Heliyon 10 (2024) e26309

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Experimental study of fire exposed expanded polystyrene (EPS) insulation protected by selected coverings

Brynhild Garberg Olsø *, Anne-Marit Haukø, Birgit Risholt

SINTEF Community, P.O. Box 4760 Torgarden, 7465, Trondheim, Norway

A R T I C L E I N F O

Keywords:
Fire testing
Fire protective covering
Combustible insulation
Fire safety
Expanded polystyrene
EPS
Fire protection engineering

A B S T R A C T

Insulation products made of expanded polystyrene (EPS) are commonly utilized in buildings. However, Norwegian building regulations restrict the use of such combustible insulation due to an increased risk of fire spread and generation of smoke and toxic gases. Installation of fire protection coverings has been adopted as a mitigation strategy to address these safety risks. Notably, the current regulations lack pre-approved solutions describing what is considered an adequate protection of combustible insulation. The present study investigated the fire protection properties of selected coverings used to protect EPS insulation in inner walls. Eight comparative fire tests were conducted using an indicative fire resistance test furnace. The test specimens consisted of EPS blocks mounted on a wooden frame and covered with one or two layers of selected board coverings. The specimens were positioned vertically within the test furnace, and each fire test lasted for 10 or 15 min. Test results revealed that only two configurations consisting of either two layers of 12.5 mm gypsum boards or a combination of 12 mm oriented strand board (OSB) and 12.5 mm gypsum board showed no evidence of damage to the EPS substrate after a 15-min fire exposure. Consequently, the findings suggest that a total covering thickness of at least 24.5 mm, comprising two layers of boards, is necessary to prevent adverse effects on EPS insulation. Furthermore, fire tests conducted on coverings with introduced damages and defects showed that the affected area around the damages and defects were limited. For the standard EPS substrate, this area extended from 28 mm to 90 mm, while for the fire-retardant EPS substrate from 28 mm to 75 mm after a 10-min fire exposure. These results suggest that minor physical failures in the covering have limited impact on the fire safety of the system.

1. Introduction

Expanded polystyrene (EPS) thermal insulation is widely employed in various construction applications due to its lightweight nature, moldability, and commendable thermal insulation properties [1–3]. In 2020, the global market size for EPS reached USD 9.5 billion, and it is projected to experience an annual growth rate of 4.8 % until the year 2028 [4]. The majority of this growth is anticipated to be driven by the increased worldwide utilization of EPS for thermal insulation in the construction sector. External insulation systems using plaster for fire protection, commonly known as External Thermal Insulation Composite Systems (ETICS), are widely employed. Additionally, EPS finds applications as insulation material in roofing materials and near ground level, such as its use in aggregates within lightweight concrete and sandwich panels [5,6].

* Corresponding author.
E-mail address: brynhild.olso@sintef.no (B.G. Olsø).

https://doi.org/10.1016/j.heliyon.2024.e26309
Received 19 December 2022; Received in revised form 9 February 2024; Accepted 9 February 2024
Available online 15 February 2024

EPS is characterized as a rigid, closed cell, thermoplastic material with a high susceptibility to combustion [2,5,6]. During fire exposure, EPS exhibits inadequate performance as it is prone to shrinkage, melting, and the generation of dense smoke and toxic gases [2,6]. Shrinkage of EPS initiates within the temperature range 70 and 100 °C, while its melting point is at approximately 100 °C. Ignition occurs when the temperature reaches a range between 290 and 320 °C [2,7]. The Vicat softening temperature of polystyrene, which represents the glass transition temperature for EPS where the material starts to melt, is in the range of 99–104 °C [7]. The melted EPS material can form droplets, which can contribute to the spread of fire to other parts within the building. Additionally, smoke and soot produced obstruct escape routes and poses a risk to both occupants and fire rescue personnel [2]. Consequently, fire protection covering is essential for EPS insulation to mitigate its susceptibility to fire.

According to the European standard EN 13501-2 [8], coverings are defined as the outmost part of vertical building components, such as walls, partition walls, and exterior walls. They also include the bottom layer of horizontal or sloping building components, such as floors, roofs and ceilings. Examples of materials and products used for fire protection of EPS include plaster boards, non-combustible insulation, and magnesium oxide (MgO) boards [1,5,6]. Despite the effectiveness of coverings in preventing EPS from actively contributing to a fire, it should be noted that melting of EPS can still occur behind the protective covering. This melted EPS can create voids or cavities, which, if there is an adequate supply of oxygen, can facilitate rapid fire spread [6,9]. Insufficient coverage of EPS insulation, particularly where timber cladding incorporates EPS decorations and air gaps behind the combustible cladding, can lead to a rapid fire development in the early stages. This was observed in the Hotel Caledonian fire in 1986 [10], which resulted in the loss of 14 lives.

The current Norwegian building regulations [11] follow a performance-based approach, i.e. any product, material, or system that meets the specified performance requirements can be used, as long as it provides an equal or higher level of fire safety compared to the corresponding pre-approved solutions outlined in the existing building standard guidelines [12]. The given pre-approved solutions currently restrict the use of combustible insulation in buildings to a maximum of two to three floor levels due to the increased fire risk associated with fire spread and smoke production. However, there are no specific pre-accepted solutions that define the required level of fire protection covering for combustible insulation. Hence, the determination of adequate fire protection in a construction project is at the discretion of the contracted fire safety consultant.

According to the Norwegian building regulations [12], materials and building products used to protect combustible insulation must meet two performance requirements: Firstly, they must prevent combustible insulation like EPS from igniting, burning, and contributing energy to a fire. Secondly, the material or product must limit the temperature rise behind the protective layer to avoid shrinkage and melting of the EPS. Due to its expanded structure, EPS has a low weight to volume ratio, with approximately 95 and 98 % air content [13]. A previous study comparing the fire load energy between a concrete building structure containing EPS and a wooden structure containing mineral wool, showed that the structure with EPS had the lowest fire load energy, thanks to its low weight and correspondingly low amount of combustible material [14]. However, EPS burns more rapidly than wood due to its porosity and low thermal capacity [1]. Even when the available fire energy is low, the risk of a rapid fire spread can still be high.

According to the Norwegian building regulations, internal coverings must provide adequate protection for combustible insulation to ensure sufficient time for evacuation and rescue. In the early stages of the present study, calculations were conducted to determine the available safe egress time in a specific 4-storey apartment building, which was determined to be 10 min [14]. However, it is important to note that the available safe egress time can vary for different buildings and may exceed 10 min. Therefore, in the current study, it was desirable to conduct fire tests on coverings that can effectively protect EPS for a duration up to 15 min.

Various test standards are employed to assess the fire properties of materials and products utilized to protect EPS during a fire. These tests range from small-scale reaction to fire tests at material level to comprehensive full-scale tests such as the SP Fire 105 facade test and fire protection ability tests for coverings [15,16]. In Europe, the EN 13501-1:2018 standard [17] requires that all materials undergo testing and receive formal classification. According to this standard, the definition of "reaction to fire" pertains a products' response, including its decomposition, when exposed to a fire under specific conditions. Since the requirement for fire protection of EPS also encompasses the risk of shrinkage and melting at temperatures between 70 and 100 °C [7], testing must also verify both the temperature rise behind the covering and its corresponding classification. Consequently, the determination of fire protection ability for coverings necessitates using EPS as the substrate beneath the covering. Thus, all the tests described in the present study include investigation of fire protection coverings mounted on EPS insulation as substrate.

Testing of fire protection coverings according to EN 14135:2004 [16], is conducted to determine their fire protection ability. The standardised test involves horizontally mounting test specimens of 2.6 × 3.0 m inside a furnace for a minimum test duration of 10 min. These tests are typically performed by boards and cladding manufacturers, with chipboard commonly used as the substrate. It is worth noting that the reports from these tests are not publicly available.

In Norway, the use of EPS as a substrate in fire testing and classification is not common. The pre-accepted solutions provided in the guidelines [12] only specify the fire protection ability class $K_2 10$, which requires testing with chipboard as the standard substrate. In contrast, the Danish building regulations explicitly describe a fire protection ability class of $K_1 10$ B-s1, d0 for the protection of combustible insulation [18]. Conducting large-scale testing in accordance with EN 14135:2004 [16] can be expensive, making smaller-scale testing more beneficial for comparative assessment of selected types of coverings. Small-scale testing with a single flame burning, in accordance with NS EN 13501-1:2018 [17], provides information on the surface performance of the board but is insufficient for evaluating the fire protection abilities for inner wall coverings. There are no international standards for intermediate-scale testing. Such testing, which involves test specimens of 1–2 m^2, offer a reasonable and cost-effective alternative for comparative studies. To obtain a realistic representation of the fire load from a room fire, testing of the fire protection abilities of boards for wall covering should also be conducted in a vertical furnace. The present study aims to compare selected boards for fire protection covering of EPS insulation used on inner walls and utilizes an intermediate scale experimental set-up.

While a limited number of studies have focused on fire protection of EPS used on inner walls, there have been several investigations into the use of plaster as a fire protection covering for EPS on facades [3,19–21]. Several factors play a role in determining the effectiveness of a fire protection covering in preventing fire and limiting temperature rise within the EPS: for ETICS facade systems (External Thermal Insulation Composite Systems), experiments have highlighted the criticality of plaster thickness [20]. Samples with plaster thickness ranging from 2 to 8 mm were exposed to a single flame burner for durations of 30 s to 25 min, following the EN ISO 11925-2 standard. It was observed that EPS protected by a thin 2 mm plaster started to melt already after 30 s of flame exposure. In contrast, the thicker plaster layers were able to withstand the fire exposure for 4–9 min before the EPS began to melt behind the plaster. The experiments also revealed that softening and shrinkage of the EPS led to deterioration of the plaster, especially in thicker plasters of 6–8 mm thickness. Therefore, it is crucial to ensure that the plaster is sufficiently thick to limit temperature rise in the EPS while avoiding mechanical damage to the plaster caused by EPS shrinkage.

