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ENSURING FIRE SAFETY: COMPLIANCE TESTS FOR THE USE OF POLYSTYRENE FOAM IN FACADES SYSTEMS

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Ensuring fire safety is the most important thing in the construction industry, especially when it comes to facade materials. The inherent flammability of polystyrene foam poses significant safety concerns, especially when integrated into facade systems. Therefore, the main focus is on meeting the strict flammability requirements set for construction products, which are assessed by applying rigorous test procedures.

This study focuses on the fire resistance testing of a facade system using EPS 70 with graphite additives. The system has been evaluated according to the strict DIN 4102-20 standards. Tests were conducted under real-world conditions to gain insight into the performance of the EPS 70 in real-world fire scenarios. Temperature measurements were taken at various points in the facade system, including at least 3.5 meters above the combustion chamber. The results showed that the temperature does not exceed 500 °C, so it is possible to quantify the thermal properties of the material and the ability to prevent the vertical spread of fire. After the tests, detailed post-test inspections were carried out to evaluate the internal flame propagation after removing the top layer of plaster. The study confirms that polystyrene foam EPS 70 with graphite additives meets the fire safety requirements of DIN 4102-20, which suggests that it can be used more widely in building facades to improve fire safety in residential and commercial buildings. The study highlights the importance of adhering to installation standards, emphasizing the need for accurate installation practices. It also encourages the development of new composite materials with similar or improved fire safety properties, laying the foundation for further innovations in fire-resistant materials

Keywords: fire safety, facade systems, building products, polystyrene foam, construction industry, flammability

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1. Introduction

The facade of a building is no longer just its outer shell. It is an essential element of architectural design, environmental responsibility, and resident safety. In today's world, where reducing energy consumption, mitigating environmental impact, and ensuring fire resistance are global concerns, the design and selection of building facade systems have taken on unprecedented importance [1, 2].

This approach to reducing energy consumption has been accelerated by strict EU targets for improving building sustainability and energy efficiency [3].

The pursuit of energy efficiency often conflicts with fire safety requirements. Ensuring fire safety is the most important thing in the construction industry, especially when it comes to facade materials. Polystyrene foam is widely used for insulation due to its affordability, ease of installation and excellent thermal properties. However, its flammability poses significant fire safety concerns and requires strict evaluation and compliance with fire safety standards. In order to solve this problem, innovative methods are being studied to increase the fire resistance of polystyrene foam facades, construction norms and standards are constantly being updated in order to ensure maximum safety.

Tragic incidents such as the Grenfell Tower fire in London, UK [4] and the Lacrosse fire in Melbourne, Australia [5] highlight the serious dangers posed by combustible facade materials. These emphasize the need to consider the reaction of materials to fire when designing facades, especially in high-rise buildings and densely populated areas.

The ultimate goal is to find a delicate balance between the energy-saving benefits of polystyrene foam and the need for fire safety in the design and construction of the facade. Through continuous research, technological innovation and building compliance, the construction industry can integrate polystyrene foam into facade systems to achieve high fire safety standards. This approach aims to create efficient, sustainable and fire-resistant buildings that protect lives and property for future generations.

Therefore, studies that are devoted to determine the flammability of facade systems with EPS while maintaining their energy efficiency are of scientific relevance.

2. Literature review and problem statement

The development of fire-resistant facade systems is vital for reducing fire losses. The components of modern building facades affect not only aesthetics and energy efficiency but also fire safety. Different facade systems have different reactions to fire, which are influenced by the materials used and their configuration, and this impact the overall safety of the building.

Generally, the choice of facade system depends on the building type, climate, design preferences and regulatory requirements. Brick and masonry remain the traditional and widely used choice, especially in regions where durability and fire resistance are paramount. These systems use polystyrene insulation as an insulating material but are highly flammable, so proper installation and the use of fire-resistant underlays and finishes are essential to improve fire performance. Additionally, due to its excellent thermal insulation properties and cost-effectiveness, polystyrene foam is widely used in ventilated facades and exterior insulation and finishing systems (EIFS) [6]. However, the flammability of EPS insulation requires careful consideration of fire safety measures. Still widely used external thermal insulating composite systems (ETICS) are classified as non-flammable. However, some countries suggest installing non-combustible materials such as mineral wool around openings and as horizontal barriers between floors to reduce the spread of fire. After examining four different configurations during the study [7], it was found that the installation of horizontal mineral wool partitions did not significantly improve the average temperature and extent of polystyrene melting, indicating that the fire safety of ETICS was not significantly improved.

In response to these realities, the construction industry is increasingly focusing on compliance testing to assess the fire resistance of facade systems. Regardless of the flammability of the facade system (which may be completely non-combustible), fires can still spread through the facade.

The material chosen for the facade system plays a key role in increasing or decreasing this risk. In work [8] substantiated the importance of quantifying the flammability of different facade systems. It is necessary to understand how the various materials and the whole facade behave in case of fire. Therefore, the quantification of the ability of the facade system to prevent the spread of fire from the outside and the possible speed of fire propagation becomes inevitable in the development of fire safety strategies [9]. Achieving this goal requires data that can be used to quantify fire efficiency [10].

