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Effect of Expanded Perlite Aggregate Plaster on the Behavior of High-Temperature Reinforced Concrete Structures

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Abstract: Polyurethane-based materials, which are widely used in exterior cladding, pose a great risk for buildings because they can easily catch fire at temperatures as low as 50–65 °C. Thus, different materials are needed to ensure that structures exposed to high temperatures do not have any stability problems. In this study, expanded perlite aggregate plaster (EPAP) was produced to eliminate the negative effects that may occur in buildings exposed to high temperatures. High temperature tests were carried out on test plates of different thicknesses to determine the effect of plaster thickness under high temperatures. In order to compare the effects of high temperatures, a test sample of normal aggregate plaster (NAP), which is widely used in buildings, was prepared. In the high temperature test, the temperature values on the back surfaces of the EPAP (≈115 °C) test plates were approximately 3 times lower than the temperature values of the NAP (≈350 °C) test plate. It can be said that structural stability loss and durability problems may occur in structures covered with NAP in a high-temperature environment, and that no negative effect will occur in terms of structural stability and durability problems in structures covered with EPAP in high temperature environments.

Keywords: expanded perlite; high temperature; plaster; structure durability; structure stability

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1. Introduction

Concrete has many advantages over other building materials, including high compressive strength, durability, and fire safety. Research is now focusing on optimizing the performance characteristics for a given set of materials, usage, and exposure conditions while meeting cost, service life, and durability requirements. These materials should meet the demand for stronger concrete with better workability, volume stability, and durability. In the existing concrete production, there is a need to use alternative aggregates that should be different from the source and that are environment friendly [1–3]. A performance-based design in reinforced concrete and steel structures is an engineer's duty. However, if there is a standard, it is obligatory to apply the regulation by leaving the authority of the engineer. The design standard guides engineers in sizing, selecting the reinforced bars, and taking action against potential adverse effects. Information in a design standard assists in finding the most suitable solution and in comparing and evaluating alternative materials. In addition to using the existing information for each of the standard reinforced concrete elements and steel structures, the use of the information obtained in practice will be more positive in terms of results. In recent years, with the increase in fires in buildings, engineers have had to consider that fire is an important factor in terms of building safety. As a result, the negative effects that may occur in the load carrying capacity of any building or structural element should be taken into account if it is exposed to fire [4]. Due to the low fire safety of the reinforcements used in reinforced concrete elements, studies should be carried out to further improve the fire safety of reinforced concrete structures. After the 9–11 attack on the World Trade Center, interest in the fire safety of structures increased greatly. In recent

years, fires in buildings have increased and put users at risk. The reason for these fires is that most of the materials used in thermal insulation have low combustion temperatures.

Energy saving has become a necessity worldwide in terms of protecting the environment and natural resources. In the near future, all new buildings will have to be built as zero-energy buildings, and existing buildings will be insulated to a low-energy building standard. New approaches to energy efficient design are not only moving in the direction of lower heat transfer coefficient (U-value) to achieve lower energy consumption, but also towards the development and use of natural and local building materials [5]. With the increase in living standards, more energy consumption has become mandatory in buildings around the world, which is mainly spent on heating and air conditioning. Many applications have been introduced to reduce increasing energy consumption, the most important of which is insulation to minimize heat loss in buildings [6]. In order to minimize heat loss, the insulation properties of the construction materials used in buildings should be improved [7].

In recent times, when materials with suitable insulation values cannot be found in construction materials, the outer surfaces of buildings have been covered with insulation materials with a low thermal conductivity value to provide the necessary insulation environment [5,8,9]. The use of thermal insulation materials in buildings is one method to reduce energy loss throughout the year, which increases the efficiency of cooling and heating systems, which in turn reduces electricity consumption. In addition, it leads to a reduction in the initial installation costs of the cooling and heating equipment [6]. Depending on the situation, thermal insulation in buildings can be carried out in the form of either outer or inner shell applications. External thermal insulation composite systems (ETICS) are preferred in terms of ease of application, low cost and thermal advantage [10].