Damage to or defects in fire protection coverings can result in the involvement of EPS in a fire [2,19]. Significant damage occurs when a larger area of EPS is directly exposed to the fire, leading to a greater contribution to the heat release rate. Poor plastering can lead to damage and weak spots that compromise the fire protection properties of coverings [3]. Examples of weak spots include cracks in the plaster, areas of thin plaster, joints between gypsum boards, and drill holes. Ensuring adequate implementation of fire protection measures around window openings and firestops is particularly crucial. In early stages of the present study, a risk and vulnerability analysis was performed to investigate the risk factors associated with the use of combustible insulation in buildings. The chosen scenario involved a building system with insulated concrete forms made of EPS in a 4-storey apartment building [14]. The risk analysis showed that when the necessary measures were taken, such as updating of assembly instructions, providing contractor training, and informing apartment owners, the risk was deemed acceptable. It was determined that the use of a building system of EPS in 4-storey apartment buildings, with these measures in place, did not compromise the fire safety level for occupants and the firefighters.

EPS is in addition to exterior applications also utilized as interior insulation and in sandwich panels [5,6]. Fire protection coverings in connection with room fire exposure have also been investigated experimentally in other studies: The interior fire protection properties of sandwich panels were examined for fire resistance for selected fire protection coverings, including a 50 mm-thick layer of rockwool, a 10 mm-thick magnesium oxide board, and a 12 mm gypsum board. The study assessed the temperature rise behind the coverings [6]. Results indicated that the magnesium oxide board, which festered an air gap towards the EPS, along with the 12 mm gypsum board and the 50 mm rockwool layer, achieved a fire resistance classification of EI 30. However, the study did not provide information on the duration required for the EPS to undergo thermal deterioration in terms of shrinkage, decomposition, and melting. In another study conducted by Murillo et al. [5], it was observed that the use of a gypsum board in combination with a cement-based board improved fire resistance by 45 min compared to the use of a single cement-based board, thereby enhancing the protection of EPS against fire.

The literature survey reveals a knowledge gap regarding the speed at which combustible insulation becomes involved in a room fire and specific fire protective covering required to safeguard EPS on inner walls from excessive heating. To address these uncertainties, a potential approach is to examine the impact on EPS insulation and subsequent degradation resulting from factors such as the type of covering, the number of protection layers, the presence of damages, and defects in the covering and the duration of fire exposure.

The purpose of the presented study was to investigate and compare the fire protection abilities of selected board coverings for fire protection of EPS insulation used on inner walls through fire testing. The objective was to determine the effectiveness and duration of protection provided by the selected board coverings during a room fire, considering the required time for building evacuation and rescue through available safe egress time analysis [14]. The main goals of the fire tests were twofold: (a) to systematically compare the performance of the selected board coverings and evaluate their ability to safeguard the underlying EPS wall insulation during a room fire, and (b) to highlight the significance of physical damage and defects in the boards as critical factors influencing the protection of combustible insulation when exposed to fire.

2. Experimental set-up

2.1. Performance criteria and test observations

The study utilized the performance criteria for fire protective coverings outlined in the NS-EN 13501-2 standard [8]. The fire protection ability (K) is defined as the ability of a wall or ceiling covering to protect the material located behind the covering protection from ignition, charring, and other damage for a specified period of time. According to the standard, EPS is categorized as a low-density material (less than 300 kg/m^3), and therefore, coverings need to undergo testing to demonstrate a fire protection ability of K_1. Under this classification, the following conditions must be met within the classification period of 10 min:

- The occurrence of cracks or other damages is prohibited.
- The mean temperature recorded on the lower side of the substrate shall not exceed the initial temperature by more than 250 °C during the test. Additionally, the maximum temperature measured on each thermocouple on this side shall not exceed the initial temperature by more than 270 °C.
- No traces of burnt, charred, melted or shrunken material shall be observed on any part of the substrate subsequent to the test.

In the first six tests, visual observations were conducted during and after each test to observe the extent of damage to the covering and any effects on the EPS, such as shrinkage, melting, charring, or burning. Furthermore, the effects of the intentionally introduced damage and defects were also observed and measured in tests 7 and 8.

Regarding the use of EPS insulation, the key acceptance criteria are associated with shrinkage. Thermal exposure causes the volume of the EPS beads to expand until the material reaches its bursting point, leading to the release of gas molecules. Further heating would likely result in shrinkage and possible formation of voids.

2.2. Preliminary test on EPS material

Prior to the fire protection ability tests on selected coverings, a preliminary test using a hot air oven was conducted on the EPS material at a smaller scale. The objective of this preliminary test was to identify the temperature range at which the specific EPS material used in the main fire tests would start to undergo structural change due to heat exposure. This criterion is one of the performance requirements outlined in the NS-EN 13501-2 classification standard [22], which states that no burnt, charred, melted, or shrunk material should be present after testing. Literature findings [6] suggest that structural changes in EPS begin at approximately 85 °C. The results obtained from the preliminary thermal analysis of the EPS used in the main tests provided insights into how closely the covering approaches failure during the indicative fire resistance tests, as further described in Section 2.3. By placing thermocouples between the EPS and the fire covering in the main tests, a temperature and time of failure for the selected covering systems can be predicted.

For the preliminary test on the EPS material, an electrical oven used for cooking purposes was utilized. The internal dimensions of the oven were 560 mm × 579 mm × 549 mm. The test involved placing a 100 mm × 300 mm x 150 mm EPS sample in the centre of the oven, allowing the hot air to circulate evenly around it. To measure the temperature rise during the test, a copper disc thermocouple type K (diameter 6.35 mm, thickness 0.3 mm) with PTFE insulated twisted wire, was positioned on the test sample surface. The test setup is shown in Fig. 1.

During the test, the air flow temperature within the oven was increased at a rate of approximately 5 °C for every 5 min. The test started at an initial temperature of 20 °C. Throughout the test, continuous visual observations were made to monitor structural changes occurring on the surface of the EPS sample. The test was concluded after 36 min, when clear visual indications of structural change were observed at the surface of the EPS material.

Observations and temperature measurements recorded during the test indicated that the structural changes, shown in Figs. 2 and 3, occurred in the temperature range of 95 °C–100 °C. A comparison of the test sample with an identical reference sample following the test revealed distinct structural differences. In Fig. 2 (right), the test sample exhibited inflated EPS beads on the surface, while the reference sample (left) remained unchanged. Additionally, Fig. 3 highlights the evident shrinkage of the test sample, particularly noticeable on the edges.

2.3. Design and preparation of intermediate-scale test specimens

The vertical fire resistance tests were conducted on eight selected coverings and configurations, as detailed in Table 2. The tests were performed in an indicative fire resistance test furnace using a non-standard intermediate-scale setup. The furnace apparatus is described in Section 2.4. The test specimens consisted of a timber frame constructed with studs measuring 48 mm × 98 mm, spaced 600 mm measured from centre to centre and with outer dimensions 1550 mm × 1550 mm, as shown in Fig. 4. The frame was securely

Fig. 1. Test setup used to determine the temperature range for structural change in the specific EPS material used in the main tests. The picture shows a sample of EPS material with a disc thermocouple attached to the side.

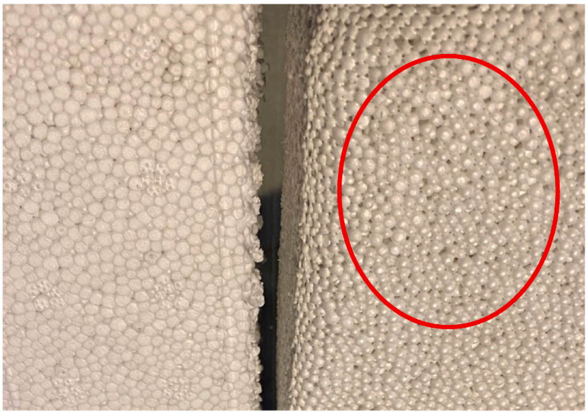

Fig. 2. Visual comparison of structural changes after the preliminary test (side view). The reference sample on the left and the test sample on the right. The red circle highlights the area where inflated beads are most distinct. Total duration of heat exposure was 36 min. At test termination the oven temperature had reached 130 °C and the surface temperature of the test sample was measured to 100 °C.

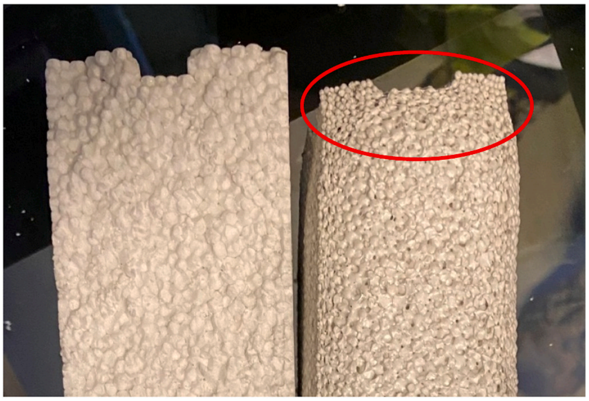

Fig. 3. Visual comparison of shrunken EPS material (top view). The heat affected test sample on the right is clearly smaller in size compared to the reference sample on the left. The red circle on the right highlights the area where shrinking is most distinct.