The paper [11, 12] presents a wide range of issues that have been identified between the current alternative assessment methods used by Member States and the fire performance characteristics presented in the BS 8414 series and DIN 4102-20 test methods. The recommendations indicate possible directions for testing facade systems in Europe. Finally, [11] showed an alternative assessment test method which is similar, and in some cases identical to BS 8414 series and DIN 4102-20 test methods.

Research conducted over the last five decades provides different small-scale and large-scale methods that are considered suitable for assessing the flammability of facade systems. Comprehensive flammability testing is essential to fully understand and mitigate risk. This approach has been used in [13] and presents the provides results from studies based on empirical analysis and controlled conditions, providing significant insights into the behavior of materials present in facade systems in fire-related scenarios. Tests were conducted to determine the influence of EPS foam with graphite additives on the flammability of the facade system. The study results indicated that the spread of fire in the facade system depends on the heating material, the flammability characteristics of the facade finishing material and the proper installation of the facade system.

To ensure the suitability of polystyrene, it is important to conduct flammability tests on various scales. An assessment described in articles [14, 15] involved testing facade systems using thermoplastic foam polystyrene (EPS) of various thicknesses and conducting flammability tests on different scales. The studies show that the outer layer of the facade is damaged first, affecting the spread of the flame. It should be noted that the orientation of the sample is also an important factor, as EPS may melt and leak during heating, which may impact the burning rate of the EPS melt. In addition, the masonry coating was found to limit the flow of the EPS melt, while the non-combustible stone wool barrier reduced the vertical flame propagation speed. However, these tests did not consider the combustibility class of the materials used in the facade systems. In addition, the study [16] tested facade systems with combustible and non-combustible insulation materials. The findings indicated that the flammability of the outer layer of the facade system has a significant impact on the overall flammability of the wall system. It was observed that the flammability of the insulating materials is affected only when the outer layer of the facade system is damaged, leading to the spread of the flame. The damage to the outer layer of the facade system can cause flames to spread because the materials in the inner layer are flammable. However, the flammability of the outer layer of the facade has not been analyzed. A different study [17] looked into how melt-flowing and melt-dripping behaviors increase the fire hazard in exterior walls. The study focused on a common thermoplastic material used in external insulation – expanded polystyrene (EPS). The experiments concentrated on how flames spread in EPS foam and aimed to enhance fire protection for exteriors. However, the study lacked a more thorough analysis of the flammability properties of EPS.

Numerous researchers have conducted simulations to assess the performance of different facade systems using various standard fire resistance tests. Many large-scale facade fire standard tests have been developed to assess the fire risk of facade systems, but they differ from country to country and their test results are difficult to compare. In a study [18] have been simulated five scenario-based tests of facade fire standards: BS 8414-1 (UK), GB/T 29416 (China), ISO 13785-2, NFPA 285 (USA) and JIS A 1310 (Japan). The simulation examined the heat flux and temperature of the spilt facade fire stream, which controls the ignition and flame propagation of the facade fire. Although equivalent facade fire scenarios for different standard tests have been examined, these are only numerical data that could help improve and optimize facade fire tests in the future. In one more study [19], fire exposure and temperature were simulated using three standard tests. The conclusions indicate that there is a need for a unified standard for fire testing of facade systems in Europe. Additionally, flame propagation properties from facade openings were investigated using five different standardized methods. During the simulation, the heat flux and temperature of the fire flow of the facade were studied, which affect the spread of fire and flame in the facade. Different methods yielded different results and flammability parameters, highlighting the need for flammability studies in real fire conditions and further development and optimization of facade fire tests. Fire modeling of facade systems is important for analyzing different fire scenarios, but it can only be tentatively applied in real situations due to different material characteristics and facade systems, installation, etc.

Therefore, it is crucial to conduct flammability tests on facade systems with known EPS flammability characteristics and proper installation of the facade system under real fire conditions.

3. The aim and objectives of the study

The aim of the study is to determine the flammability properties of the facade system with insulation material EPS 70 polystyrene foam with graphite additives in the event of a natural fire.

To achieve this aim, the following objectives are accomplished:

– conduct flammability tests of the facade system following the standard requirements;

– conduct temperature measurements during testing and analyze the results;

– evaluate the spread of flame through facade systems and assess their structural damage after testing.

4. Materials and methods

4. 1. Object and hypothesis of the study

An object of research is EPS 70 polystyrene foam with a graphite additive behavior in a facade system simulating a real fire scenario as defined by the DIN 4102-20 test methodology.

The main hypothesis of the study is that Lithuanian-manufactured polystyrene foam EPS 70 with additives and installed according to the recommendations of the building regulations valid in Lithuania for insulation of partitions with polystyrene foam will not exceed DIN 4102-20 requirements in terms of temperature, flame spread through the facade and structural changes in the facade system.

Assumptions made in the work are:

– the test conditions, including the installation of a combustion chamber and the use of softwood chips, adequately replicate a real fire scenario to evaluate the fire resistance of the facade;

– the temperatures and fire behavior observed during the test reflect actual conditions that may occur in real building fires;

– the points selected for temperature measurement allow a comprehensive assessment of the effect of fire on the facade system.

