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Fire performance of sandwich wall assemblies

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ABSTRACT

Fire performance is often identified as a difficult obstacle to overcome in designing lightweight sandwich panels suitable for use in building applications. Fireproofing generally increases the weight and cost of sandwich panels, reducing the field of application of such solutions. This study presents the fire performance evaluation of different non-loadbearing sandwich wall assemblies, based on the fire resistance test methods recommended by EN 13501-2, EN 1363-1 and EN 1364-1. The main objectives of the present study are: **(i)** to evaluate the fire performance of different core materials; **(ii)** to evaluate the fire performance of different fireproofing materials; **(iii)** to classify the fire resistance of different wall assemblies; and **(iv)** to design a sandwich panel which withstands a 60 min fire exposure without compromising its integrity (E) and thermal insulation (I) capabilities. Expanded polystyrene foam (EPS), polyethylene terephthalate foam (PET), cork agglomerate (CA) and stone wool (SW) were tested as core materials. Fireproofing gypsum boards (FG) and magnesium oxide boards (MGO) were tested as fireproofing materials. The skins of all sandwich panels tested were glass fibre reinforced polymers (GFRP). Cork agglomerate cores exhibited the lowest thermal decomposition rate under fire exposure and cork agglomerate core sandwich wall assemblies proved to withstand fire exposure for the intended duration, presenting the required performance, even dismissing the use of fireproofing boards.

1. Introduction

Sandwich panels are increasingly being used as structural and non-structural components in buildings, such as wall and floor assemblies. These generally comprise a thick core of a light insulating material sandwiched between two thin skins of a very resistant material. The main advantages of such assemblies are the lightness and the highly efficient insulation characteristics, whereas the fire performance has been an obstacle to the widespread of their use [1,2]. The poor fire performance of lightweight sandwich panels often requires the use of heavy and expensive fire protections, limiting the appeal and the economic potential of such solutions.

It is well known that due to their highly flammable nature, expanded polystyrene core sandwich panels present poor fire performances [3,4] and their extensive use in buildings ought to be avoided, unless fireproofing boards are used. Alternative core materials, such as cork agglomerate, polyethylene terephthalate foams and stone wool panels, or the use of gypsum boards for fire protection [5,6], may also be used to increase the fire resistance of sandwich panels with glass fibre reinforced polymer (GFRP) skins.

The fire performance of sandwich composite materials has been a topic of investigation in recent years [7–10]. Thermosetting resin skins exposed to heat tend to char, soften and delaminate conducing to the thermal decomposition (i.e. the temperature from which the material becomes unstable) of the core. Materials with high char yield generally possess longer ignition times, lower heat release rates, slower flame spread rates, and generate less smoke and toxic gases than low char-forming materials [9].

The goal of the present research was to develop a sandwich panel with a fire resistance higher than about 60 min, keeping the two main advantages of the expanded polystyrene foam sandwich panels, namely the reduced cost and self-weight. With these three characteristics, the sandwich panel may be efficiently used as a wall element in buildings.

With the purpose of quantifying the fire resistance of expanded polystyrene sandwich panels with fireproofing boards and of sandwich panels with alternative core materials, the fire performance of seven sandwich wall assemblies with different core materials and different fire protections was evaluated. All specimens had two glass fibre reinforced polymer skins. The core materials

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used were: expanded polystyrene foam; polyethylene terephthalate foam; cork agglomerate; and stone wool. Some wall assemblies had fireproofing gypsum boards or magnesium oxide boards for additional fire resistance.

The fire resistance was evaluated according to the test procedures described in EN 13501-2 standard [9]. The wall assemblies tested are not intended to present loadbearing characteristics, thus the performance analysis solely focuses on integrity (E) and thermal insulation (I) criteria. Reaction to fire classification is not addressed in this paper.

The wall assemblies tested in the present experimental campaign were developed within the scope of the *MMB – Multi-Modular Block* research programme, aimed at developing a modular building concept suitable to face the fast growth of urban areas in several parts of the world.

2. Fire resistance tests

2.1. Wall assemblies tested

All the sandwich panels used in the tests had skins composed by a glass fibre textile (750 g/m^2) impregnated with epoxy resin (GFRP) and 80 mm thick cores.

The core materials used were the following: **(i)** expanded polystyrene foam (EPS) with a density of 15 kg/m^3 and a thermal conductivity of 0.038 W/m·K [10]; **(ii)** polyethylene terephthalate foam (PET) with a density of 65 kg/m^3 and a thermal conductivity of 0.033 W/m·K [11]; **(iii)** cork agglomerate (CA) with a density of 105 kg/m^3 and a thermal conductivity of 0.040 W/m·K [12] and **(iv)** stone wool (SW) with a density of 145 kg/m^3 and a thermal conductivity of 0.039 W/m·K [13].

For additional fire resistance, some sandwich panels were protected with fireproofing gypsum boards (FG) or with magnesium oxide boards (MGO). The fireproofing gypsum boards had a density of 770 kg/m^3 and a thermal conductivity of 0.25 W/m·K [14]. The magnesium oxide boards had a density of 1100 kg/m^3 and a thermal conductivity of 0.047 W/m·K [15]. The fireproofing boards were fixed to the sandwich panels by steel screws, without any vertical or horizontal joints.