There is a need to develop and produce an insulating material with suitable mechanical and physical properties for energy saving that is also inexpensive. In general, there are many materials and composites used in building thermal insulation: inorganic materials (e.g., glass, rock, slag wool and ceramic products) and organic materials (e.g., wood, cellulose, cotton, pulp, synthetic fibres, cork, foamed rubber, melamine foam, polystyrene (PS), polyethylene (PE), polyurethane (PU) and other polymers) [11,12].

Expanded polyurethane-based materials are widely used in the thermal insulation industry for many reasons, such as being light, strong and durable, for heat and electrical insulation, safety, design flexibility and ease of production. Despite these properties, polyurethane materials are flammable and continue to burn easily, so they are modified by various techniques to increase their high temperature resistance. The most common technique is to use a composite of polyurethane and flame retardant materials [13]. Polyurethane materials are generally considered optimum for building insulation due to their low density and U-value. This means lighter assembly, thinner walls and therefore less space usage.

In recent years, there has been increasing criticism about certain aspects of standard fire tests [14,15]. Fire resistance is an important element in the design of structural building elements. Although fires are not as frequently encountered as other disasters, the increase in fire incidents in recent years makes high temperature resistance as critical to deal with as other disasters. Fires, throughout the life of structures, are rare but potentially catastrophic events that have serious consequences on properties, such as usage, aesthetics, safety and carrying capacity. Fire scenarios in different parts of buildings should be considered. In general, because it is very difficult to predict where a fire will occur in a structure, the worst case should be taken into account in the fire design of structures [14].

One of the advantages of concrete over other building materials is its high temperature resistance. The presence of steel reinforcement in reinforced concrete structures makes them vulnerable to high temperatures. Therefore, it is important to take this into consideration when designing a reinforced concrete structure. Due to the monolithic nature of reinforced concrete structures, they can carry dead and live loads up to a certain temperature without collapsing, even if there are strength losses that occur in the concrete and steel during high temperatures [15].

The reason for the majority of recent fires in buildings is the use of insulation materials with a low combustion temperatures on the exterior [16]. For this reason, research has focused on insulation materials that have both thermal insulation properties and high temperature resistance.

Until now, thermal insulation has been provided by adding various organic materials such as straw, sawdust, and paddy husk as well as industrial rocks such as perlite and pumice to the plasters. There are studies examining the mixture design, strength, thermal conductivity and high temperature resistance properties of various composite structures using pumice [17,18] and perlite [19–22]. According to the global production forecast for 2019, the world's leading perlite producers were China, Greece, Turkey and the USA, with 47%, 20%, 16% and 13% of world production, respectively [23]. In Turkey, there are large reserves of perlite found as natural aggregate around Erzincan, Nevşehir and Ankara. Perlite is a glassy volcanic rock with rhyolitic composition that can be expanded for the formation of microporous cellular structures and is one of many natural insulation materials [24]. Perlite is an aluminium silicate that contains 72–76% SiO_2, 11–13% Al_2O_3 and 2–5% water. When subjected to 900 °C flame shock, it loses its water and expands up to 7–12 times the grain volume as a result of the explosion, turning into a low-density, porous, light material. This material is called expanded perlite (EP) [25]. EP has many excellent properties such as low thermal conductivity, good chemical stability, non-flammability, non-toxicity and sound absorption [26]. It can be used as an insulator owing to its low thermal conductivity [27].

In the literature, there are many studies on the fire safety of both existing thermal insulation materials and various composite materials that can have different thermal insulation properties with different application methods. Reinforced concrete, called composite material, shows different behaviours at different temperature values. This is because the steel and concrete that comprises reinforced concrete behave differently in the presence of heat. Especially when steel is exposed to high temperatures, there is a great decrease in tensile stress, while a rapid increase in creep value occurs and thus the stability of the reinforced concrete structure deteriorates.