Simplifications adopted in the work are:

– the study uses a controlled fire scenario with a specific fuel source (a 25-kilogram softwood chip pile), which may not cover all possible variations in real-world fire conditions and fuel types;

– the test setup uses a specific wall construction (approx. 250 mm thick silicate bricks) which may not represent all building construction types where polystyrene foam facade systems could be applied;

– the dimensions of the combustion chamber are standardized, and the size of the air inlet is chosen freely, which can simplify the complexity of the airflow dynamics and the different flame propagation in the facade system;

– benefits of a specific EPS 70 with graphite additives, which may not be reflected using another type of EPS.

4. 2. Test methodology

The standard DIN 4102-20 [20] developed by the German Standardization Institute was chosen for the tests. This standard is intended to assess the effect of fire on exterior wall finishes. It strictly evaluates the reaction of building materials to fire, including their flammability, flame spread, heat release and smoke generation. These assessments help to make informed decisions about construction projects.

Compliance with DIN 4102-20, as an international standard benchmark, ensures the reliability of fire safety assessments, promotes resilience and protects lives and property from fire hazards.

4. 3. Natural fire exposure test for facade

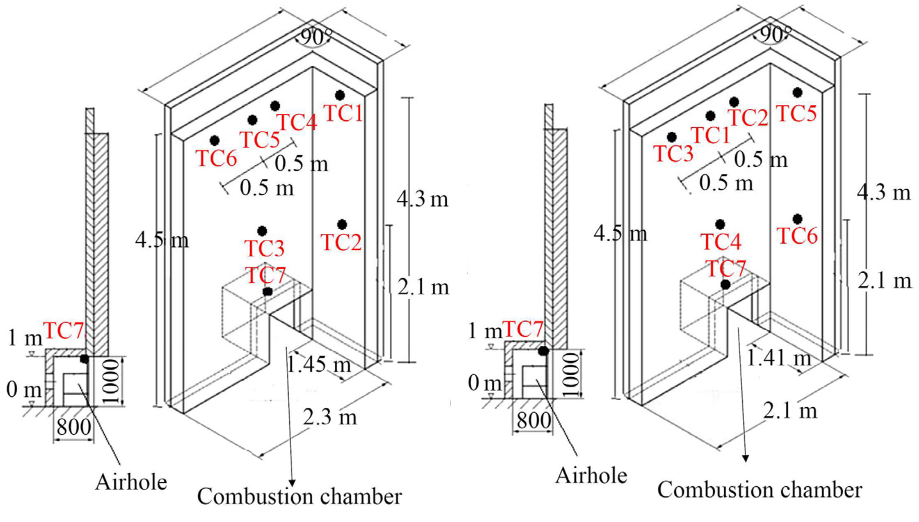
This test methodology aims to replicate real-world conditions as closely as possible to simulate a fire scenario. A fragment of the existing building was used for the test stand. The walls of the existing building were made of silicate bricks, and the thickness of the walls was about 250 mm. The test of the effect of fire on the facade system was performed on the surface of the test bench, by installing the insolation system and temperature measuring devices at selected points. The lower part of the wall contained a combustion chamber of approximately 1 m^3 volume, which simulated a room fire. Flames from the chamber opening were directed at the facade to study their effect. The combustion chamber had a 350×200 mm air inlet to enhance the air supply to the fire source and increase the combustion temperature. To simulate a fire, a 25-kilogram pile of coniferous wood shavings was used.

4. 4. Temperature measurements

The measurements were conducted in the laboratory of the Product Research Department at the Fire Research Centre. Type K thermocouples were used for temperature measurements, and the data was processed and recorded during the test using a Eurotherm 6180A recorder.

The temperature of the samples was measured according to DIN 4102-20 [20] during the test. Thermocouples were used to measure the temperature at a height of 3.3 m from the top edge of the hole in the inner layer and the surface layer. A more significant rise in temperature can be attributed to the spread of the flame inside the structure. The test method recommends measuring the temperature in the outer layer and inner layer of the specimen at a height of 1.0 m from the upper edge of the opening in addition to the existing measurements.

The behavior of the structure during a fire was observed during the test. It is important to note the appearance of flames, deformations, falling of broken particles, dripping of molten materials, and other relevant factors. Video equipment was used to record the test so that all observations could be evaluated in more detail. Thermocouples were installed in the layers of the specimen during the facade system installation work. The locations, markings, dimensions, and positions of the thermocouples in the samples are detailed in Fig. 1.



a *b*

Fig. 1. Thermocouple placement for samples: *a* – sample No. 1; *b* – sample No. 2

Sample No. 1:

– thermocouples TC1, TC4, TC5, TC6 are inserted on the surface of the sample, under the finishing layer of decorative plaster, at a height of 3.3 m above the roof of the combustion chamber;

– thermocouples TC2 and TC3 are located at a height of 1.1 m above the top of the combustion chamber;

– thermocouple TC7 is installed in the combustion chamber, at the upper edge of the opening.

Sample No. 2:

– thermocouples TC1, TC2, TC3, TC5 are inserted on the surface of the sample, under the finishing layer of decorative plaster, at a height of 3.3 m above the roof of the combustion chamber;

– thermocouples TC4 and TC6 are located at a height of 1.1 m above the top of the combustion chamber;

– thermocouple TC7 is installed in the combustion chamber, at the upper edge of the opening.