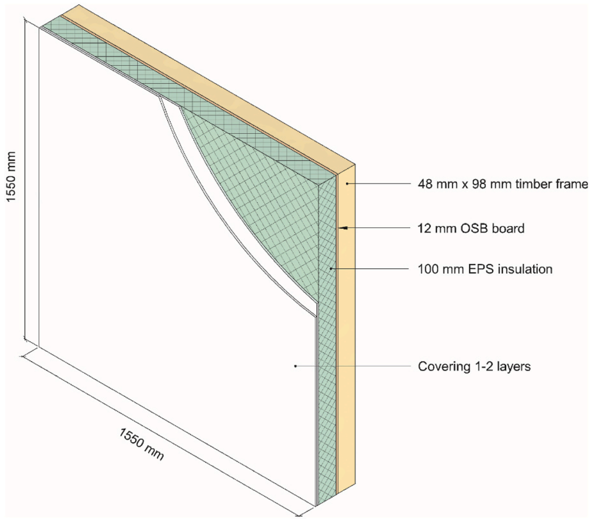

Fig. 4. Test setup. The EPS was mounted on a 12 mm OSB board on a timber frame of 48 × 98 mm studs c/c 600 mm and fitted with one or two layers of covering.

fixed with 5 mm × 90 mm stainless steel wood screws. On top of the frame, a layer of 12 mm OSB boards (Oriented Strand Board) was placed affixed with 4.2 mm × 35 mm sheet metal screws. The screws were spaced 200 mm apparat vertically and 600 mm apart horizontally. OSB-boards are engineered structural-used panel composed from thin wood strands bonded together with water-based resin glue [23]. Next, a single layer of 100 mm-thick EPS blocks measuring 300 mm × 1200 mm were placed on top of the OSB boards, covering them completely. The EPS blocks were secured with two 6 mm × 140 mm wood screws. Finally, each specimen was fitted with one or two layers of covering on top of the EPS, as outlined in Table 2 and shown in Figs. 4 and 5. In cases where two layers of covering were used, the joints between the layers were staggered to ensure sufficient protection.

Declared fire classifications and material properties of the EPS and the coverings used in the tests are given in Table 1. The properties are taken from the manufacturer's DoPs (Declaration of Performance).

In tests 7 and 8, damaged or defective fire protection coverings were intentionally used to assess the impact of poor installation or coverings with pre-existing damages. Two different types of EPS substrates were employed for these tests: Standard EPS in test 7 and fire-retardant EPS in test 8. The objective was to determine whether there would be any variations in the extent of damage to the underlying substrate and, if so, to quantify the magnitude of the difference. For tests 1 to 6, a standard EPS insulation was used as it was considered to be the most conservative substrate with regards to fire properties.

In both test 7 and 8, the following damage and defects were introduced deliberately identically:

1. A hole with a diameter of 28 mm was drilled through the covering to simulate mechanical damage to the covering, leaving the EPS fully exposed in that specific area.
2. To simulate poor installation, a 3 mm gap was left in the joint between the gypsum boards. This included the absence of joint tape and filler in the upper part of the test specimen joint.
3. A gypsum anchor and gypsum plug, along with a metal screw, were introduced to imitate wall suspension points typically used for objects such as picture frames.
4. A gypsum plug was initially installed and then intentionally removed, causing damage to the covering that imitated the removal of a suspension point.

Fig. 6 shows the test specimen setup including the introduction of damage and defects as described above. Positioning dimensions are approximate and given in mm (the numbers 1, 2, 3 and 4 in red corresponding to the items in the list above).

Table 2 lists the eight selected test setups, with number and type of coverings, total thickness of the protective covering, the type of EPS and whether the test was performed with damage or defects in the covering.

2.4. Fire test setup and experimental procedure

The eight fire tests were conducted in a vertical orientation in an indicative fire resistance test furnace that complies with ISO 834-1

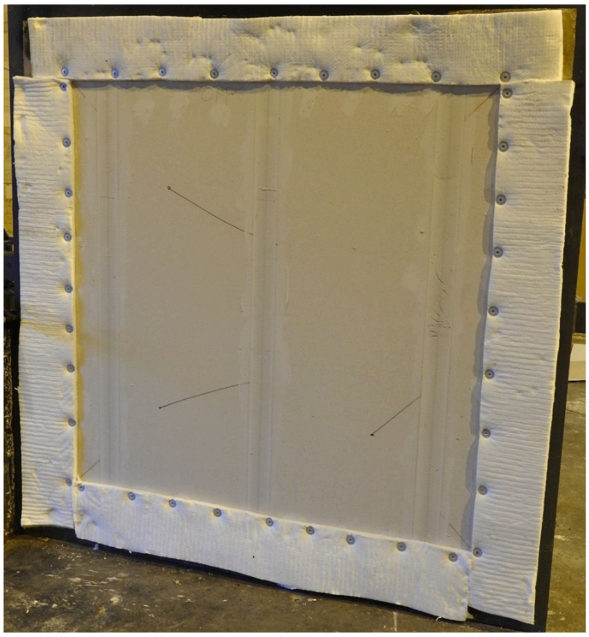

Fig. 5. Example picture of a test specimen, including covering of gypsum board, prepared for fire testing. The joints and screw holes were treated with joint strips and fillers like commonly fitted on a wall in a building. Lines on the specimen are pencil marks showing the location of thermocouples.

Table 1
Material properties and reaction to fire classifications.

Test number	Material	Density [kg/m^3]	Reaction to fire classification according to EN 13501-1	Thermal conductivity [W/mK]
1–7	Standard EPS	21.5	F	0.035
8	Fire-retardant EPS	21.5	E	0.031
1	12 mm chipboard	700	D-s2,d0	0.13
2	11 mm fire-retardant chipboard	840	B-s1,d0	0.15
3, 5, 6, 7 and 8	12.5 mm gypsum board type A	720	A2-s1,d0	0.25
4	12 mm fibre gypsum board	1150	A2-s1,d0	0.32
5	12 mm OSB board	640	D-s2,d0	0.13

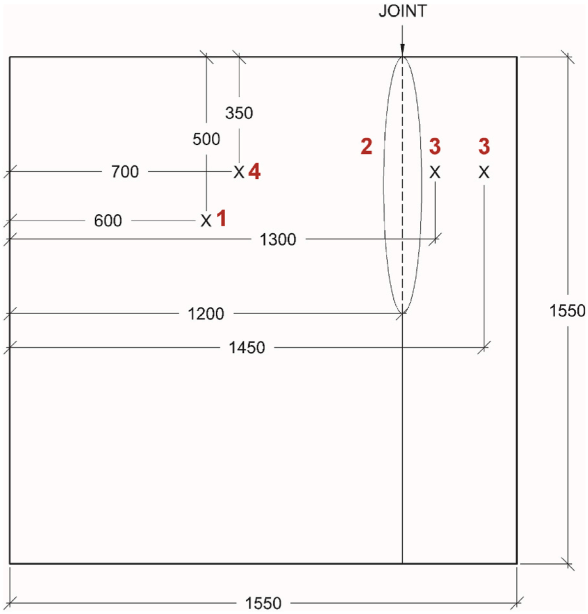

Fig. 6. Test specimen setup illustrating damage and defects introduced to the test specimen. Dimensions given in mm. The test furnace dimensions were 1550 mm × 1550 mm × 1550 mm.

Table 2
List of the eight intermediate-scale test set-ups.

Test no.	Number of coverings	Total thickness of fire protective covering	Type of fire protective covering	Type of EPS	Introduced damage/defects
1	1	12 mm	Chipboard	Standard EPS	No
2	1	11 mm	Fire-retardant chipboard	Standard EPS	No
3	1	12.5 mm	Gypsum board, type A	Standard EPS	No
4	1	12 mm	Fibre gypsum board	Standard EPS	No
5	2	24.5 mm	12 mm OSB board +12.5 mm gypsum board, type A	Standard EPS	No
6	2	25 mm	12.5 mm gypsum board, type A	Standard EPS	No
7	1	12.5 mm	Gypsum board, type A	Standard EPS	Yes[a]
8	1	12.5 mm	Gypsum board, type A	Fire-retardant EPS	Yes[a]

[a] An illustration of introduced damage/defects is given in Fig. 6.

[24] and EN 1363-1 [25] standards. The furnace, shown in Fig. 7, possesses inner dimensions of 1550 mm × 1550 mm × 1550 mm. Vertical orientation was selected to mimic wall configurations. The furnace was fuelled with a premixture of propane gas and air, and it features three gas burners embedded in the sides of the chamber, one on the right side and two on the left side. The temperature-time relationship followed the cellulosic fire curve (ISO-834) [24], which was considered relevant for the present study as it is also used in the standardized test for coverings as per EN 14135:2004 [16]. The cellulosic fire curve represents a model of a fully developed fire in a fire compartment and is used to classify and demonstrate fire resistance in standardized fire tests.

Fig. 7. Indicative fire resistance test furnace.

The duration of the tests was determined to be either 10 min (tests 1-2-7-8) or 15 min (tests 3-4-5-6), on two factors: 1) The fire protection ability classification K_1 specified in standard EN 13501-2 [8], which describes a classification period of 10 min to meet the performance criteria on substrates with a density below 300 kg/m^3, and 2) The time required to protect the EPS for evacuation and rescue purposes in a building based, as calculated in the initial phase of the present study [14]. The inclusion of a 15-min test duration aimed to explore whether certain test configurations could achieve a longer test period than 10 min, thereby potentially qualify for future standardized testing in accordance with EN 14135 [16]. Tests 3, 4, 5, and 6 were conducted for 15 min to evaluate the performance of gypsum, fibre gypsum, and two layers of protective covering, which were anticipated to meet the performance criteria based on prior knowledge. Conversely, chipboard and fire-retardant chipboard were not expected to meet the criteria. The performance criteria are further described in chapter 2.1.