Two expanded polystyrene foam core sandwich panels were tested with two different fireproofing boards: 12 mm thick fireproofing gypsum board (P-EPS-FG) and 3 mm thick magnesium oxide board (P-EPS-MGO). Two polyethylene terephthalate foam core sandwich panels were tested with two different fireproofing protections: 12 mm thick fireproofing gypsum board (P-PET-FG) and 10 mm thick magnesium oxide board with a hollow space of 30 mm (P-PTE-MGO/HS). A two-layered core panel with stone wool and expanded polystyrene foam was tested without any fire protection (P-SW/EPS). The stone wool core layer was placed on the side exposed to fire. Two cork agglomerate core sandwich wall assemblies were fire tested: one with no fire protection (P-CA) and another with a 12 mm thick fireproofing gypsum board (P-CA-FG). Properties of the seven wall assemblies subjected to fire resistance tests are shown in Table 1. The dimensions of the specimens tested were 2280 × 1250 mm.

The core layers were obtained by assembling plate elements, partially filling with epoxy resin the joints between them during the impregnation of the GFRP skins. Exception is made for the 80 mm thick PET core which was made of a single plate of 2280 × 1250 × 80 mm. The 80 mm thick EPS core was obtained by assembling 1000 × 500 × 80 mm plates. The 100 mm thick SW-EPS double layered core was obtained by the assemblage of 1000 × 500 × 50 mm stone wool plates and 1000 × 500 × 40 mm expanded polystyrene foam plates. The 80 mm thick CA cores were obtained by bonding two 40 mm thick layers, assembled with 1000 × 500 × 40 mm plates which were overlapped with special care to avoid continuous joints from the exposed to the unexposed face.

2.2. Setup and experimental procedure

The setup used and the procedure followed were the ones described in EN 13501-2 [9], EN 1363-1 [16] and EN 1364-1 [17] standards. The resistance to fire classification of non-loadbearing walls was based on the exposure of different assemblies to a fire scenario simulated using the standard temperature/time curve, which is a model of a fully developed fire inside a compartment [9]. This curve is given by equation (1).

$$T(t) = 345 \log_{10}(8t + 1) + 20 \quad (1)$$

where,

t is the time from the start of the test in minutes (min);
T is the average temperature inside the furnace in degree Celsius (°C).

A vertical furnace, as described in EN1363-1 [16], was used for the application of the standard temperature/time curve. The furnace is fired by 6 gas burners and the inside temperature is measured by 3 type K thermocouples, allowing a computer to regulate the fuel feed to adjust the inside temperature to the standard temperature/time curve (Fig. 1a). The frontal opening of the furnace was covered by the wall assemblies, fully exposing to fire one side of the specimens (Fig. 1b). It is worth mentioning that, according to the standards specifications, the panels were not directly exposed to the flames.

The fire performance characteristics evaluated were the integrity (E) and thermal insulation (I) of the wall assemblies. Integrity (E) refers to the ability of a construction element to withstand fire exposure on one side, without transmitting fire to the unexposed side as a result of passage of flames or hot gases. The assessment is based on visual observations of significant cracks or openings or of sustained flaming on the unexposed side of the wall. Thermal insulation (I) refers to the ability of the construction element to withstand fire on one side, without transmitting significant heat to

Table 1
Specimens of wall assemblies.

Label	Core material	Fire protection
P-EPS-MGO	EPS (80 mm)	MGO (3 mm)
P-EPS-FG	EPS (80 mm)	FG (12 mm)
P-SW/EPS	SW (50 mm) + EPS (40 mm)	No fire protection
P-PET-FG	PET (80 mm)	FG (12 mm)
P-PET-MGO/HS	PET (80 mm)	MGO (10 mm) + hollow space (30 mm)
P-CA	CA (80 mm)	No fire protection
P-CA-FG	CA (80 mm)	FG (12 mm)

Fig. 1. Vertical furnace: (a) 6 gas burners fired; (b) frontal opening covered by a wall assembly.

the unexposed side. The assessment is based on limiting the average temperature rise on the unexposed side to 140 °C above the initial temperature, with a maximum temperature rise of 180 °C. The designation of the fire resistance performance is a combination of the designation letters (E and I) with the elapsed exposure minutes of the nearest lower class, during which the functional requirements are satisfied (EI15, 20, 30, 45, 60, 90, 120, 180 or 240) [9].

Temperatures on the wall assemblies were measured using type K thermocouples placed on the exposed surface (TE) and on the unexposed surface (TU), in both cases within the core/skin interface. In some test specimens, other type K thermocouples were placed on the interface between two layers of core materials (TC). All thermocouples were positioned in duplicate at approximately mid-height and mid-width of the wall assemblies and were connected to data acquisition unit (sampling frequency of 300 reading/minute on all channels). Every value of temperature presented is the average value of at least 2 thermocouples.

Prior to the fire resistance testing of wall assemblies, an expedite test using a heat gun was performed on samples of different core materials in order to determine their thermal decomposition temperatures (T_d). The air flow temperature was risen at a rate of approximately 25 °C every 4 elapsed minutes, starting from an initial temperature of 50 °C. These tests were concluded after detecting visible decomposition of the core materials.

3. Results and discussion

3.1. Thermal analysis

The decomposition tests performed allowed the determination of approximate values of thermal decomposition temperatures (T_d)

Table 2
Thermal decomposition temperatures for different core materials.