4. 5. Test preparation

Two samples were prepared to test the fire resistance of the facade decoration. The samples were installed according to the requirements and recommendations of DIN 4102-20 [20], which pertains to the response of building materials and structural elements to fire, specifically focusing on the effect of fire on exterior wall decoration.

For the tests, EPS 70 type polystyrene foam with a graphite additive (grey) was used. The polystyrene foam is manufactured by UAB "Šilputa", and 100 mm thick panels were installed. The nominal density of the polystyrene foam used is 14 kg/m^3.

The polystyrene foam panels were glued to the masonry wall with cement adhesive Capatect Damkleber CT185 (gypsum mixture). The yield of glue is about 4.0–5.0 kg/m^2. The gluing was carried out by the recommendations of the construction regulation in force in Lithuania ST 2124555837.01:2013 "Insulation of partitions with polystyrene foam" (Fig. 2). Declared glue combustibility class A2-s1, d0.

The polystyrene foam panels were additionally fastened with studs. Studs "EJOT exotherm STRU 2 G" were used, and their density is 4 pcs/m^2. Also, the polystyrene foam panels were covered with Capatect reinforcing compound 186M using a glass fabric mesh Capatect Gewebe 650. The area weight of the glass fabric mesh is about 165 g/m^2. The yield of the reinforcement mixture is about 9 kg/m^2, declared flammability A2-s1, d0. The reinforcement mixture was coated with Capatect AmphiSilan Fassadenputz K20 ready-to-use silicone textured plaster (according to EN 15824) with organic binders. The yield of facade plaster is about 2.2–2.4 kg/m^2. Declared decorative plaster combustibility class A2-s1, d0. The total thickness of the plaster is 3–4 mm. The components of the facade insolation system are detailed in Fig. 3.

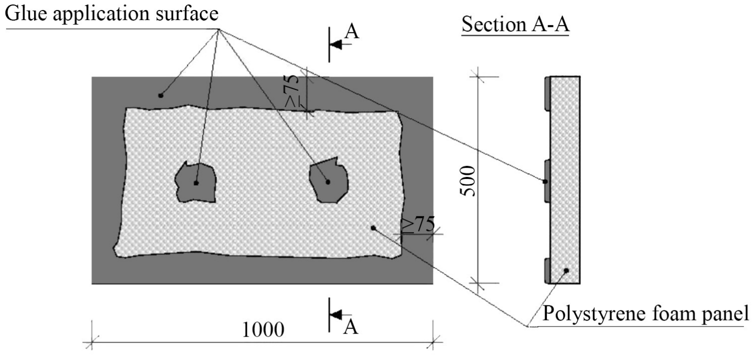


Fig. 2. Insulation board gluing scheme

Sample No. 1. Polystyrene foam panels of UAB "Šilputa" used in the first sample were glued by applying glue with a spatula on the edges and points in the center of the panel, the plastic studs were not deepened. In the upper window, the bottom edge of the polystyrene foam was additionally protected with solid 20 mm thick mineral wool (the second sample was prepared without the additional protection of the bottom edge of the polystyrene foam with mineral wool). The edges of the openings in the upper window and on the sides were protected with Capatect reinforcement mixture 186M and Capatect AmphiSilan Fassadenputz K20 facade plaster about 3–4 mm thick. The unit of the insolation system in the upper window is detailed in Fig. 4.

Sample No. 2. The polystyrene foam panels of UAB "Šilputa" used in the second sample were glued by applying glue with a spatula on the edges and points in the centre of the panel, the plastic studs were not deepened. The edges of the openings in the upper window and on the sides were protected with about 3–4 mm thick Capatect reinforcement mixture 186M and Capatect AmphiSilan Fassadenputz K20 facade plaster (in the first sample in the upper window, the polystyrene foam edge was additionally protected from the bottom with solid 20 mm thick mineral wool). The insolation system unit in the upper window is detailed in Fig. 4, *b*.

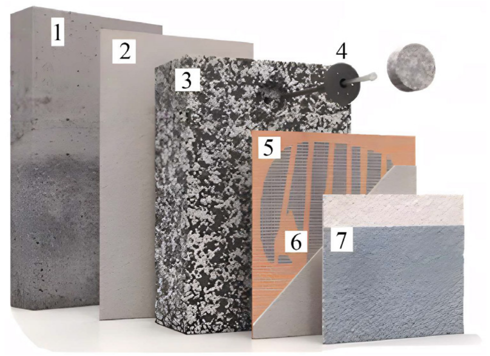
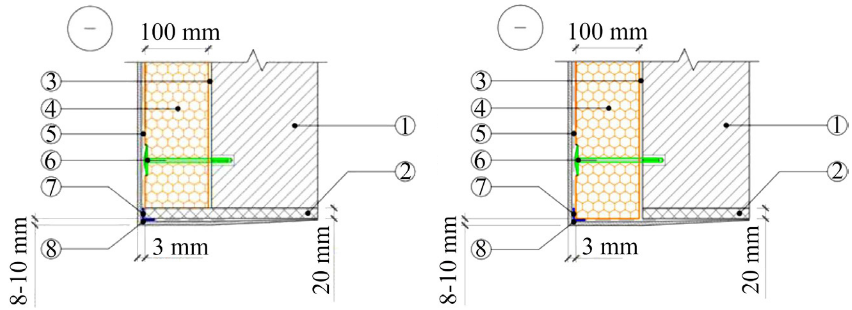