Immediately after test termination, the test specimen was promptly removed from the furnace, and any ongoing combustion was extinguished using water. Subsequently, the covering board layers were removed, allowing for a visual inspection of the EPS substrate.

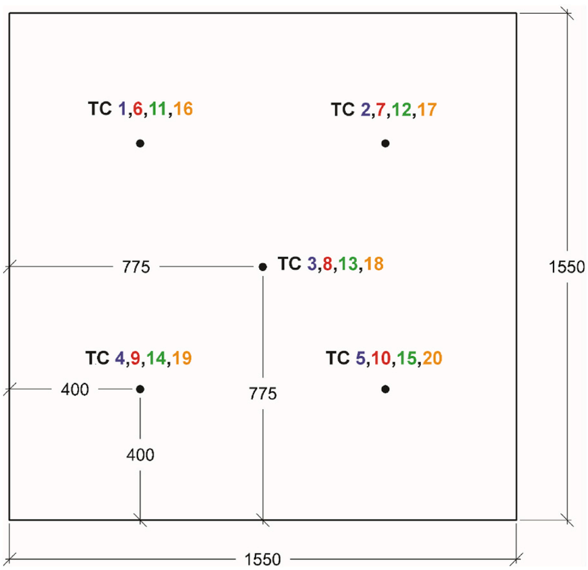

Fig. 8. Locations of the thermocouples (TC). Dimensions in mm.

2.5. Instrumentation

Five 0.51 mm diameter type K thermocouples (TC), as described in EN 1363-1 [25], were placed between each layer of coverings in order to measure the temperatures during the test. The locations of the thermocouples were selected according to the EN 14135:2004 standard [16], with 400 mm from side and top, and in the centre of the board, as shown in Fig. 8. The locations were as follows:

1. Locations with one layer of covering:
   - TC1-TC5 (purple font) between the EPS substrate and the OSB board.
   - TC6-TC10 (red font) in the centre of the EPS substrate.
   - TC11-TC15 (green font) between the EPS substrate and the covering.
2. Locations with two layers of covering:
   - TC1-TC5 (purple font) between the EPS substrate and the OSB board.
   - TC6-TC10 (red font) in the centre of the EPS substrate.
   - TC11-TC15 (green font) between the EPS substrate and the first layer of covering.
   - TC16-TC20 (orange font) between the first and second layer of covering.

3. Test results and observations

3.1. Thermal analysis and temperature development

The results from the preliminary tests performed in the hot air oven indicated a thermal degradation temperature range of 95–100 °C for the tested EPS insulation. This finding serves as an indication of when the EPS material may start to shrink behind the covering in the main fire tests performed in the indicative fire resistance test furnace. For each thermocouple, temperature measurements were recorded and plotted against time. Additionally, the average temperature of the five thermocouples placed between the EPS insulation and the covering (TC11-TC15) was calculated. Given the limited number and their placement on the test specimen, temperature development for each TC was compared with visual observations of the EPS insulation after test termination to investigate any correlation between the temperature measurements and the observed effects on the EPS material.

3.1.1. Standard chipboard versus fire-retardant chipboard

Figs. 9–11 show the results and a comparison of the temperature development during a 10-min fire exposure of 12 mm standard chipboard and 11 mm fire-retardant chipboard (Tests 1 and 2, respectively).

In Test 2, where the EPS insulation was covered with fire-retardant chipboard, a noticeable difference in temperature rise compared to Test 1 was observed during the first 4 min. The fire-retardant chipboard delayed the ignition and spread of fire in the initial stages of the test, resulting in lower temperature readings. However, after 4 min, the temperatures in Test 2 started to increase and eventually stabilized at around 102 °C after 5 min. It is worth noting that the surface temperature of the EPS insulation in Test 2 reached 95 °C approximately 30 s earlier than in Test 1 and maintained a slightly higher temperature towards the end of the fire tests. Towards the end of both fire tests, the temperatures rose due to burn-through of the coverings, as illustrated in Figs. 21 and 22.

3.1.2. Single layer of gypsum board versus gypsum fibre board

The results and a comparison between recorded temperatures during fire tests for a covering of a single 12.5 mm gypsum board layer (Test 3) and a single 12 mm gypsum fibre board layer (Test 4) are shown in Figs. 12–14. Both fire tests were run for 15 min.

The single layer of gypsum board covering (Test 3) exhibited a rapid temperature development, with temperatures rising significantly after just 1 min and reaching 95 °C after approximately 3 min. Test 4, which utilized a single layer of gypsum fibre board, exhibited a much slower temperature rise, reaching 95 °C after approximately 9 min and 30 s according to the average temperature curve. However, thermocouple TC15 had a considerably lower temperature rise compared to the other four thermocouples, most likely

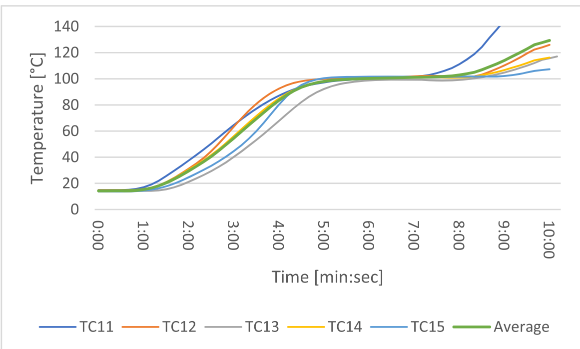

Fig. 9. Test 1 – standard chipboard. Recorded temperatures for Test 1 (single layer of standard chipboard covering).

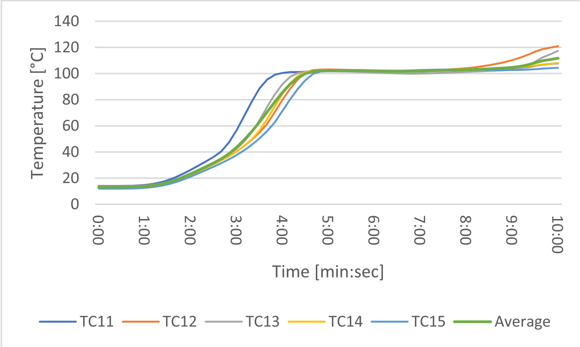

Fig. 10. Test 2 – fire-retardant chipboard. Recorded temperatures for Test 2 (single layer of fire-retardant chipboard covering).

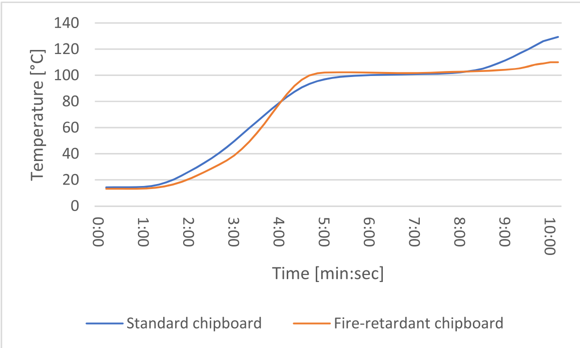

Fig. 11. Comparison of recorded temperatures for Test 1 (standard chipboard covering) and Test 2 (fire-retardant chipboard covering) based on average TC temperatures.

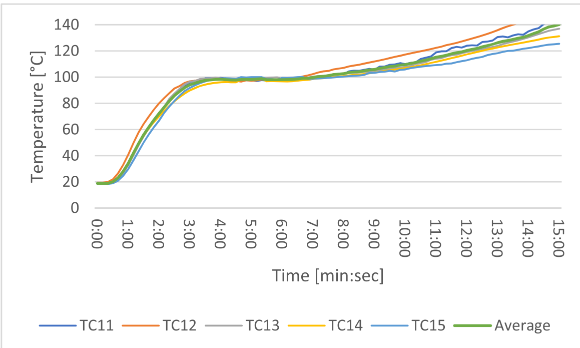

Fig. 12. Test 3–12.5 mm gypsum board. Recorded temperatures for Test 3 (single layer gypsum board covering).

due to thermocouple failure. This likely failure affected the average temperature development curve. In Fig. 14 TC15 was excluded from the average curve, resulting in a more uniform temperature measurement that reached 95 °C after 4 min and 40 s.

3.1.3. OSB + gypsum board versus two layers of gypsum board

The fire tests 5 and 6, both lasting 15 min, examined different combinations of coverings. Test 5 employed a combination of a single layer of 12 mm OSB board placed directly on the EPS insulation, covered by a layer of 12.5 mm standard gypsum board. In contrast, Test 6 employed a combination of two layers of 12.5 mm standard gypsum board resulting in a total thickness of 25 mm. The temperature curves and their comparison for these fire tests are shown in Figs. 15–17.

In Tests 5 and 6, the differences in temperature development became apparent after approximately 2 min. The covering consisting of a combination of an OSB board and a gypsum board (Test 5), exhibited a considerably slower and lower temperature rise compared to Test 6. Test 5, utilizing one layer of OSB board and one layer of standard gypsum board, resulted in a gradual temperature rise but did not reach 95 °C during the 15-min fire test. In Test 6, the recorded temperatures stabilized just below 100 °C during the fire

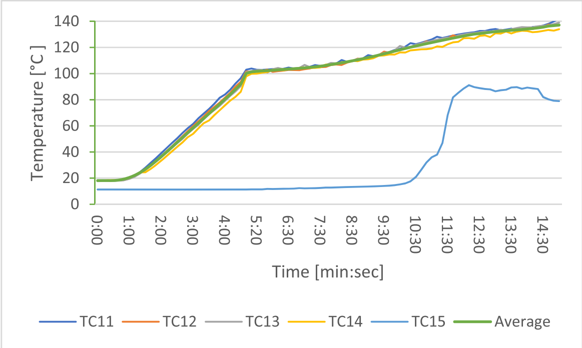

Fig. 13. Test 4 – gypsum fibre board. Recorded temperatures for Test 4 (single layer gypsum fibre board covering).