Material	Thermal decomposition temperature (T_d)
EPS foam	≈85 °C [18,19]
PET foam	≈250 °C [18,20]
Cork agglomerate	≈210 °C [21].
Epoxy resin (skin)	≤120 °C[a] [24]
Glass fibre textile (skin)	≈830–860 °C[a] [25,26]

[a] Glass transition temperature or softening temperature.

higher than: 85 °C for EPS foam cores; 210 °C for CA cores and; 250 °C for PET foam cores. Other authors (Table 2) indicate temperatures ranging from 80 to 100 °C for EPS foam [18,19], from 244 to 265 °C for PET foam [18,20] and of 200 °C for CA [21]. According to the manufacturer, EPS foam is stable under heat exposures up to 85 °C [10].

The fire resistance of GFRP skins is related to the glass transition temperature (T_g) of the epoxy resin and to the softening temperature of the glass fibre textile. The epoxy resin used was diglycidyl ether of bisphenol A (DGEBA) with aliphatic amine as a curing agent [22,23]. According to Ratna [24], aliphatic amine-cured epoxy presents a low glass transition temperature ($T_g \leq 120$ °C). Although glass fibres are chemical and physically stable under fire exposures up to 830 °C, some mechanical properties decrease for temperatures well below the softening temperature [25].

Thermal decomposition temperatures (T_d) are vital for a proper evaluation of fire performance of wall assemblies.

Regarding EPS core wall assemblies with external fire protection, observation of the tests indicated that the decomposition of the core material ($TE \geq T_d = 85$ °C) started after 6 min of fire exposure in P-EPS-MGO wall assembly and after 9 min of exposure in P-EPS-FG wall assembly (Fig. 3a). The complete decomposition of the core thickness ($TU \geq T_d = 85$ °C) occurred after 14 min of fire exposure for P-EPS-MGO specimen and after 23 min for P-EPS-FG specimen (Fig. 3b). Comparing the performance of these specimens, it is clear that the FG board used (12 mm thick) constitutes a better fire protection than the MGO board (3 mm thick). Both wall assemblies have shown poor fire performances by maintaining integrity (E) and thermal insulation (I) characteristics for periods under 30 min (EI0 and EI20).

In order to improve fire performance of wall assemblies using EPS foam as core material, a 50 mm layer of stone wool (SW) was added to a 40 mm layer of EPS foam, forming P-SW/EPS specimen (90 mm thick). No other fire protection was used. The SW layer delayed decomposition of EPS foam ($TC \geq T_d = 85$ °C) to 22 min of fire exposure (Fig. 4). Complete decomposition of P-SW/EPS specimen core thickness was visually detected after 35 min of fire exposure, even though the unexposed surface temperature never reached temperature limit ($TU \leq T_d = 85$ °C), as shown in Fig. 3b. This wall assembly was considered to be EI30 fire resistant.

Considering the behaviour observed during the fire tests, the use of EPS foam as a suitable core material was dismissed for wall assemblies with adequate fire performance. An alternative core

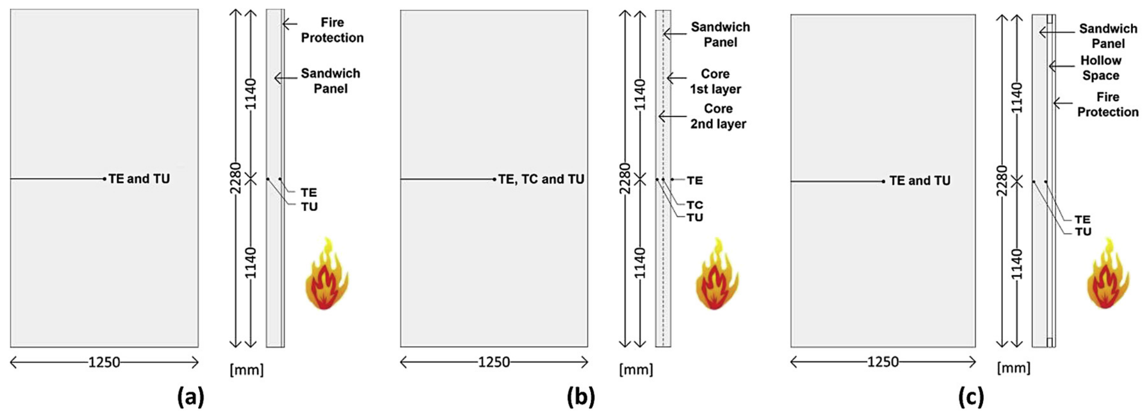

Fig. 2. Location of type K thermocouples in wall assemblies: (a) P-EPS-MGO, P-EPS-FG, P-CA-FG and P-PET-FG; (b) P-CA and P-SW/EPS; (c) P-PET-MGO/HS.