Fig. 3. Facade insulation system components: 1 — the foundation of masonry; 2 — glue Capatect Damkleber CT185, yield about 5 kg/m^2; 3 — grey polystyrene foam EPS 70, thickness 100 mm, density 14 kg/m^2; 4 — plastic studs EJOT ejotherm STRU 2 G, yield 4 pcs/m^2; 5 — fibreglass mesh Capatect Gewebe 650/110, area weight about 165 g m^2; 6 — mineral reinforcement plaster 186M, yield about 9 kg/m^2; 7 — decorative plaster Capatect AmphiSilan Fassadenputz K20, yield about 2,4 kg/m^2



a *b*

Fig. 4. The unit of the insolation system: *a* — wall insulation at the top of the opening of sample No. 1: 1 — Masonry foundation; 2 — Mineral wool; 3 — Cement adhesive, Capatect Dammkleber CT185, yield about 4.0–5.0 kg/m^2; 4 — Grey polystyrene foam EPS 70, thickness 100 mm, density 14 kg/m^3; 5 — Glass fabric grid Capatect Gewebe 650/110, area mass about 165 g/m^2; 6 — Plastic stud, EJOT exotherm STRU 2 G, density 4 pcs/m^2; 7 — Corner profile; 8 — Capatect reinforcement mixture 186M, yield about 9 kg/m^2 and Capatect AmphiSilan Fassadenputz K20 facade plaster, yield about 2.2–2.4 kg/m^2; *b* — wall insulation at the top of the opening of sample No. 2: 1 — Masonry foundation; 2 — Mineral wool; 3 — Cement adhesive, Capatect Dammkleber CT185, yield about 4.0–5.0 kg/m^2; 4 — Grey polystyrene foam EPS 70, thickness 100 mm, density 14 kg/m^3; 5 — Glass fabric grid Capatect Gewebe 650/110, area mass about 165 g/m^2; 6 — Plastic stud, EJOT exotherm STRU 2 G, density 4 pcs/m^2; 7 — Corner profile; 8 — Capatect reinforcement mixture 186M, yield about 9 kg/m^2 and Capatect AmphiSilan Fassadenputz K20 facade plaster, yield about 2.2–2.4 kg/m^2

5. Results of natural flammability tests of facade systems with polystyrene foam according to DIN 4120-20

5. 1. Results of flammability tests of the facade system

Sample No. 1. At the start of the test, the ambient temperature was +13 °C. Here are some excerpts from the testing process in Fig. 5.

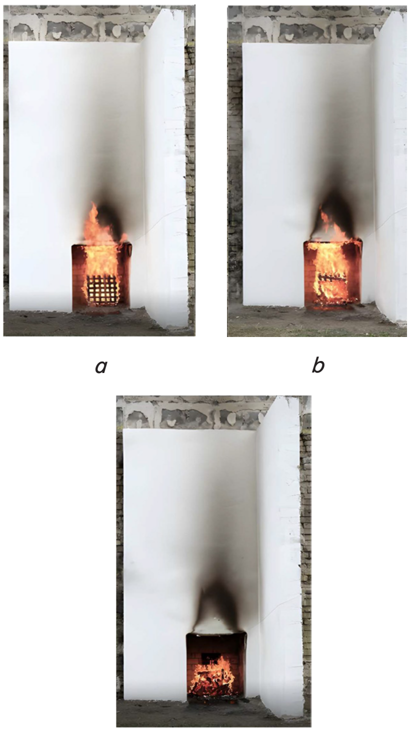
At 09 minutes and 58 seconds, the molten mass of EPS was observed dripping from the roof, onto the ground, through the resulting cavities in the plaster layer. The added melted EPS mass was exposed to a hot flame. After 17 minutes and 49 seconds, flames of melted EPS mass falling from the roof to the ground were observed. At 19 minutes 37 seconds, a tower of burning chips was observed collapsing, and the effect of the flame was decreasing. After 30 minutes and 01 seconds, the extinguishing of smouldering wood stain residues started, and temperature measurements in the facade system continued.

a *b* *c*

Fig. 5. View the progress of the sample No. 1: *a* — image after 09 min 58 s; *b* — image after 17 min 49 s; *c* — image after 19 min 37 s

After removing the effects of smouldering wood stains after 1 hour and continuing the observations, no signs of combustion were detected in the facade system during the 30-minute observation period, and the temperature in the facade system decreased.

