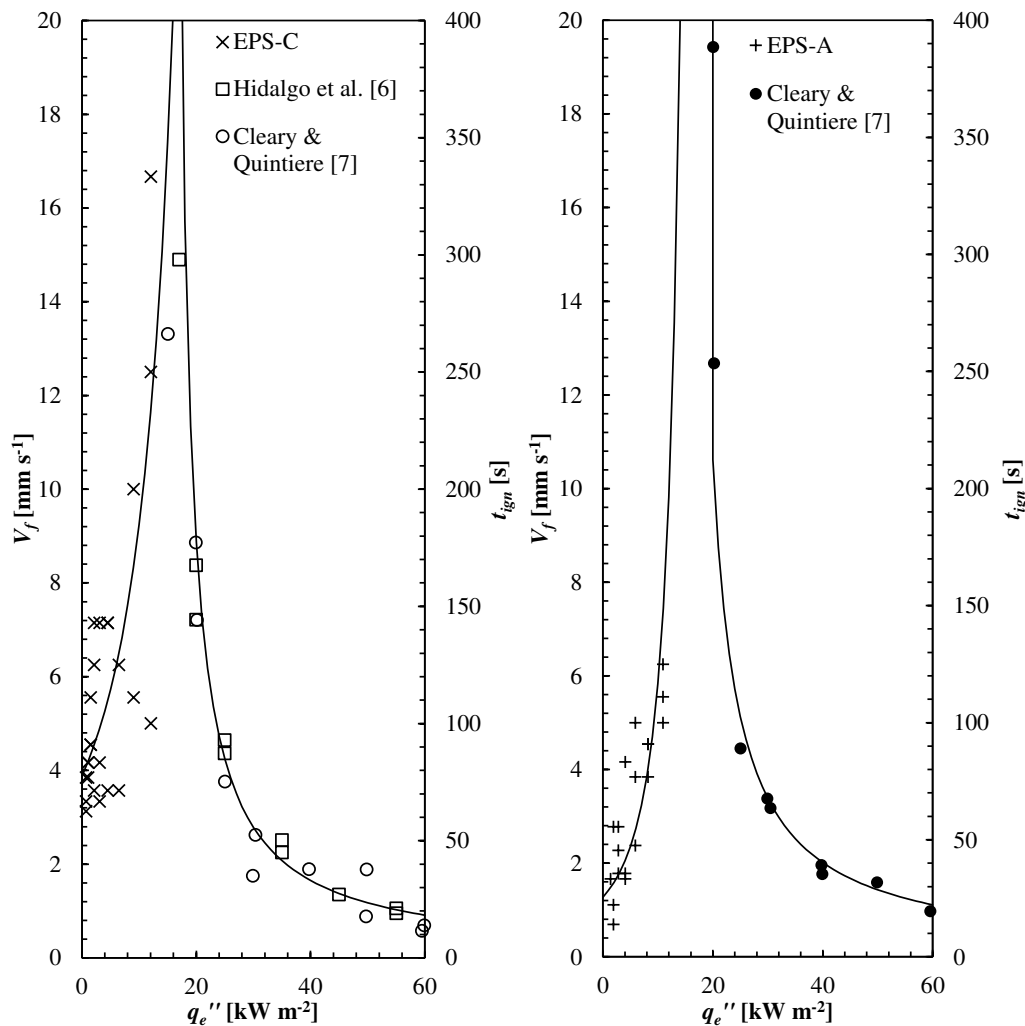

Fig. 2. Flammability diagrams for white EPS (EPS-C, left) and black EPS (EPS-A, right). Ignition data is taken from Hidalgo *et al.* [6] for 50 mm non-FR EPS, and Cleary & Quintiere [7] for both FR and non-FR 50 mm EPS samples.

CONCLUDING REMARKS

A successful method for extracting apparent flame spread properties from flame retarded polystyrenes has been outlined. This has shown to be effective for FR EPS containing expanded graphite where the minimum critical heat flux is greater than 0 kW m^{-2}. For ordinary white EPS, the flame spread velocity is too high and no external energy is required to sustain flame spread and thus a flame spread parameter cannot adequately be determined. These results are in agreement with the literature obtained using a different methodology. MCC results quantify the char yield in micro-scale and show that the black EPS products have lower heat release. Additional work will extend this method to EPS with render in place to simulate ETICS kits, and attempt to determine relevant flame spread properties for modelling and predicting full-scale tests. From this, product development to define optimal thermal properties and thickness of the insulation and render can be performed.

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