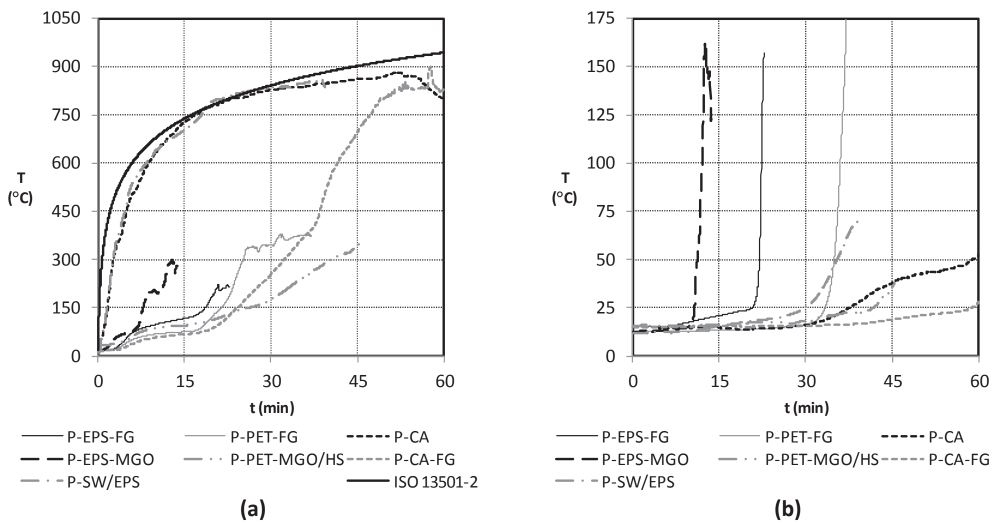

Fig. 3. Surface temperature of wall assemblies: (a) exposed surface – TE; (b) unexposed surface – TU.

material is the polyethylene terephthalate foam (PET) which presents a better fire resistance than the expanded polystyrene foam (EPS).

Two wall assemblies with PET foam as core material were tested: P-PET-FG with a FG board (12 mm thick) fire protection and; P-PET-MGO/HS protected with a MGO board (10 mm thick) and a 30 mm hollow space between this board and the sandwich panel (Fig. 2c). In P-PET-MGO/HS specimen, the hollow space between the MGO board and the sandwich panel was framed using MGO board strips. Some of these strips were placed near thermocouples, causing some temperatures measured by TC and TU thermocouples to be not as accurate as in the other wall assemblies tested. Decomposition of the core material (TE $\geq T_d = 250$ °C) started after 23 min of fire exposure for P-PET-FG wall assembly and after 36 min for P-PET-MGO/HS wall assembly (Fig. 3a). However, complete decomposition of the core thickness (TU $\geq T_d = 250$ °C) was visually observed in both specimens at approximately the same time: after 37 min of fire exposure for P-PET-FG and after 40 min for P-PET-MGO/HS (Fig. 3b).

After testing these two PET specimens, the first conclusion drawn was that the two different fire protections used (12 mm thick FG board and 10 mm thick MGO board) provided similar fire resistances. The second conclusion drawn was that after reaching the thermal decomposition temperature (T_d) the time elapsed for complete decomposition was approximately the same in EPS foam and PET foam cores.

PET core specimens were rated as EI30 non-loadbearing walls. In

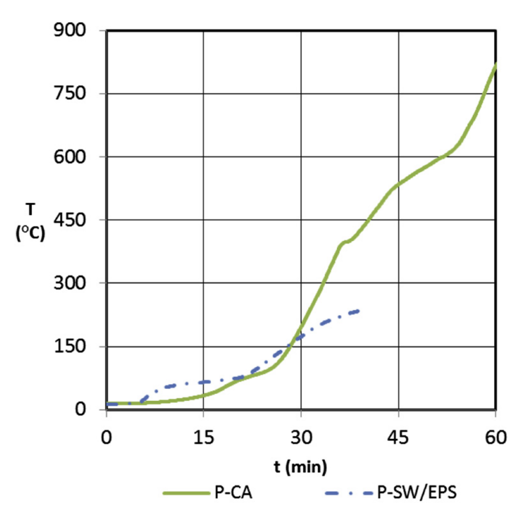

Fig. 4. Core temperature of wall assemblies (mid-thickness).

order to obtain sandwich panels with the desired fire performance, cork agglomerate was tested as an alternative core material. Cork is a well-known insulation material with relatively low mass loss when exposed to thermal decomposition temperature (T_d) and ashes at about 450 °C [21].

As mentioned, two 40 mm thick layers of cork agglomerate were bonded to achieve the required 80 mm thick core, which was used in the two tested CA core sandwich panels. The specimen P-CA-FG had a fireproofing gypsum board on the exposed surface and the P-CA panel was tested without any fire protection. The specimen with no fire protection started thermal decomposition ($TE \geq T_d = 210$ °C) after 2 min of fire exposure, while the specimen with FG boards begun to decompose after 25 min (Fig. 3a). Therefore, the fire protection delayed the beginning of thermal decomposition in about 23 min.

In P-CA wall assembly, thermocouples were placed between the two core layers (Fig. 2b) and the temperatures measured show that the second layer of core material started to decompose after approximately 30 min of fire exposure (Fig. 4). By the end of the fire test the average temperature of the unexposed surface of P-CA and P-CA-FG was well under the thermal decomposition temperature ($TU < T_d = 210$ °C), as shown in Fig. 3b. Taking into account the readings of the TU thermocouples, both cork agglomerate core wall assemblies were classified as EI60 resistant.

It is clear that the contribution of fireproofing boards in reducing temperatures on the exposed surface of the sandwich core. Temperatures measured by TE thermocouples were closer to the standard temperature/time curve and were far greater in wall assemblies without fireproofing (P-SW/EPS and P-CA) than in wall assemblies with FG or MGO boards (Fig. 3a).