Zhang et al. [28] carried out a comparative laboratory scale experiment to investigate the properties of flame spread on the thermal insulation material extruded polystyrene (XPS) foam. Flame spread pattern and temperature values were recorded during the experiment. It was stated that the material thickness has an effect on the spread of the flame on the material. It has been reported that when the thickness of the XPS insulation board is less than 8 cm, heat dissipation occurs by the conventional method, while in plates thicker than 8 cm it is emitted by the radiation method. Rossi et al. [29] investigated the deformation and smoke formation of expanded polystyrene foam (EPS) insulation boards with and without fire retardant during a fire. According to the test results, the smoke extraction time of the EPS containing fire retardant could be delayed from 47 s to 75 s, without any reduction in the amount of deformation.

Jiang et al. [30] measured the burning length of polyurethane foam and XPS insulation boards by fire test. According to the results, XPS insulation boards burned more than polyurethane foam. For example, when the burn test was applied to 100 mm wide samples, 99.2 mm combustion occurred in the polyurethane foam, while 195 mm combustion occurred in the XPS. Fang et al. [22] used the mortars obtained by using EP as the thermal insulation and protection on various material surfaces. They measured the heat transfer behind the surface and examined the effects of the flame acting on the surface of the coating material. They stated that the heat transfer on the back side of the coating surface was significantly low and visible cracks were formed on the coating surface.

Fu et al. [31] used EP aggregate and calcium chloride hexahydrate ($CaCl_2.6H_2O$/EP composite PCM) in various proportions to form a latent heat storage phase. They determined that the calcium chloride hexahydrate contained in the composite PCM prevents the temperature increase on the opposite surface by retaining the heat.

The numerous small cavities that perlite aggregate contains prevent heat transfer and provide 20 times more thermal insulation of the perlite aggregate concrete compared to normal aggregate concrete [32]. This will enable the safe use of the building after the fire by minimizing the negative effects of the perlite aggregate plasters that may arise from the heat during the fire.

Vaou and Panias [19] produced a thermal insulation material using raw perlite powder by the geopolymerization method. In the study, they created a porous structure by using hydrogen peroxide (H_2O_2), and the effect of the formed pores on the thermal properties was investigated. They stated that the geopolymer foam material formed using raw perlite is more suitable as an insulation material than the geopolymer foam material formed using EP. The thermal conductivity coefficient of the developed thermal insulation material was measured as 0.03 W/mK.

Recently, fire that may occur with the increase in the amount of flammable and combustible materials (natural gas, furniture, carpet, ceiling/wall/floor covering and some exterior/interior insulation materials, etc.) used in homes and workplaces is one of the most important problems of buildings. Although they have a high insulation value, materials such as EPS and XPS are flammable with an increase in temperature. These and other materials have recently been used as insulation in building shells, which are flammable at low temperatures and pose a great risk for building users. These problems demonstrate that insulation materials have fire safety as well as insulation properties. For this reason, using a material with both specific thermal insulation properties and high temperature resistance may be an alternative to using EP. When the properties of EP are examined, it is concluded that insulation materials produced using this material can contribute to both better insulation and high temperature resistance. Previous studies have focussed on the use of EP for insulation purposes. However, no study has been found on how insulation materials produced using EP aggregate will behave at high temperature values. This study was conducted to investigate the high-temperature resistance properties of the insulation plaster produced using EP aggregate, which is produced by Erzincan PERSAN company.

2. Materials and Methods

EP is a high temperature, heat and mechanical resistant material with a porous structure. Perlite has surface absorption and lightweight characteristics due to its porous nature. Perlite's unit weight is influenced by gradation and expansion. Generally, perlite is used in constructions as a plaster owing to its heat and high-temperature resistance properties.

Generally, the materials used in the experiments here can be obtained easily from local and country sources. Erzincan Persan perlite was used in these experiments. Some properties of EP are showed in Table 1.

Table 1. Physical properties of EP (PERSAN) [33].

Physical Properties	
Colour	White
Softening point (ore)	900–1100 °C
Melting point (ore)	1260–1343 °C
Specific heat	0.20 kcal/kg °C
Rough (Expanded) density	80–160 kg/m^3
Thermal conductivity (Expansion)	0.05 W/mK

In order to see the high temperature resistance of the EPAP in the ash furnace (Figure 1), it was kept for 180 min at temperatures of 300, 600, 900 and 1200 °C. These temperatures were reached gradually.