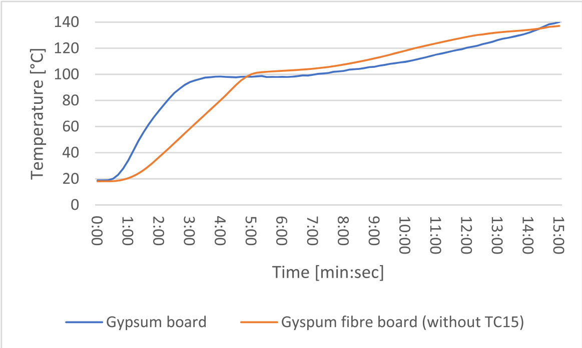

Fig. 14. Comparison of recorded temperatures for Test 3 (gypsum board covering) and Test 4 (gypsum fibre board covering) based on average TC temperatures. TC15 is left out due to TC failure).

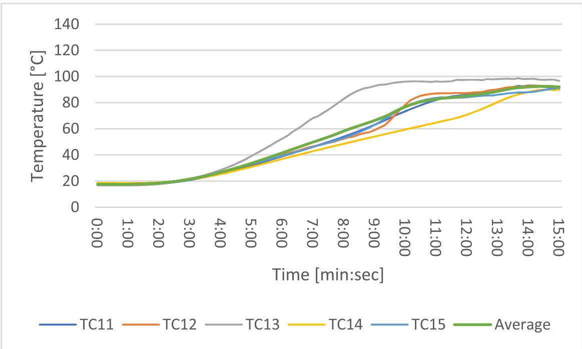

Fig. 15. Test 5 – OSB board + gypsum board. Recorded temperatures for one layer of OSB covered with one layer of gypsum board covering.

exposure time of 15 min. These findings suggest that there should be no shrinkage, melting or damage to the EPS insulation once the coverings are removed in either of the two fire tests. Visual observations are discussed afterwards (see Section 3.2).

3.1.4. Gypsum board on standard EPS versus fire retardant EPS

Figs. 18–20 show the temperature development and their comparison using coverings consisting of a single 12.5 mm gypsum layer covering standard EPS insulation (Test 7) and a single 12.5 mm gypsum layer covering fire-retardant EPS (Test 8). In both cases the test duration was 10 min.

Temperature developments during Tests 7 and 8 were very similar. However, the fire test utilizing fire-retardant EPS insulation exhibited a more consistent and lower temperature rise compared to the test performed with standard EPS.

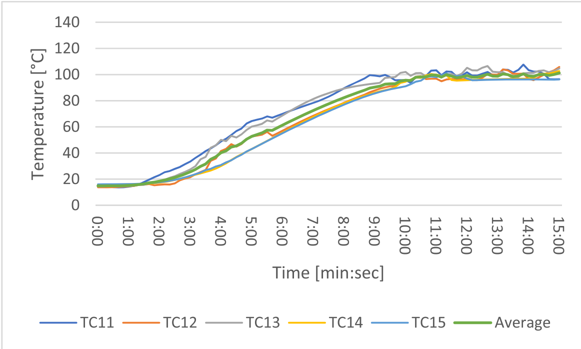

Fig. 16. Test 6 – Two layers of gypsum board. Recorded temperatures for two layers of gypsum board covering.

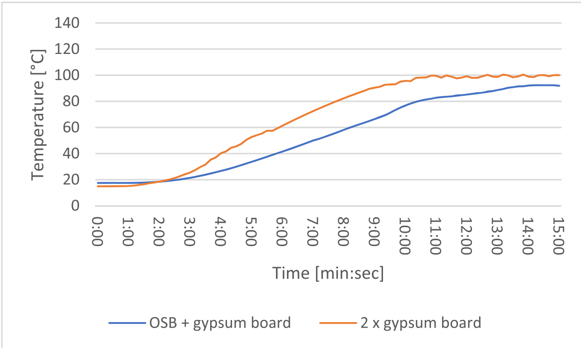

Fig. 17. Comparison of recorded temperatures for Tests 5 and 6. The coverings investigated are described in the text.

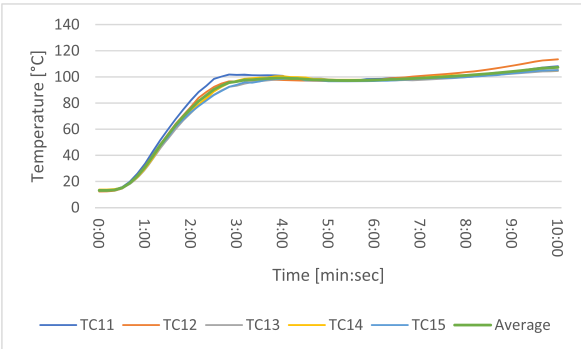

Fig. 18. Test 7 – single gypsum board on standard EPS. Recorded temperatures for a single layer of gypsum covering standard EPS.

3.2. Visual observations of damage to the EPS insulation

Fig. 21 shows the EPS insulation test specimen after Test 1, which lasted for 10 min. In this test, the EPS insulation was protected by a single layer of 12 mm standard chipboard. The visual inspection of the specimen revealed significant damage to the EPS insulation: The covering joint was completely burned through, exposing the underlying OSB construction, as indicated by the red circle in Fig. 21. Additionally, the upper half of the EPS insulation had considerable damage and melting. In contrast, the damage to the lower half of the EPS specimen was limited to shrinkage in areas where the covering remained intact. Yellow arrows in Fig. 21 highlight local shrinkage observed around the screw holes. The regularly black vertical stripes (example shown by a thick, black arrow in the figure) are binders made of high-density polyethylene (HDPE) and polypropylene (PP) used for screw fastening purposes.

Fig. 22 shows the EPS insulation test specimen following Test 2, which lasted for 10 min. In this test the EPS insulation was protected by a single layer of 11 mm fire-retardant chipboard. Immediate visual inspection carried out after the fire test confirmed that the covering had burned through, resulting in an involvement of the underlying EPS insulation. The damage is evenly distributed across the top and bottom of the specimen. The damage includes melted EPS and charring of the supporting OSB construction as

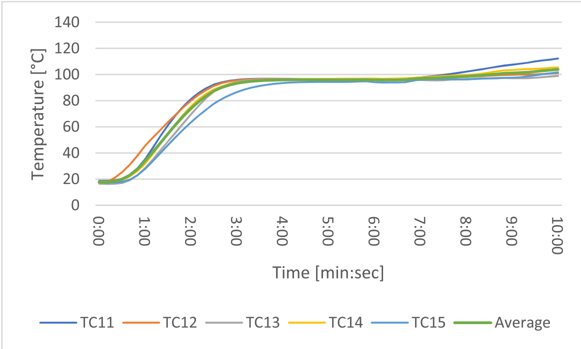

Fig. 19. Test 8 – single gypsum board on fire-retardant EPS. Recorded temperatures for a single layer of gypsum board covering fire-retardant EPS.

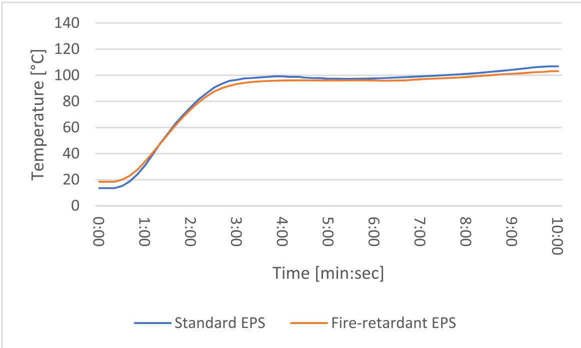

Fig. 20. Comparison of recorded temperatures for Tests 7 (single layer of gypsum covering standard EPS) and 8 (single layer of gypsum covering fire-retardant EPS).

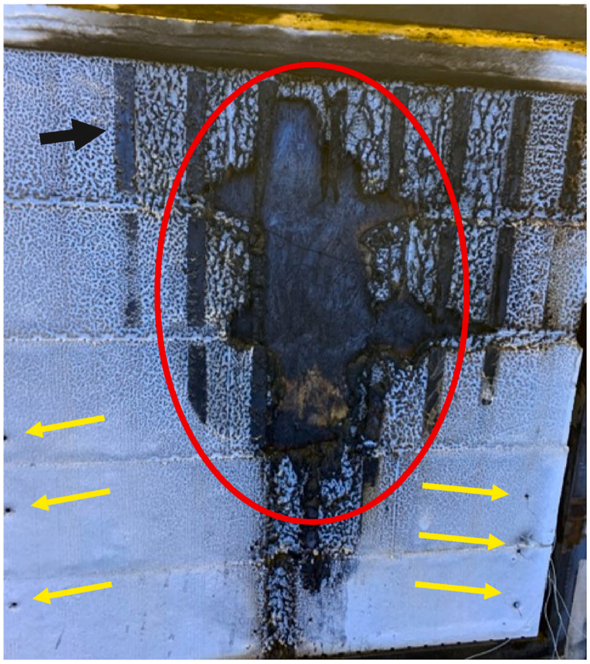

Fig. 21. Damage to the EPS insulation following Test 1 (a single layer of standard chipboard, test duration: 10 min).

Fig. 22. Damage to the EPS insulation following Test 2 (a single layer of fire-retardant chipboard, test duration: 10 min).

indicated by the red ovals in Fig. 22. Significant damage is particularly evident in the area of the covering joint, where the effects of the fire are prominent. Furthermore, local melting around the screw holes is observed as denoted by the yellow arrows in Fig. 22.