The FG boards withstood direct heat for about 15 min, after which the exposed surface temperature greatly increased. In the wall assemblies with cork agglomerate core, even though the fireproofing integrity was compromised, the exposed surface temperature (TE) of the fireproofed specimen (P-CA-FG) only reached TE temperature of the non-fireproofed specimen (P-CA) after 55 min of exposure (Fig. 3a).

FG boards 12 mm thick are clearly a more effective fireproofing means than 3 mm thick MGO boards, evidenced by comparing temperature/times curves of P-EPS-FG and P-EPS-MGO wall assemblies in Fig. 3a (TE) and b (TU). Due to misconception of P-PET-MGO/HS specimen and misplacement of its TE thermocouples, no accurate fireproof performance comparison, based on measured temperatures, may be made between 12 mm thick FG board and 10 mm thick MGO board.

Both cork agglomerate core wall assemblies were classified as EI60 resistant, although TU temperature of P-CA specimen (50 °C) is twice the TU temperature of P-CA-FG specimen (25 °C), as shown in Fig. 3b. This fact evidences that the fireproofing provided by a 12 mm thick FG board does not affect the fire resistance classification of an 80 mm thick cork agglomerate core sandwich panel. For P-CA specimen, the temperature readings of TE and TC thermocouples after 60 min of fire exposure were similar (Figs. 3a and 4). Thus, by the end of the fire test, the first layer of core in P-CA specimen completely lost its integrity (E) and thermal insulation (I) capabilities.

3.2. Failure mode and post-failure assessment

As mentioned, the present study intended to evaluate the fire performance of wall assemblies with different core materials and different fireproofing protections of the exposed surface, focussing on integrity (E) and thermal insulation (I) capabilities. Therefore, admissible failure modes were the passage of flames or hot gases from inside the furnace trough the wall assembly, the formation of significant cracks or openings visible on the unexposed surface or significant heat transfer from inside the furnace to the unexposed side.

The allowable heat transfer to the unexposed surface was limited to an average temperature rise of 140 °C above the initial temperature, with a maximum measured temperature rise of 180 °C [9]. Thus, the unexposed GFRP skin remains almost undamaged at the end of the test, since glass transition of the epoxy resin occurs for temperatures around 120 °C [24] and softening of the glass fibre for temperatures around 630 °C [25].

Some of the core materials tested presented complete mass loss or changed to a different phase of matter under heat or fire exposure. Hence, the formation of significant hollow spaces inside the sandwich panels, resulting in the outer GFRP skin to be laterally unrestrained, was considered to be a failure mode as well.

Failure of wall assemblies with EPS foam cores (P-EPS-FG, P-EPS-M and P-SW/EPS) was due to complete mass loss of the core material, leaving significant hollow spaces between the GFRP skins. This mass loss was followed by a sudden temperature rise above 140 °C on the unexposed surface, as shown in Fig. 3b.

It is worth mentioning that in P-EPS-FG specimen the FG protection board stayed in place until the end of the test. However, the FG board dehydrated due to the heat exposure and, after 15 min, breaches opened allowing the heat to be directly transferred to the outer skin. Whilst placed in the furnace, even after failure was attained, this specimen maintained its overall appearance albeit its core experienced a complete mass loss and only the GFRP skins, the dehydrated FG board and the edges of core material remained in place and partially intact (Fig. 5a).

A very similar scenario occurred in the fire resistance test of P-EPS-MGO specimen. In this case, the MGO board was completely fragmented and only small pieces remained attached to its internal fibreglass mesh. The skins and a residual frame of core material were the only other identifiable debris (Fig. 5b).

The P-SW/EPS specimen had a different failure during the fire resistance test. In this specimen the stone wool maintained the consistency throughout the fire exposure, although became severely scorched. Nevertheless, the second core layer (EPS foam) experienced complete mass loss. The fire test residues were, in this case, the stone wool core layer, the GFRP skins (the internal completely damaged and the external almost undamaged) and a residual frame of the EPS core layer (Fig. 5c).

In the case of wall assemblies with PET foam cores (P-PET-FG and P-PET-MGO/HS), the failure mode was similar to the failure occurred for EPS foam core wall assemblies. The failures of wall assemblies with PET foam cores were due to mass loss of the core material, leaving significant hollow spaces between the GFRP skins. However, instead of complete mass loss with no residues, PET foam core melts into a viscous black by-product.

Severe scorch of the unexposed surface was registered for both P-PET-FG (Fig. 6a) and P-PET-MGO/HS (Fig. 6b) specimens. This scorching was not apparent in EPS foam core wall assemblies because the unexposed skin surfaces were painted with common façade water based white paint. In Fig. 6b, it is clear the absence of scorching in the specimen's mid-width, where strips of MGO board were overlapped to create the intended hollow space thickness (30 mm). TC and TU thermocouples were placed in this section, thus their readings were not considered to be accurate. The behaviour of the fireproofing boards was similar to the one registered in other fire resistance tests. The residues of the fire test were also very similar to the ones obtained in the other fire tests.

The use of PET foam in wall assemblies resulted in a fire resistance higher than the one presented by the EPS foam wall assemblies, but still insufficient for building applications. An alternative core material with similar costs and with a reduced self-weight is the cork agglomerate (CA).