Sample No. 2. At the start of the test, the ambient temperature was +13 °C. Here are some excerpts from the testing process in Fig. 6.



a *b*

c

Fig. 6. View the progress of the sample No. 2: *a* — image after 11 min 37 s; *b* — image after 17 min 13 s; *c* — image after 20 min 44 s

At minute 06 minutes and 59 seconds, the molten EPS mass was observed dripping from the roof, onto the ground, through the resulting cavities in the plaster layer. The added melted EPS mass is exposed to a hot flame. After 11 minutes and 37 seconds, the flaming of the melted EPS mass that fell from the roof to the ground was observed. At 17 minutes and 13 seconds, the beginning of the collapse of the tower of burning wooden points was visible, and the effect of the flame was decreasing. When the burning intensity decreased after 18 minutes and 44 seconds, the burning of the facade was visible above the upper edge of the opening. The collapse of the tower of burning wood chips was observed after 20 minutes and 44 seconds, and the effect of the flame was decreased. At 30 minutes and 14 seconds, the extinguishing of smouldering remains of wood chips was started, and temperature measurements in the facade system continued.

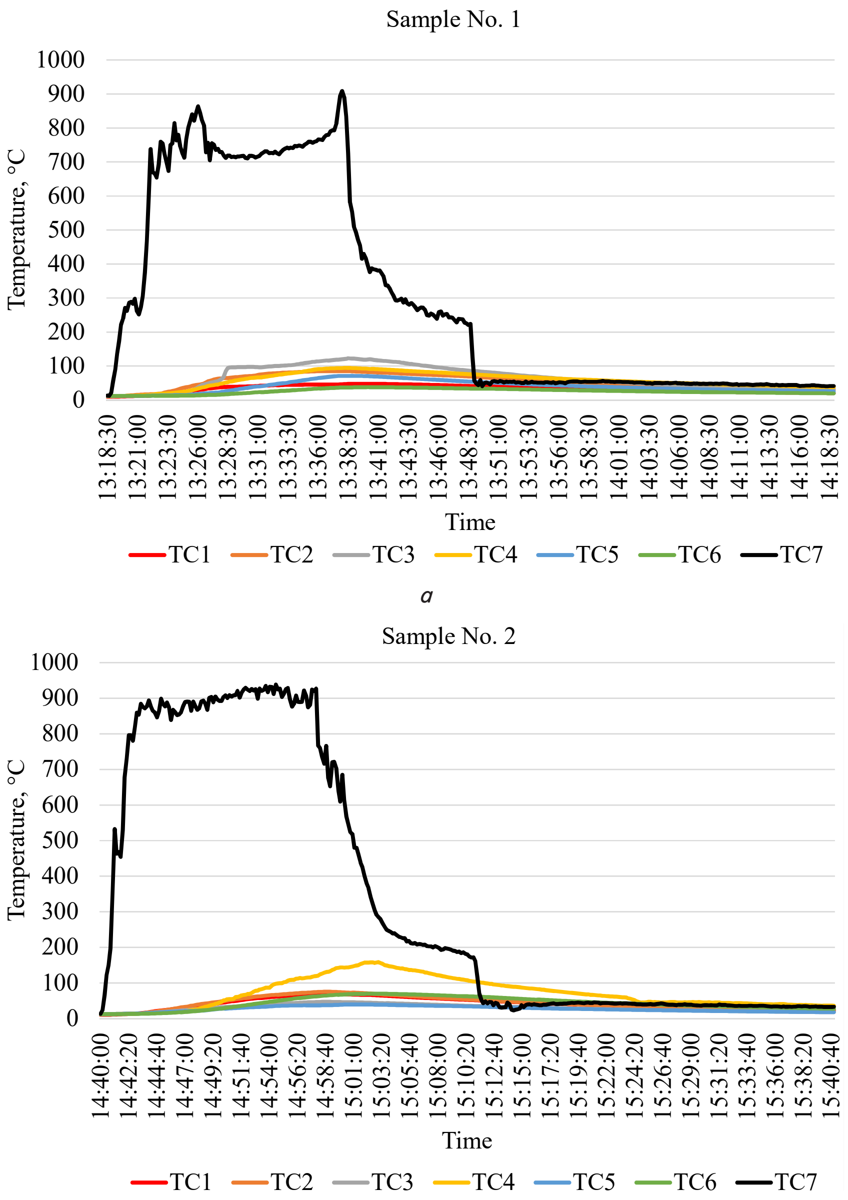
Finally, 1 hour after removing the effect of smouldering wood spots and continuing the observations, during the 30-minute observation period, no signs of combustion were detected in the facade system, and the temperature in the facade system was decreased.

Several visual observations were made during the test. Under the influence of heat from the combustion chamber, the plaster layer at the edges of the openings deformed and crumbled. The polystyrene foam also disintegrated, with molten foam dripping and evaporating through the resulting voids in the plaster. As the heat persisted in these cavities and at the edges of the openings, heated polystyrene foam accumulated, which eventually ignited. After the heat subsided, the flames died down.

5. 2. Results of temperature measurement in samples and analysis of its changes

The curves of sample temperatures over time are shown in Fig. 7.