Figure 1. Ash furnace.

In this study, the aim was to examine the effect of plaster on high temperature resistance in reinforced concrete structures. To see this effect, test plates of different thickness were prepared with EP, water, white cement and a chemical material. In order to obtain 1 m^3 of EPAP, 170 kg of EP, 100 kg of white cement, 1.36 kg of a chemical material and 50 kg of water were used. Test plates of 500 × 500 mm size and different thickness (30 mm, 40 mm and 50 mm) were made up.

Temperatures were obtained using K-type thermocouples attached to both sides of the plaster plates. Thermocouples were calibrated by a company according to TS 5154-1 EN 60584-1 standard. A Verth brand CK 104L model four-channel digital thermometer with K-type thermocouple was used as the temperature sensor. At the same time, temperature distribution on the back surface of the test plates was monitored with a Testo 875 thermal camera.

A 12 kg liquefied petroleum gas (LPG) cylinder was used as the flame source. LPG is the general name given to mixtures in certain proportions of butane and propane gases. The LPG used in household cylinders in Turkey consists of 70% butane and 30% propane, which is obtained by refining crude oil in refineries or from natural gas.

During the test (Figure 2), the flame was kept at a constant temperature of 900 °C and at a distance of 3 cm on one side of the plasterboards for 180 min. At the same time, the change of temperature on the back side of the test plates was measured at two points. The temperature readings of the thermocouples were taken at 5 min intervals.



(**a**) (**b**)

Figure 2. Front (**a**) and side (**b**) view of the experimental system.

3. Results and Discussion

In order to see the change of the material with temperature, the material was gradually heated from 0 to 1200 °C in the ash furnace. Sixty minutes after reaching 300, 600, 900 and 1200 °C, the ash furnace was opened and photographs of the test samples were taken, as in Figure 3. No change was observed on the outer surface of the material up to 900 °C. After 900 °C, colour change started in the material. At around 1200 °C, the material started to melt.