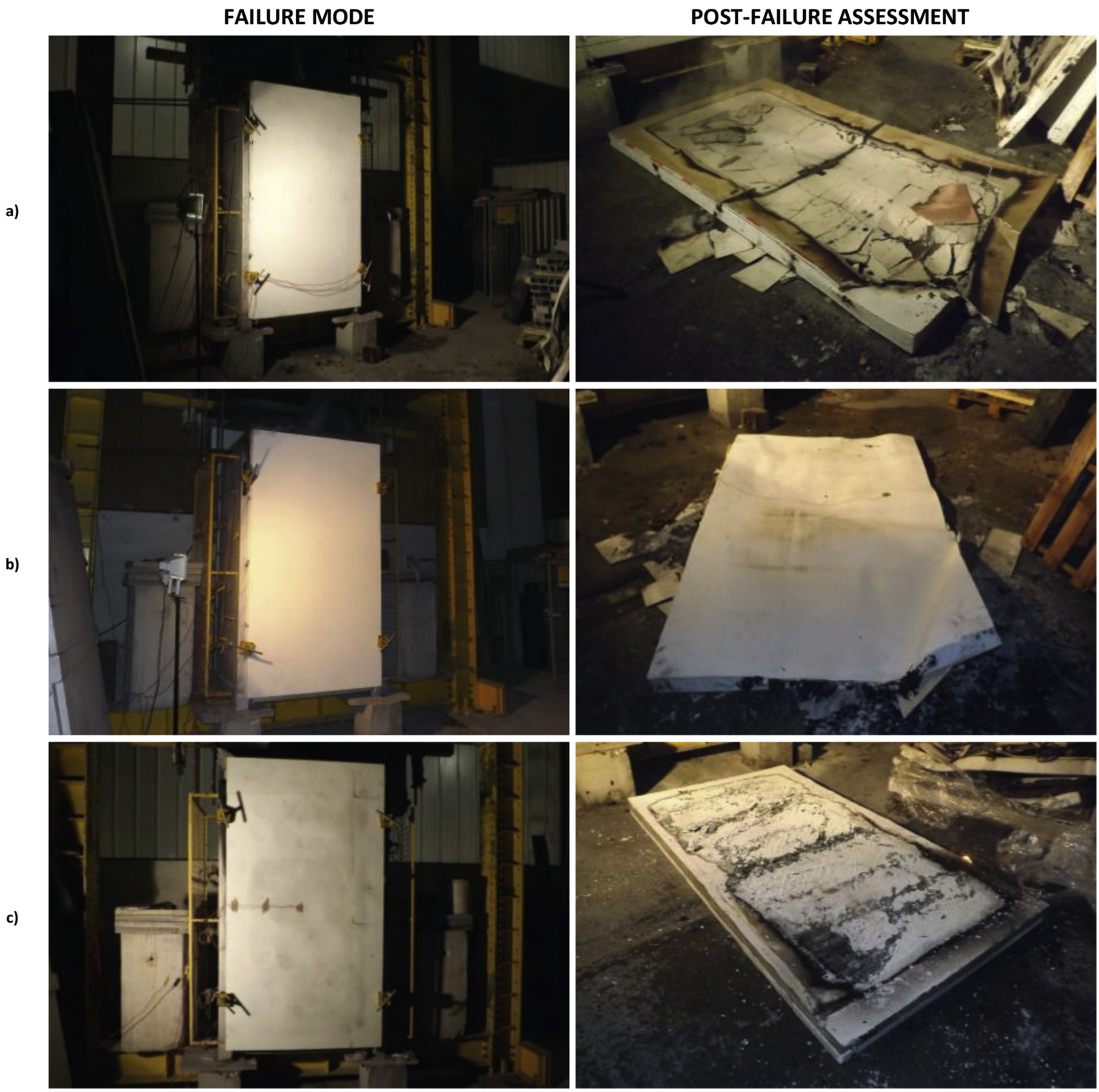

Fig. 5. Failure mode and post-failure assessment of EPS foam core wall assemblies: (a) P-EPS-FG; (b) P-EPS-MGO; (c) P-SW/EPS.

The fire performance of the CA core wall assemblies was very distinct from the other wall assemblies tested. The registered thermal decomposition rate of the core material was very low, of about 1.0 mm per elapsed minute of fire exposure. In fact, by the end of the fire tests 75% of P-CA and 50% of P-CA-FG specimens' core thicknesses were charred and completely lost any integrity (E) or thermal insulation (I) capabilities. The different degree of decomposition is related to the 15–20 min delay of the beginning of core's decomposition provided by the FG board in P-CA-FG specimen. The charred surface of the CA core on the exposed side of the wall assemblies acts as a protective layer which slows down thermal decomposition and heat transfer by reducing oxygen penetration, allowing for longer EI resistances to be achieved.

The failure of the CA core wall assemblies was due to flame passage through the specimens, from inside the furnace to the unexposed surface (Fig. 7a and b), even though the TU temperature readings on this surface were quite low (Fig. 3b). This fact is explained by the assemblage characteristics of these specimens. Indeed, the CA core was formed by several smaller boards placed side by side without any joint sealant or filling, bonded together by the GFRP skins. Special care was taken in preventing the joints from different core layers to be overlapped. Nonetheless, in both specimens, heat transfer and flame passage occurred trough these joints after the first layer of core material was completely burnt (Fig. 7a and b). Due to the longer duration of P-CA-FG specimen fire test, in comparison with other fireproofed wall

Fig. 6. Failure mode and post-failure assessment of PET foam core wall assemblies: (a) P-PET-FG; (b) P-PET-MGO/HS.

assemblies, the FG board completely deteriorated, solely retaining the edges which were not directly exposed to fire (Fig. 7b). Although flame passage occurred, proper detailing of the CA plates' joints, using sealants or fillings or by employing splice joints, would allow CA core wall assemblies to withstand an EI60 fire exposure, as referred in the thermal analysis.