Sample No. 1 (Fig. 7, *a*). The maximum 122,85 °C temperature of the first sample was recorded after 1220 seconds from the start of the test on the TC3 thermocouple which was on the surface of the sample under a layer of decorative plaster at a height of 1.1 m above the top of the combustion chamber opening. The temperatures recorded by other thermocouples did not exceed 100 °C. The temperature decreased consistently with increasing distance from the combustion chamber. Specifically, the temperatures recorded by thermocouples TC4, TC5, and TC6, located in the main wall 3.3 meters above the top of the combustion chamber, were lower than those recorded by TC3, which was closer to the combustion chamber. In the formed wing, thermocouple TC1, located 4.3 meters above the ground, recorded a lowe temperature compared to thermocouple TC2, which was 1.1 meters above the ground and closer to the combustion chamber.



a

b

Fig. 7. Curves of sample temperature over time: *a* – sample No. 1; *b* – sample No. 2

Sample No. 2 (Fig. 7, *b*). The maximum temperature reached 158.47 °C was recorded at 1380 seconds after the start of the test with the TC4 thermocouple (1.1 m above the top of the combustion chamber). The temperature recorded by the other thermocouples did not reach 100 °C. Depending on the distance of the thermocouples from the perspective of the combustion chamber, the recorded temperature was consistently decreasing. The temperature of thermocouples TC1, TC2, and TC3 located in the main wall (height 3.3 m above the top of the combustion chamber) was lower compared to thermocouple TC4 inserted in the same layer and closer to the combustion chamber.

In the formed wing, the TC5 thermocouple (4.3 m above the ground) had a lower temperature compared to the TC6 thermocouple (1.1 m above the ground) inserted in the same layer and closer to the combustion chamber.

5. 3. Results of flame spread and structural changes in facade systems after testing

The flame spread and structural changes in facade systems after testing are shown in Fig. 8.

Sample No. 1 (Fig. 8, *a*). After conducting the test and demolishing the plaster layer in the area affected by the fire, it was found that the polystyrene foam in the main wall was damaged (collapsed) in the vertical direction at a height of up to 241.0 cm from the edges of the combustion chamber openings, and in the horizontal direction, the affected width was up to 140.0 cm above the combustion chamber to the side of the inner corner of the specimen. In the moulded wing, the affected area of the polystyrene foam was damaged (collapsed) in the vertical direction up to 357.0 cm from the ground, and the affected area in the horizontal direction was up to 99.0 cm from the main wall.

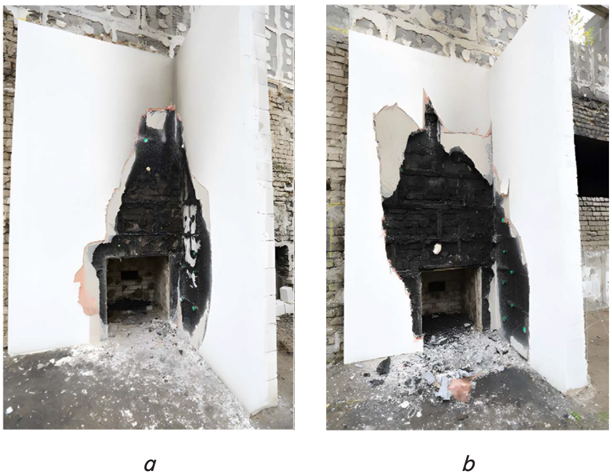


Fig. 8. Image of the samples after the test after breaking off the outer layer of plaster: *a* — sample No. 1; *b* — sample No. 2

Sample No 2 (Fig. 8, *b*). After performing the test and demolishing the plaster layer in the area affected by the fire, it was found that the polystyrene foam in the main wall was damaged (collapsed) in the vertical direction up to a height of 242.0 cm from the edges of the combustion chamber, and the affected width in the horizontal direction up to 190.0 cm above the combustion chamber angle edges. To the side of the inner corner of the specimen in the wider part. In the moulded wing, the area affected by the polystyrene foam was damaged (collapsed) in the vertical direction at a height of 230.0 cm from the ground, and the affected area in the horizontal direction was up to 90.0 cm from the main wall.

6. Discussion of the results of natural flammability tests of facade systems with polystyrene foam according to DIN 4120-20

In this study, the flammability of polystyrene foam used in the facade system was evaluated. It was selected Lithuanian-manufactured polystyrene foam EPS 70, which contains additives that reduce its flammability, for our study. Samples of the facade system (Fig. 2–4) were created according to the recommendations of the building regulations valid in Lithuania for insulation of partitions with polystyrene foam. The results of the tests under real fire conditions corresponded to the evaluation criteria set by the DIN 4102-20, which were applied to the test wall of the main facade system and the formed test wing.

The first task was to assess its flammability. Natural tests were performed as planned to determine whether the chosen insulation material and facade system meet fire safety requirements and whether it is possible to recommend it to architects and designers. The test method was chosen according to DIN 4120-20 [20] to assess the effect of a fire in the room on the facade system. The results of the performed tests showed that the critical indicators of facade damage specified in the standard were not reached. During the flammability tests of the facade systems, it was determined that there was no significant flame spread on the surface of the facade system (Fig. 5, 6).

The thermocouples were placed in the facade system according to DIN 4102-20 [20] requirements (Fig. 1). It should be noted that during natural tests, the air inlet formed in the combustion chamber significantly increased the temperature (in previous tests without additional air supply, the average of the highest temperature reached in the combustion chamber was 823.5 °C, and in this case, with air supply, the temperature in test with sample No. 1 reached 908.68 °C, and in test with sample No. 2 – 934.89 °C (Fig. 7)). This created a greater temperature effect on the formed window edge and the facade insulation layers above the simulated edge. Despite the higher temperature load, the unit of the opening edge remained structurally stable, and the upper silicate layers of the reinforced plaster did not disintegrate and did not expose the internal insulation layer of the insolation system to the direct effect of the flame.