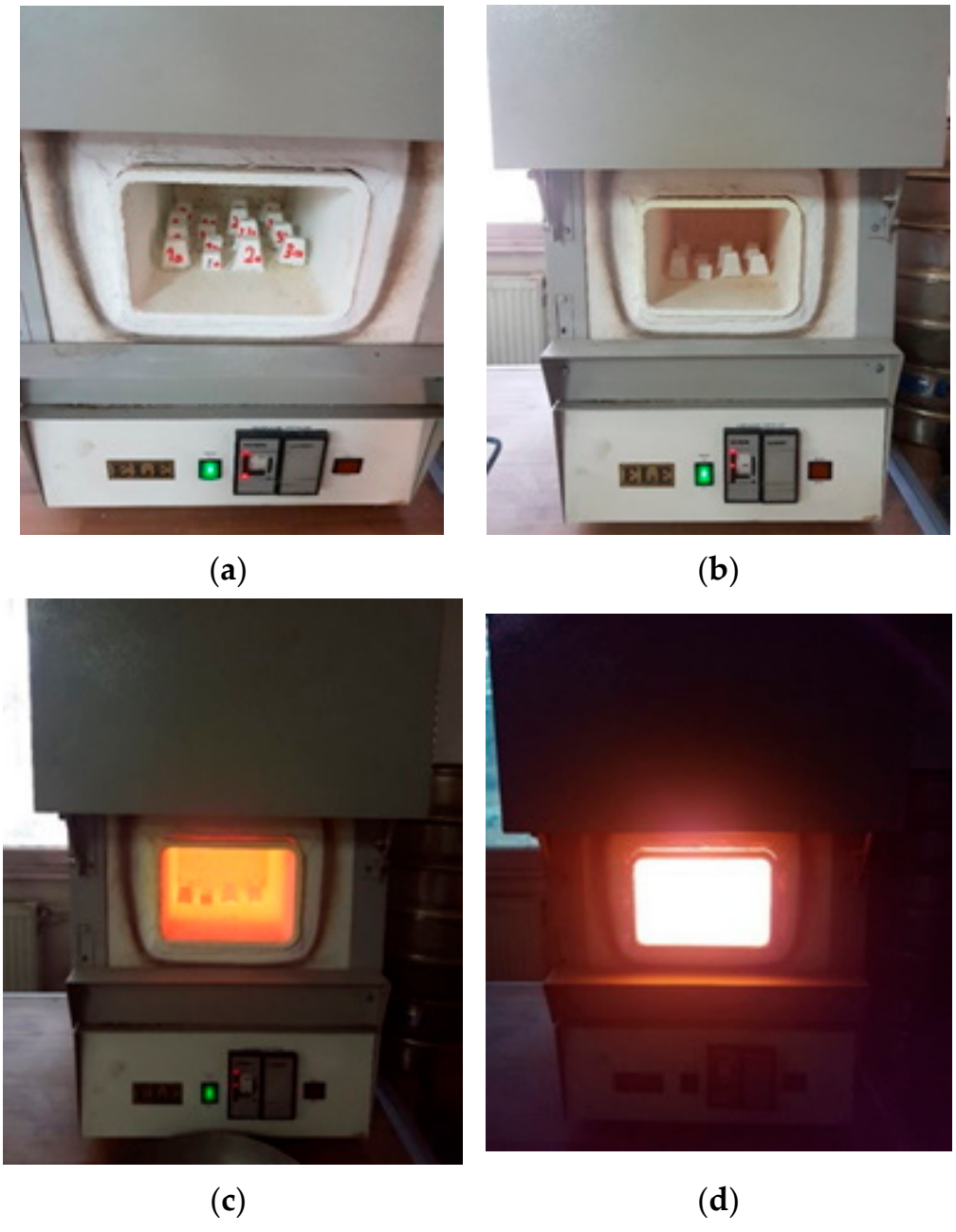


Figure 3. Photos of test samples in the ash furnace (**a**) 300 °C, (**b**) 600 °C, (**c**) 900 °C, (**d**) 1200 °C.

In order to determine the mechanical properties of the plaster, compressive strength tests were performed (Figure 4a) on the test samples (Figure 4b), according to ASTM C39. It was observed that the compressive strengths varied between 4 and 5 MPa. These values are also quite high compared to other insulation materials.



(**a**) (**b**)

Figure 4. Compressive strength tests (**a**), test samples (**b**).

High-Temperature Resistance of EPAP Test Plate

The temperature changes on the back surface of the test plates depending on the plaster thickness can be seen in Figure 5. It can be seen that the temperature change is minimized when the plate thicknesses are similar. The lowest temperature of 126 °C on the back surface was measured on a 5 cm test plate, and the highest temperature of 183 °C was measured on a 3 cm test plate.

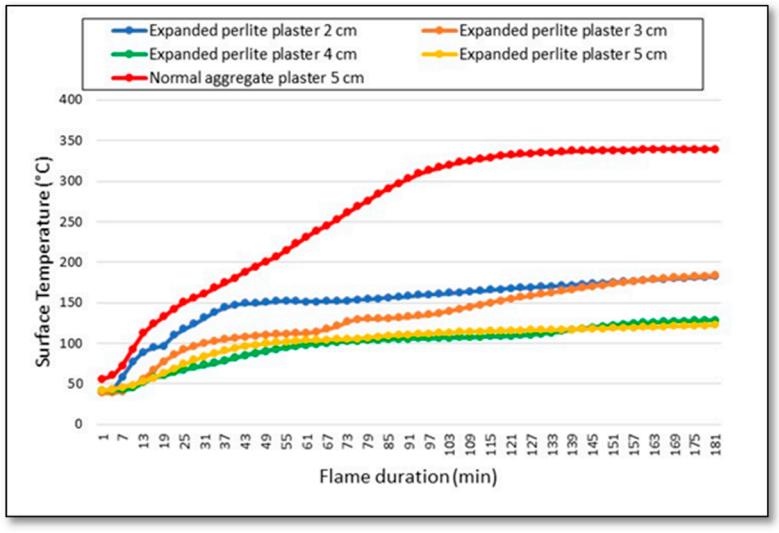


Figure 5. Time-temperature graph of the back surface of test plates.