3.3. Classification of fire resistance

The fire resistance classification of the tested walls assemblies followed the procedure of EN 13501-2 and was based on the thermal analysis, failure mode and post-failure assessment of all wall assemblies tested, focussing on integrity (E) and thermal insulation (I) capabilities.

In general, failure mode and post-failure analysis confirm the fire resistance classification attributed in the thermal analysis. Exception is made for CA core wall assemblies that failed due to passage of flames well before limit temperatures were attained on the unexposed surface of the wall. That was due to the fact that the 80 mm CA core was composed by two bonded 40 mm thick layers of cork agglomerate and the joints, even mismatched, were the weakest points of the sandwich panel.

Considering the data collected and visual observations of specimens during and after fire exposure, wall assemblies P-EPS-MGO and P-EPS-FG presented low fire resistances of 12 and 23 min, hence classified as not resistant and EI20 resistant, respectively (Fig. 8). These classifications are closely related to the low thermal decomposition temperature of EPS foam ($T_d = 85\ ^\circ C$).

Intermediate fire resistances (35–40 min) were achieved by wall specimens P-SW/EPS, P-PET-FG and P-PET-MGO, accordingly classified as EI30 resistant (Fig. 8). Stone wool (SW) proved to be a fire resistant material which enables to considerably delay the EPS foam thermal decomposition. Nevertheless, the lack of consistency of fairly low density wools and the high weight of proper consistency wools makes this material unsuitable for use as a core material. The intermediate fire resistance of PET foam core wall assemblies relates to the high thermal decomposition temperature of this material ($T_d = 250\ ^\circ C$). This fire resistance is not higher because PET foam melts into a viscous black by-product under fire exposure, leaving a hollow space between the GFRP skins.

The highest fire resistances were achieved by P-CA and P-CA-FG wall assemblies. Fire penetration to the unexposed surface occurred after 55 and 45 min of fire exposure, respectively, though thermal analysis showed the unexposed surface temperatures were well under the allowable limit. As mentioned, fire penetration occurred through poorly detailed joints of core boards. Alas, the fire protected assembly lasted less than the unprotected one. After careful post-failure examination, it was determined that fire breached a zone where core joints of different layers were overlapped. Both assemblies were classified as EI45 resistant and with proper care of these joints EI60 classification may be attained (Fig. 8). This high classification is related to cork's low thermal decomposition rate due to char of the exposed surface which hinders heat propagation.

Fire resistances achieved are not correlated with the weight of the wall assemblies. In fact, specimen P-CA presented the highest

Fig. 7. Failure mode and post-failure assessment of CA core wall assemblies: (a) P-CA; (b) P-CA-FG.

fire resistance and the third lowest weight of all specimens tested (Table 3). Furthermore, weights of wall assemblies with EI30 fire resistance range from 8.1 to 17.2 kg/m^2 (Table 3).

4. Conclusions

Lightweight sandwich panels are suitable for building application as non-loadbearing walls, considering the fire exposure according to EN 13501-2 standard, from a fire resistance stand of view. Reaction to fire classification was not addressed in this paper. Fire resistance of sandwich wall assemblies is closely related to the nature of the core material, especially to its thermal decomposition temperature and decomposition rate.

In wall assemblies with EPS and PET foam cores, although the thermal decomposition temperature for PET foam is higher than for EPS foam, the time elapsed between the beginning and the complete decomposition of the core material was approximately the same. Complete mass loss occurred for both core materials, leaving a significant hollow space between the GFRP skins. Thermal decomposition of the EPS foam presented a complete mass loss with no residues, while the PET foam melted into a viscous black by-product.

Of the core materials tested, cork agglomerate has proven to be the most effective in achieving high fire resistances. As mentioned, the slow decomposition rate presented by CA core is due to the

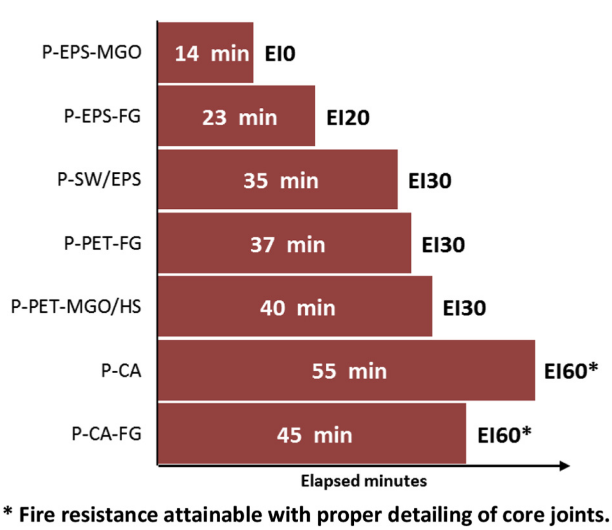

Fig. 8. Fire resistance classification of sandwich wall assemblies.