Fig. 23 shows the damage observed in the EPS insulation protected by a single layer of 12.5 mm standard gypsum board after a 15-min fire test (Test 3). The upper part of the specimen exhibits moderate levels of shrinkage and damage, with notable effects in the joint area, as indicated by the red oval in the figure. The lower part of the specimen exhibits less visual damage but does show signs of shrinkage, especially in the transition between EPS blocks, as indicated by a yellow arrow. Furthermore, local melting around the

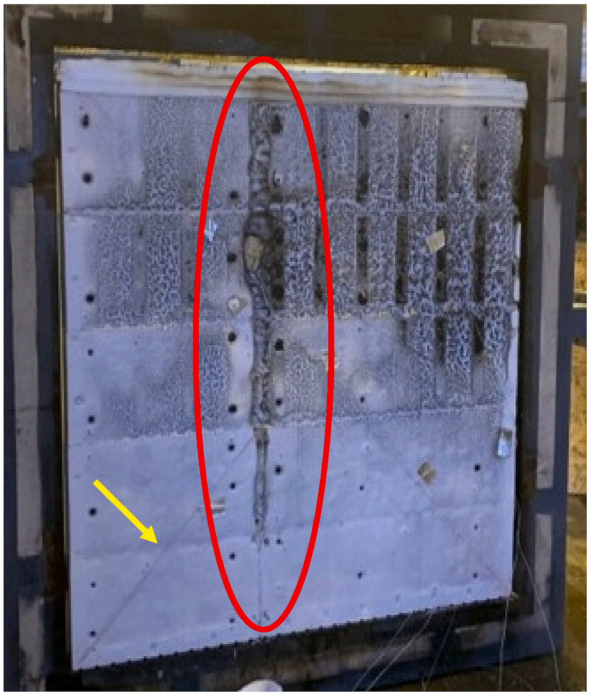

Fig. 23. Damage to the EPS insulation following Test 3 (a single layer of standard gypsum board, test duration: 15 min).

screw holes is clearly visible in the figure.

The results from Test 4, during which the EPS insulation was covered by a single layer of 12 mm gypsum fibre board, are presented in Fig. 24. The damage inflicted to the EPS material is comparatively less and more evenly distributed than in Test 3. The EPS material was primarily affected by melting rather than other forms of damage. Weak areas are apparent in the board joints, and Fig. 24 shows significant damage throughout the EPS material, especially in two of the joints. This is identified by the red ovals in the figure. Local melting around screw holes is also observed, as highlighted by the yellow arrows.

The results from Tests 5 and 6, which involved covering the EPS insulation with two protective layers with a total thickness of 24.5 mm and 25 mm respectively, are shown in Figs. 25 and 26. The visual observations correlate well with the recorded temperatures shown in Figs. 15–17. There are no signs of shrinkage, melting, charring or surface damage to the EPS insulation surface after the 15-min test. However, localized melting was observed around the screw holes, despite the relatively low surface temperatures of the EPS. The screw holes are marked with red arrows in Fig. 25 and are clearly visible in Fig. 26. This suggests that the fastening screws posess a relatively high thermal conductivity, and that the use of screws with lower thermal conductivity or other types of fastening mechanism should be considered in future fire tests.

The results from Tests 7 and 8, which involved covering standard EPS insulation and fire-retardant EPS insulation with one protective layer of 12.5 mm gypsum board, are presented in Figs. 27 and 28. The visual observations align well with the recorded temperatures shown in Figs. 18–20, indicating a stabilization of the temperature at approximately 95 °C after about 3 min, and maintaining a stable temperature of 100 °C throughout the test duration. The visual damages observed in both fire tests are similar, but the fire test involving fire-retardant EPS insulation exhibited more surface charring compared to Test 7 involving standard EPS. Both fire tests showed evidence of shrinking in the EPS insulation, especially in the transition between the EPS blocks. The simulated mechanical damage in the form of a 28 mm diameter hole in test 7 (standard EPS) and test 8 (fire retarded EPS) resulted in a damage of about 90 mm and 75 mm, respectively, as shown in Figs. 29 and 30. Weak spots were identified at the joints and screw holes in both fire tests, the spots are clearly visible in Figs. 27 and 28.

3.3. Summary of test results

The results obtained in the present study are summarized in Table 3.

4. Discussion

The objective of the present study was to investigate and compare the fire protection properties of selected board coverings for fire protection of EPS insulation used in inner walls. The test setup involved vertical orientation of test samples in a furnace, simulating a realistic room fire scenario as outlined in EN 14135 [16]. This setup allowed for consistent testing conditions, including the same fire load and exposure to a standardized fire curve. The study maintained uniform protocols for temperature measurements and visual

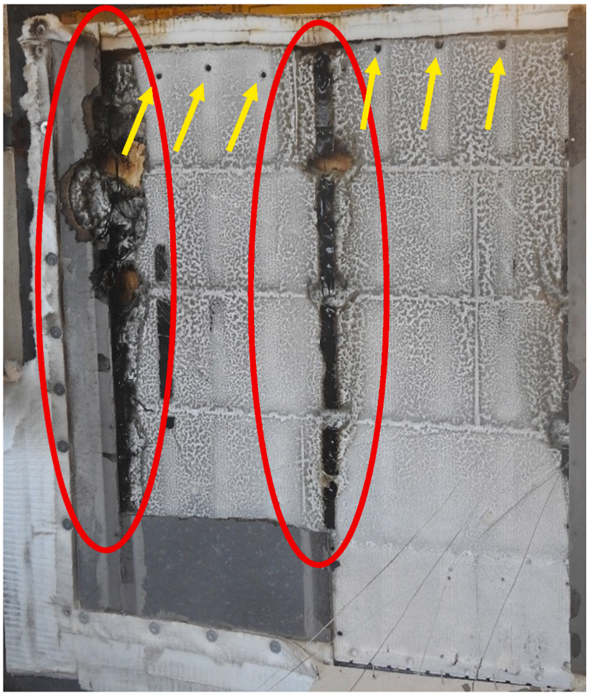

Fig. 24. Damage to EPS insulation following Test 4 (a single layer of gypsum fibre board, test duration: 15 min).

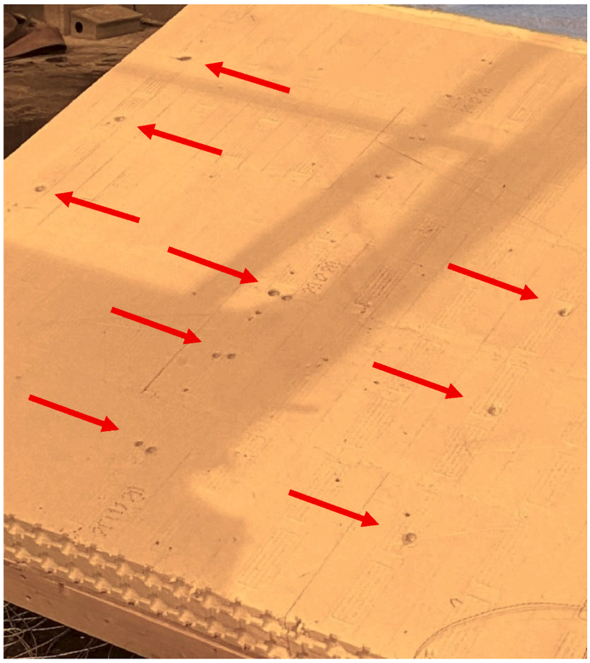

Fig. 25. Damage to the EPS insulation following Test 5 (,a single layer of OSB board and a single layer of gypsum board, test duration: 15 min).

Fig. 26. Damage to the EPS insulation following Test 6 (two layers of standard gypsum board, test duration: 15 min). The lines on the specimen are pencil marks showing the location of the thermocouples.

observations, ensuring reliable data collection and assessments.

4.1. Limitations and product variations

It should be noted that only one fire exposure test for each board material was carried out in this study, which limits the ability to perform statistical analysis on the results. There may be differences in quality within boards from the same manufacturer and between

Fig. 27. Damage to the EPS insulation following Test 7 (a single layer of gypsum board, test duration 10 min).

Fig. 28. Damage to the EPS insulation following Test 8 (fire-retardant EPS covered by a single layer of gypsum board, test duration 10 min).

boards from different manufacturers. Therefore, the results are indicative and specific to the tested boards. However, it is possible to observe correlation between certain fire tests, allowing for some comparative analysis. For example, Test 1 and Test 2 involving chipboards yielded similar results despite differences in board type and make. Similarly, Tests 3, Test 7 and Test 8, all using a single gypsum board, showed similar temperature rise behind the board, as presented in Table 3. This suggests that the fire tests were conducted under comparable conditions across all eight tests, enabling a meaningful comparison of the fire protection ability of the selected boards. The primary objective of Test 7 and Test 8 was to examine the impact of damage and defects on the covering, as well as to assess the differences and extent of damage to the substrate when using standard EPS and fire-retardant EPS. The study of

Fig. 29. Extent of damage to underlying EPS substrate behind 28 mm hole in the covering. Standard EPS substrate experienced an extent of damage of approximately 90 mm.

Fig. 30. Extent of damage to underlying EPS substrate behind 28 mm hole in the covering. Fire-retardant EPS substrate experienced an extent of damage of approximately 75 mm.

temperature development behind the covering was subordinate.

The preliminary fire test conducted on the EPS material revealed changes in the material at a temperature range of 95 °C-100 °C, which differs from the temperature range of approximately 85 °C reported in the literature. It is unclear what exactly causes this variation in temperature range for thermal changes in the EPS structure. It is possible that differences between EPS manufacturers or variations in the product recipe contribute to these discrepancies.