When the free moisture contained in the concrete mass evaporates, the effect of temperature on concrete typically occurs between 95 °C to 205 °C; immediate exposure can cause spalling by the formation of high internal steam pressure. Dehydration, or the loss of non-evaporable water or water of hydration, begins as the temperature approaches 260 °C. The first significant decrease in compressive strength is usually observed between 205 °C and 400 °C [19]. The measured maximum and minimum temperature (183 and 126 °C) values will not cause any problems in concrete and steel.

In order to control the temperature values measured with the thermocouple on the back surface, the measurements made with the thermal camera were compared. The results were found to be compatible with each other. Both the measured thermocouple values (Figure 5) and thermal camera image show that the heat transfer rate is very fast and high in 5 cm NAP. It is also seen in the thermal camera image in Figure 6 that both the heat transfer rate and the temperature values on the EPAP test plate are lower than the NAP.

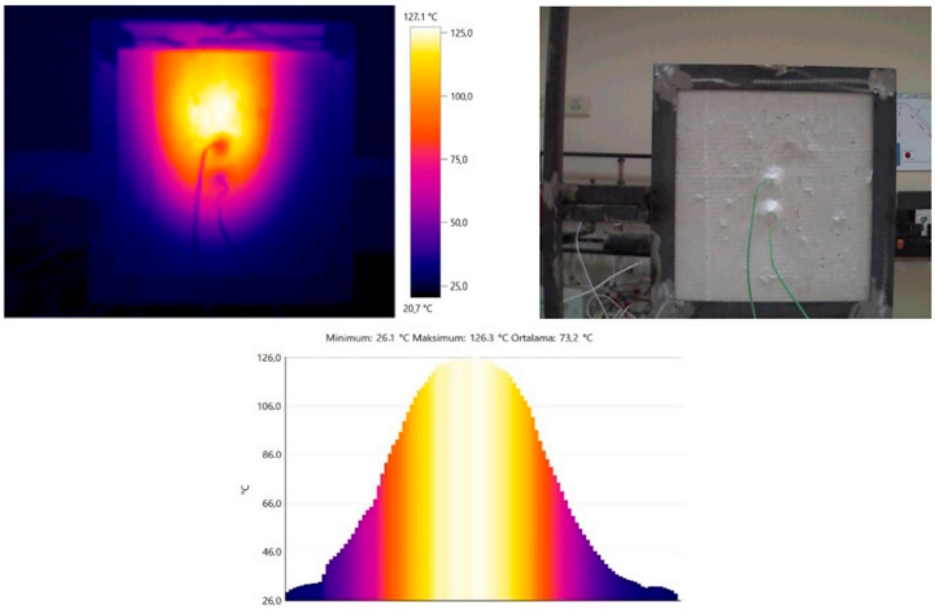


Figure 6. Thermal image of the test plate with 5 cm EPAP after 180 min.

60 min after the start of the experiment, wide cracks were formed in the NAP test plate. After the crack occurred in the NAP test plate, the temperature increase on the back surface continued up to 340 °C. This situation is also seen in Figure 5. When the NAP test plate was exposed to flame for 60 min, it was determined by both thermocouple value and thermal camera images that the temperature value on the back surface exceeds the temperature of 205 °C (Figure 7), which will cause degradation in the concrete [34].