Table 3
Fire resistance classification and weight of different wall assemblies.

Wall assembly	Fire resistance classification	Weight
P-EPS-MGO	Not resistant	5.2 kg/m^2
P-EPS-FG	EI15	11.1 kg/m^2
P-SW/EPS	EI30	8.1 kg/m^2
P-PET-FG	EI30	14.7 kg/m^2
P-PET-MGO/HS	EI30	17.2 kg/m^2
P-CA	EI60[a]	9.2 kg/m^2
P-CA-G	EI60[a]	18.7 kg/m^2

[a] Fire resistance attainable with proper detailing of core joints.

charred layer which slows the burning process and, therefore, improves the fire resistance of the wall assembly. In fact, cork agglomerate performs so well under fire exposure that placing fireproofing gypsum boards on the exposed surface does not have significant impact on the fire resistance of the wall assembly.

Regarding the two different fire protections employed in some wall assemblies, the 12 mm thick fireproofing gypsum board and the 10 mm thick oxide magnesium board, similar fire resistances were attained.

A sandwich wall assembly with GFRP skins (1 mm thick) and cork agglomerate core (80 mm thick) presented the best fire resistance to weight ratio, withstanding a 60 min fire exposure without compromising its integrity (E) and its thermal insulation (I) capabilities and weighing 9.2 kg/m^2. Although the density of the CA core (105 kg/m^3) is much higher than the density of the EPS foam core (15 kg/m^3), it is still a suitable material for a lightweight sandwich panel.

The EI60 fire resistance of the CA core wall assembly depends on proper detailing of joints between core plates, using sealants and fillings or by employing splice joints. Disregarding this aspect would result in a smaller fire resistance, of about 30 min.

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References

[1] Mouritz AP, Gardiner CP. Compression properties of fire-damaged polymer sandwich composites. Compos Part A 2002;33:609–20.
[2] Scudamore MJ. Fire performance studies on glass-reinforced plastic laminates. Fire Mater 1994;18:313–25.
[3] Gu Pei, Asaro RJ. Designing sandwich polymer matrix composite panels for structural integrity in fire. Compos Struct 2009;88:461–7.
[4] Nguyen Quynh T, Tran Phuong, Ngo Tuan D, Tran Phong A, Mendis Priyan. Experimental and computational investigations on fire resistance of GFRP composite for building façade. Compos Part B 2014;62:218–29.
[5] Park Seul Hyun, Manzello Samuel L, Bentz Dale P, Mizukami Tensei. Determining thermal properties of gypsum board at elevated temperatures. Fire Mater 2010;34:237–50.
[6] Kolarkar Prakash, Mahendran Mahen. Experimental studies of gypsum plasterboards and composite panels under fire conditions. Fire Mater 2014;38: 13–35.
[7] Bakhtiyari Saeed, Taghi-Akbari Leila, Ashtiani Masoud Jamali. Evaluation of thermal fire hazard of 10 polymeric building materials and proposing a classification method based on cone calorimeter results. Fire Mater January/February 2015;39(1):1–13.
[8] Gu Pei, Asaro RJ. Designing polymer matrix composite panels for structural integrity in fire. Compos Struct 2008;84:300–9.
[9] Michael Davies J, Yong Wang C, Petter Wong MH. Polymer composites in fire. Compos Part A 2006;37:1131–41.
[10] Mouritz PA, Gibson GA. Fire properties of polymer composite materials. Springer; 2006.
[11] Babrauskas Vytenis. Sandwich panel performance in full-scale and bench-scale fire tests. Fire Mater 1997;21:53–65.
[12] EN 13501-2. Fire classification of construction products and building elements. CEN; 2007.
[13] Plastimar. Technical datasheet: EPS foam. 2011. Peniche, Portugal.
[14] DIAB Group. Technical datasheet: divinycell PET foam. 2012. Laholm, Sweden.
[15] Isocor. Technical datasheet: expanded cork agglomerate ICB40. 2004. Abrantes, Portugal.
[16] Rockwool, "Technical datasheet: stone wool panel 755," Zaragoza, Spain.,
[17] FibroPlac. Technical dasheet: fireproofing gypsum boards. 2009. Pombal, Portugal.
[18] Magnoboard. Technical datasheet: magnesium oxide boards. 2009. UK.
[19] EN 1363-1. Fire resistance tests − part 1: general requirements. CEN; 1999.
[20] EN 1364-1. Fire resistance tests for non-loadbearing elements − part 1: walls. CEN; 1999.
[21] Beyler C, Hirschler M. Thermal decomposition of polymers. In: SFPE handbook of fire protection engineering. 2nd ed. Boston, Massachusetts, USA: National Fire Protection Association; 1995. p. 110–31. 1-7.
[22] EUMEPS. Behaviour of EPS in case of fire. Brussels, Belgium: European Manufacturers of EPS; 2002.
[23] Vitkauskiene I, Makuska R, Stirna U, Cabulis U. Thermal properties of polyurethane-polyisocyanurate foams based on poly(ethylene terephthalate) waste. Mater Sci March 2011;17(3):249–53.
[24] Pereira H. The thermochemical degradation of cork. Wood Sci Technol 1992;26:259–69.
[25] Lavesan. Eponol LT 740: thecnical datasheet. 2008. Italy.
[26] Lavesan. Catalyst L97: technical datasheet. 2009. Italy.