The fire tests in the indicative fire test furnace were carried out using vertical test specimens with height x width of 1.55 × 1.55 m. For the purpose of classification of fire protection ability for coverings, further testing on a larger test specimen in a horizontal furnace in accordance with EN 14135 [22] is required. Classification according to this standard is required for product documentation. Thus, test results in the present study cannot be used as a basis for classification and certification.

Table 3
Summary of intermediate-scale fire test results.

Test no.	Fire protective covering	Number of board layers	Duration of fire test [min]	Time taken to reach 95 °C EPS surface temperature [min:sec]	Visual damage on EPS surface
1	12 mm Chipboard	1	10	04:40	Distinct paths of flowed material; EPS melted away and underlying OSB board is charred.
2	11 mm Fire-retardant chipboard	1	10	04:15	Considerable damage and melting down to underlying OSB board.
3	12.5 mm Gypsum board	1	15	03:10	Shrunken and melted EPS down to underlying OSB board; distinct paths of flowed material.
4	12 mm Gypsum fibre board	1	15	09:30[a]	Considerable melting; distinct paths of flowed material on plain surface. EPS melted down to underlying OSB board in joint areas.
5	12 mm OSB +12.5 mm gypsum board	2	15	Not reached	None on plain surface, local melting around screw holes.
6	12.5 mm gypsum board +12.5 mm gypsum board	2	15	09:50	None on plain surface, local melting around screw holes.
7	12.5 mm Gypsum board w/defects	1	10	02:50	Shrunken EPS; no melting on plain surface. Visible melting in joints at the top of the specimen.
8	12.5 mm Gypsum board w/defects, EPS w/ additives	1	10	03:20	Shrunken EPS, especially in the transition between EPS blocks. Limited signs of visible damage; more charred than melted material.

[a] 04:50 if TC15 is left out of the average temperature measurements.

4.2. Fire properties of OSB

The fire tests on two-layer fire protection suggested that Test 5, involving covering the EPS insulation with the combination of a 12 mm OSB board and a 12.5 mm Type A gypsum board (total thickness of 24.5 mm) demonstrated improved outcomes in terms of lower temperatures between the EPS insulation and the covering than Test 6, which involved two layers of 12.5 mm Type A gypsum board (total thickness of 25 mm). In general, gypsum boards classified as A2-s1,d0, indicating superior reaction to fire properties, are expected to provide better fire protection than OSB boards that are classified as D-s2,d0. Products are often evaluated based on reaction to fire properties for the surface. However, when the products are used as fire protection coverings, the reaction to fire properties should be considered on a material level.

The results from the fire tests show that OSB boards perform better as the inner layer of a protective covering, leading to a slower temperature rise between the EPS substrate and the covering. Thermal conductivity is a critical parameter influencing the heat transfer through gypsum, with values ranging from 0.25 W/mK to 0.78 W/mK across temperatures from ambient to approximately 220 °C [26]. The particular gypsum board used in the present study exhibited a thermal conductivity of 0.25 W/mK, while literature values for the thermal conductivity of OSB boards are considerably lower, in the range 0.19 W/mK to 0.24 W/mK [27]. The particular OSB board used in the present study had a thermal conductivity of 0.13 W/mK. The lower thermal conductivity implies a reduced rate of heat transfer through the material, supporting our findings that employing an OSB board as the inner protective layer offers enhanced protection to the underlying EPS substrate. It is important to note that OSB boards used as a single layer would result in poorer fire protection properties compared to gypsum boards due to the presence of combustible wooden fibres. Fire resistance calculations, conducted in accordance to EN 1995-1-2 [28] standard, compared two layers of 12.5 mm gypsum boards with a combination of one layer of 12 mm wood based board covered by one layer of 12.5 mm gypsum board [29]. These calculations demonstrated that two layers of gypsum boards offer improved fire protection for structural elements over a period of 30 min. In contrast, the temperature data measured in the present study indicated a slower temperature rise for the fire test including an OSB board protected by a gypsum board. These results suggest that during the initial stages of a fire, where time for evacuation is critical, a 12 mm OSB board protected from direct fire exposure by an outer layer of 12.5 mm gypsum board may sustain its fire protection properties on EPS as a substrate for longer duration compared to the use of two layers of 12.5 mm gypsum board had been used.

4.3. Standard chipboard versus fire-retardant chipboard

Test 2 yielded a result similar to Test 1, despite that the boards were different in type and make. The fire-retardant chipboard, classified as B-s1, d0 in terms of reaction to fire, exhibited a slower temperature increase during the initial 4 min of the fire test, aligned with its intended enhanced fire-retardant properties. The chipboard used in this fire test consisted of a standard particle board applied with a fire-retardant surface treatment. However, as the board is not a uniformly fire-retarded throughout its cross section, its fire-retardant properties are limited and will only remain effective until the surface treatment is consumed. This is supported by the temperature curve observed in Test 2, as shown in Fig. 10. The curve shows a slower temperature rise during the initial minutes of the fire test, followed by a higher temperature rise compared to the standard particle board. Although reaction to fire properties are typically described in relation to surface requirements in the Norwegian building regulations guidelines [11], it is important to recognize that reaction to fire classification is used to distinguish non-combustible and limited combustible materials from combustible materials on material level. The guidelines may not adequately emphasize this distinction when considering fire protection ability.

The test method used to establish the fire classification of building products, as outlined in the EN 13823:2020 standard [15], utilizes a propane gas burner with an output of 30.7 +- 2.0 kW and a test duration of 20 min. The heat output from the indicative fire resistance test furnace used in the present study was not measured, but it is anticipated to be significantly higher due to the larger scale of these tests. This suggest that the small-scale test method employed for building product fire classification may not sufficiently predict materials behaviour in large scale fires. Additionally, the thermal conductivity and density of the fire-retardant chipboard was 15 % and 20 % higher respectively than that of the standard chipboard (ref. Table 1), implying improved fire resistance properties compared to the standard chipboard.

4.4. Consequences of damages and defects in the protective covering

The results of Tests 7 and 8 showed that when the protective covering remained intact, the EPS insulation experienced local melting only around areas of damage and defects. The extent of damage was lower for the fire-retardant EPS (fire class E) than for the standard EPS (class F) as depicted in Figs. 29 and 30. The fire-retardant EPS used in the fire test contains graphite additives that reduce heat transfer because the graphite expands and forms a layer that can act as a thermal insulated barrier. Fire spread around areas of damage was probably prevented by a lack of oxygen ingress behind the covering. Additionally, the fire-retardant EPS exhibited more charring, and less melting compared to the standard EPS. Previous studies on the impact of rendering on EPS insulation have revealed that defects diminish the fire protection properties of the covering [2,3,19]. However, the results of Tests 7 and 8 suggest that when the covering remains securely attached to a wall, the use of EPS in wall constructions with board coverings is less vulnerable to damage caused by poor installation. The temperature rise was identical for tests with and without intentional damages and this observation indicates that minor damages will only have a local effect due to heat exposure. Hence, the effect on the remaining test specimen is negligible.

The results also indicate that fire-retardant EPS (class E) provides superior protection compared to class F EPS in terms of mitigating the effects of fire when encountering damage and defects to the covering, although the extent of damage observed in both fire tests is considered minimal. The risk and vulnerability analysis from the early stages of the present study [14] takes the results from Tests 7 and 8 into account when evaluating the consequences of poor installation or damage to the covering.

4.5. Thickness and number of layers of fire protective covering

According to the research conducted by Murillo et al. [5], it has been established that using two board layers with a total thickness of 22.5 mm provides significantly better fire resistance compared to a single layer of 10 mm. This finding is supported by the results obtained from the fire test with two layers of covering performed in the present study. Additionally, Uygunoğlu et al. [20] conducted experiments on facades and determined that the thickness of the plaster is a critical factor when determining the fire protection capabilities of the covering, particularly in preventing fire propagation and temperature rise within the EPS. In the present study, the following observations were made during and after the fire tests involving a single layer of covering with a total thickness of 11 mm–12.5 mm:

- burned, charred, melted, and shrunk EPS material behind the joints and under the fire protective covering
- rapid and more extensive smoke production
- more rapid and steeper rise in temperature behind the covering
- local melting around screw holes

A comparison of the results from the present study, involving one single layer of board covering, and the results of studies from two board layers of covering supports the findings reported by Uygunoğlu et al. [20].

4.6. Adequacy of pre-accepted solutions for fire protection of combustible insulation

In Norway, the installing of fire protection covering of combustible insulation typically follows established approaches outlined in national guidelines [30,31]. These guidelines specify that a fire class of $K_2$10 covering is considered acceptable for buildings with a maximum of two or three floors. The Norwegian building regulations also identify fire class $K_2$10 as a pre-accepted solution for the fire protection covering of sandwich elements containing combustible insulation in evacuation routes.

The performance criteria for fire class K_2 as defined in the relevant standard [22], are based on the use of particle board as a substrate. The classification is applicable to all substrates, regardless of density. However, since the performance criteria for fire classes K_1 and K_2 regarding burnt and charred material are the same, it indicated that class K_2 materials are not suitable for covering substrates that are prone to shrinkage or melting when exposed to fire. The results obtained from the fire tests performed in the present study reveal that the EPS substrate behind a single layer of covering show signs of burning, charring, melting, and shrinking after being exposed to a standard ISO 834 fire curve heat exposure for a duration of 10 min. Thus, a single layer of covering is not sufficient to protect the underlying substrate from damage during a fire exposure of 10 min, suggesting that current installation practice of fire protective coverings of combustible insulation in Norway may be inadequate. In comparison, Danish building regulations define the fire class $K_1$10 B-s1, d0 as the pre-accepted solution for the protective covering of combustible insulation [18].