To evaluate the external flame spread, there were no flaming fragments of the specimen at a height of ≥3.5 meters or more above the opening of the combustion chamber, and the temperature of the wall surface at a height of ≥3.3 meters or more above the opening did not exceed 100 degrees °C. Also, there was no continuous flame at ≥3.3 meters or higher for more than 30 seconds.

Regarding internal flame propagation, there was no flaming debris (other than melting or charred elements) ≥3.5 meters or more above the combustion chamber opening. During the test, the fire did not spread to a height of 3.5 meters above the opening, and the polystyrene foam was vertically damaged (melted) up to a height of 193.5 cm (Fig. 8).

When evaluating flaming particles and droplets, the standard requires that falling combustible and non-combustible particles and horizontal flame spread must cease within 90 seconds after the flame source is extinguished. Our tests showed that both burning and non-burning particles stopped falling and horizontal flame spread stopped before the flame source was extinguished.

After conducting tests, it is possible to found that the facade system and polystyrene foam EPS 70 used did not exceed the temperature or damage limits set in the test methodology. The completion of the third and fourth research tasks proved to be worthwhile.

The proven fire resistance of EPS 70 with graphite additives may lead to its wider application in building facades, significantly improving fire safety in residential and commercial buildings. It is important to note that the study was carried out on a newly installed facade system in compliance with the regulations in Lithuania. The specific fire scenario results are based on tests that adhere to DIN 4102-20. Differences in real-world conditions, material quality, and installation practices may affect reproducibility. In practical applications, factors that are beyond control, such as human error and installation mistakes, may occur, and may not be easily reproducible, which can cause potential variations in results. Moreover, different facade configurations, thicknesses of facade systems, and composition of EPS layers can impact the attainment of similar results.

It is necessary to note that this study has limitations of practical application. In particular, the controlled test conditions used, such as using a specific fuel source (softwood chips) and a standardized combustion chamber, may not fully replicate the variety of fire sources and conditions encountered in the real world. Different building materials and structures, in addition to the 250 mm thick silicate bricks used in the test, may react differently to fire, which limits the direct applicability of the results to different types of buildings. In addition, the standardized parameters of the combustion chamber and the dimensions of the air inlet on the chosen vessel simplify fire dynamics and airflow patterns, which do not take into account the complex changes in fire intensity and duration that can occur in a real fire. The controlled test environment also ignores environmental factors such as wind, humidity and temperature fluctuations, which have a significant impact on fire and facade performance.

Limitations for further theoretical studies could also be identified. The specificity of the test parameters, including combustion chamber size, fuel type, and air inlet dimensions, may limit the generalizability of the results, and further studies that consider a wider range of parameters are needed for wider applicability. Theoretical studies often oversimplify the complexities of real fires, such as variable fuel loads, multiple flash points, and unpredictable fire spread patterns, which may lead to an incomplete understanding of the fire performance of facade systems under various conditions. Furthermore, focusing on one type of insulation material (EPS 70 polystyrene foam with additives) does not provide insight into the behavior of other commonly used insulation materials, so comparative studies involving multiple materials are needed for a comprehensive understanding. Finally, scaling the test setup to larger or differently designed buildings is not addressed, and reproducing the exact test conditions in different settings can be problematic, potentially affecting the consistency and reliability of findings across applications.

In this study, some disadvantages were identified. Specifically, due to little attention being paid to reinforcing the edges of the opening niche, which led to faster flame penetration into the facade system interior; the tests were conducted with a low fire load, so results may vary with a higher fire load. Another issue is that the fire resistance of the outer protective plaster should be increased for tests with the outer layer of the facade, which affects the time of flame penetration into the interior of the facade.

In addition, the study did not investigate the performance of the material over an extended period under diverse environmental conditions and mechanical load (e.g., wind load, critical air temperatures, seismic activity), and different fire scenarios. Hence, further analysis is required.

7. Conclusions

1. During the tests according to DIN 4102-20, the outer layer of plaster deformed and crumbled, the mass of dissolved EPS dripped through the formed cavities, which were exposed to the heat of the flame, and gesso as the effect decreased. After 30 minutes from the beginning of the test and after removing the effects of the remains of sparking wood spots and continuing observations, within 30 minutes during the observation period, there were no signs of combustion in the facade system.

2. The temperature changes during the test did not exceed the values set in the standard. Temperature measurements indicated that in all samples, the temperature of the facade system in the outer and inner layers, at least 3.5 meters above the top of the combustion chamber, did not exceed 500 °C. The fire only spread slightly through the facade systems.

3. Based on post-test inspections, it was determined that after a 60-minute test removing the top layer of plaster, the internal flame spread did not reach the limits set by the DIN 4102-20 standard.

The study confirms that EPS 70 with graphite additives in the facade system, installed by the building regulations in force in Lithuania, meets the fire protection requirements. These results are significant for researchers and practitioners.

Conflict of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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