4.7. Test compatibility and need for further testing

The fire tests performed as part of the present study were carried out using an indicative fire resistance test furnace. The results are thus solely indicative and must not be used as a basis for classification. Further testing will be required before such results can be applied to determine classifications according to the NS-EN 13501-2:2016 standard [22]. The fire tests were carried out using a fire load representing a fully developed fire as defined by the cellulosic fire curve specified in the ISO 834 standard. As a result, these findings can be used for evaluations of fire safety design in buildings. In Section 3, a range of thermocouples was employed to document the performance of the test specimens during fire exposure. The recorded temperatures reflect temperature rise in response to fire load and the standard fire curve, thereby enhancing the reliability of the results.

According to the regulations, an internal board covering must provide sufficient protection to the EPS insulation for the required evacuation time of the building and rescue operations. In the case of a four-storey apartment building, the evacuation time may be around 10 min [14]. The results of the present study suggest that two layers of protective covering of the EPS insulation would be required to achieve the required level of protection. However, since the fire tests involve a much smaller area of exposure to fire than the test set-up described in NS-EN 14135:2004 [16], and since the fire tests are performed in vertical orientation and not in horizontal orientation, further testing will be required in order to reach a robust conclusion.

5. Conclusions

The major findings of the present study can be summarized as follows:

1) Fire tests conducted with a single layer of protective covering resulted in reaching critical temperatures within 10 min of fire exposure, causing structural changes in the EPS material due to heat exposure.
2) Fire tests using two layers of covering including an inner 12 mm OSB board layer protected by a 12.5 mm gypsum board, exhibited a slower temperature rise on the EPS surface compared to tests employing two layers of 12.5 mm Type A gypsum board.
3) Fire tests conducted with coverings that had introduced damage and defects showed limited extension of damage around the heat-exposed area during 10 min of fire exposure. The use of fire-retardant EPS substrate with graphite additives led to less melting but more charring, and fewer visible effects of heat exposure on the substrate surface. Both the standard EPS substrate and the fire-retardant EPS substrate experienced a limited extent of damage. These results suggest that the impact of minor physical damage and defects in the covering have a limited impact on the fire safety of the system as long as the covering remains intact.
4) Weaknesses were identified at joints and screw holes in all fire tests. Observations of local shrinkage and melting around the screws indicate the importance of using screws with low thermal conductivity or other suitable fastening mechanisms.

To gain a better understanding of the fire protection properties of selected coverings and their performance on larger wall areas, it is important to conduct future research using standardized full-scale fire tests in accordance with EN 14135 [16]. These standardized tests will provide more comprehensive insights into the fire protection ability of the coverings and their suitability for real-world applications.

Funding

We acknowledge the contributions made by the Research Council of Norway and the company Jackon AS in funding this research as a part of the project "309380 Thermomur construction system. Fire safe and sustainable (2020–2022)". We would like to thank Odne Oksavik and Dr. Petra Rüther from SINTEF for valuable input to the manuscript.

Data availability statement

The authors do not have permission to share data regarding manufacturers or specific product names. Datasets from testing are saved in SINTEF's system for filing data. The data is not publicly available.

CRediT authorship contribution statement

Brynhild Garberg Olsø: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Anne-Marit Haukø:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Birgit Risholt:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

Acknowledgements

This study is a part of the research project "Thermomur construction system. Fire safe and sustainable (2020-2022)" owned by Jackon AS, and is funded by the Research Council of Norway, grant no. 309380. We would like to thank Odne Oksavik and Dr. Petra Rüther from SINTEF for valuable input to the manuscript.

References

[1] N.H. Ramli Sulong, S.A.S. Mustapa, M.K. Abdul Rashid, Application of expanded polystyrene (EPS) in buildings and constructions: a review, J. Polym. Sci. 136 (20) (2019) 47529.

[2] M. Kumm, J. Söderström, A. Lönnermark, EPS insulated facade fires from a fire and rescue perspective, in: Matec WEB of Conference 9, 2013 05003.

[3] M. Hajduković, N. Knez, F. Knez, J. Kolšek, Fire performance of external thermal insulation composite system (ETICS) facades with expanded polystyrene (EPS) insulation and thin rendering, Fire Technol. 53 (1) (2017) 173–209.

[4] Grand View Research, CA USA, "Global Expanded Polystyrene Market Size Report 2021-2028," Grand View Research, CA USA, 2021 available at: https://www.grandviewresearch.com/industry-analysis/expanded-polystyrene-eps-market.

[5] A.M. Murillo, G.V. Abisambra, P.A. Acosta, Q.C. Quesada, B.F. Tutikian, H.Z. Ehrenbring, Comparison of the fire resistance behaviour of structural insulated panels with expanded polystyrene core treated with intumescent coating, Mater. Res. Technol. 12 (2021) 1958–1969.

[6] D. Pereira, A. Gago, J. Proença, T. Morgado, Fire performance of sandwich wall assemblies, Composites, Part B 93 (2016) 123–131.

[7] "EPS material data sheet, Material Data Web," Matweb Material Property Data, [Online]. Available: https://www.matweb.com/search/datasheet.aspx?matguid=5f099f2b5eeb41cba804ca0bc64fa62f&ckck=1. [Accessed 31 March 2022].

[8] Standard Norge, NS-EN 13501-2:2016 Fire Classification of Construction Products and Building Elements. Part 2: Classification Using Data from Fire Resistance Tests, excluding ventilation services, 2016.

[9] K. Livkiss, S. Svensson, B. Husted, P. van Hees, Flame heights and heat transfer in facade system ventilated cavities, Fire Technol. 54 (3) (2018) 689–713.

[10] The Norwegian Directorate for Civil Protection (DSB), Report Regarding the Fire in Hotel Caledonien, Kristiansand 5.9.86 (In Norwegian), DSB, Oslo, 1987.

[11] Norwegian Building Authority, Building Regulations TEK17, Norwegian Building Authority, 2017 [Online]. Available: https://dibk.no/regelverk/byggteknisk-forskrift-tek17/?_t_q=forskrift. Accessed 1o 5 2022.

[12] Norwegian Building Authority, Buildings Regulations (TEK17) with Guidance Document, Norwegian Building Authority, 2017 [Online]. Available: https://dibk.no/regelverk/byggteknisk-forskrift-tek17/. (Accessed 13 June 2022).

[13] The association for European Manufacturers of Expanded Polystyrene (EUMEPS), "What is EPS?," [Online]. Available: https://eumeps.org/what-is-airpop. [Accessed 27 May 2022].

[14] A.-M. Haukø, B.G. Olsø, B. Risholt, Use of EPS Formwork Blocks in 4-storey Apartment Buildings. Risk and Vulnerability Anaysis, Nordic Fire ans Safety Days, Malmø, 2021.

[15] Standard Norge, EN 13823:2020 Reaction to fire tests for building products, in: Building Products Excluding Floorings Exposed to the Thermal Attack by a Single Burning Item, 2020.

[16] Standard Norge, NS-EN 14135:2004 Coverings - Determination of Fire Protection Ability, 2004.

[17] Standard Norge, NS-EN 13501-1 Fire Classification of Construction Products and Building Elements - Part 1: Classification Using Data from Reaction to Fire Tests, Standard Norge, 2018.

[18] Danish Civil Aviation and Railway Authority, Building Regulations, Br18, 2022.

[19] A. Hofmann, S. Kaudelka, S. Hauswaldt, Fire safety of facades with polystyrene foam insulation, Fire Mater. 42 (5) (2018) 466–474.

[20] T. Uygunoğlu, S. Özgüven, M. Çalış, Effect of plaster thickness on performance of external thermal insulation cladding systems (ETICS) in buildings, Construct. Build. Mater. 122 (1) (2016) 496–504.

[21] E. Mikkola, T. Hakkarainen, A. Matala, Fire Safety of EPS insulated facades in residental multi-storey buildings, in: MATEC Web of Conferences, vol. 9, 2013 04002, 2013.

[22] Standard Norge, NS-EN 13501-2:2016 Fire Classification of Construction Products and Building Elements Part 2: Classification Using Data from Fire Resistance Tests, Excluding Ventilation Services, Standard Norge, Oslo, 2020.

[23] Q. Yuan, Z. Liu, K. Zheng, C. Ma, 5.4.3 Oriented strand board, in: Civil Engineering Materials: from Theory to Practice, Elsevier Ltd., Hunan, China, 2021, p. 398.

[24] Standard Norge, ISO 834-1:1999 Fire-resistance Tests — Elements of Building Construction — Part 1: General Requirements, 1999.

[25] Standard Norge, EN 1363-1 Fire Resistance Tests Part 1: General Requirements, Standard Norge, Oslo, 2020.

[26] G. Thomas, Thermal properties of gypsum plasterboard at high temperatures, Fire Mater. 26 (1) (2002) 37–45.

[27] R. Igaz, L. Krišťák, I. Ružiak, M. Gajtanska, M. Kučerka, Thermophysical properties of OSB boards versus equilibrium moisture content, Bioresources 12 (4) (2017) 8106–8118.

[28] Standard Norge, EN 1995-1-2:2004 Eurocode 5: Design of Timber Buildings Part 1-2: General - Structural Fire Design, Standard Norge, Oslo, 2004.

[29] SINTEF, Building Design Sheet 520.322 Fire Resistance for Walls Made of Wood, Concrete and Bricks, SINTEF, Oslo, 2021.

[30] Norwegian Roof Manufacturers Research Group (TPF), TPF Information Sheet Nr. 6: Fire Rated Roof Constructions, 2019 [Internett]. Available: https://tpf.zoom-grafisk.no/files/TPF_nr_6_2019.pdf. (Accessed 20 May 2022).

[31] SINTEF, in: Building Design Sheet 520.339 Use of Combustible Insulation in Buildings, 2021. https://www.byggforsk.no/dokument/3212/bruk_av_brennbar_isolasjon_i_bygninger. (Accessed 20 May 2022).