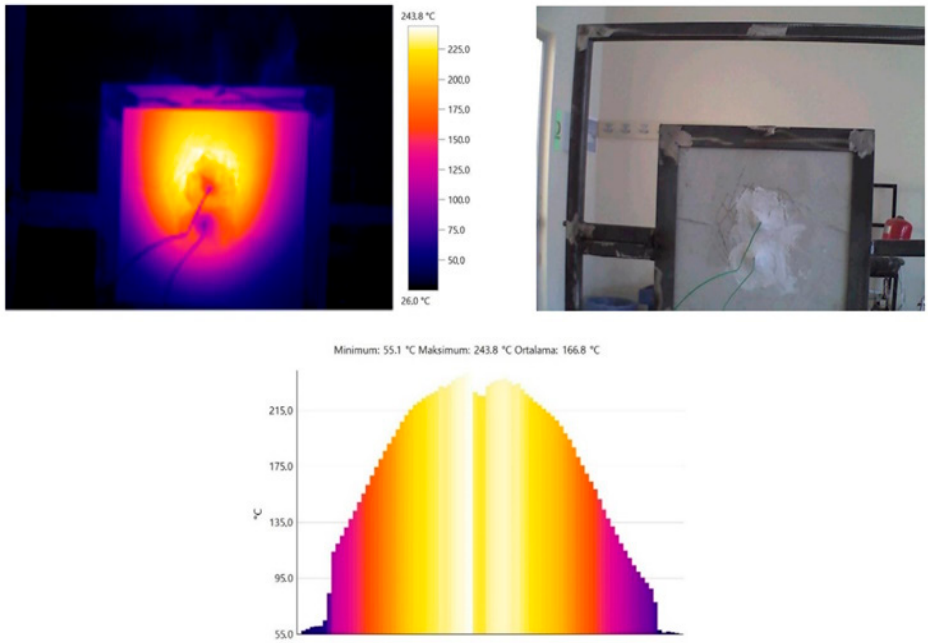


Figure 7. Thermal image of the test plate with 5 cm NAP after 60 min.

Temperature values were measured as being approximately 3 times higher in the NAP test plate compared to the EPAP test plate. These temperature values are above the initial deterioration temperatures for both concrete and steel [34].

At the end of the test, the surfaces of the plaster plates were photographed. As seen in Figure 8, very small visible cracks were formed in the EPAP. While these cracks were

seen on the front face exposed to the flame, no cracks were formed on the back face. Wide cracks were formed on both surfaces as a result of the test on the 5 cm NAP test plate.

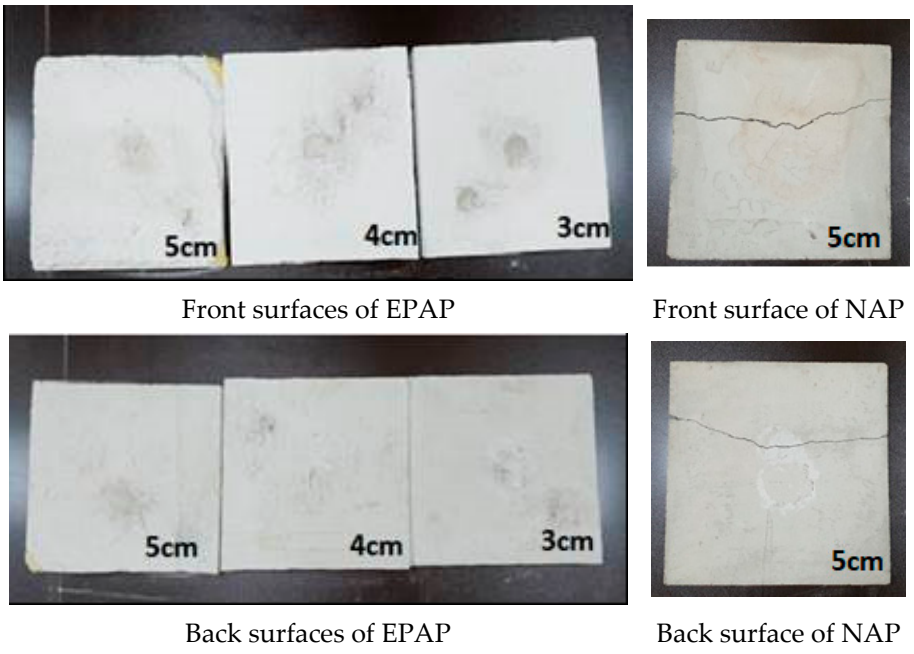


Figure 8. Photographs of the front and back surfaces of the test plasters after the high temperature test.

Because the EP aggregate has a porous structure, the surface distribution of heat conduction is considerably higher than the vertical distribution. For this reason, after 3 h of exposure to flame, very low temperatures were measured on the back surfaces, which would not pose a problem for concrete and steel. Even if the cracks formed as a result of the flame do not reduce the bearing capacity of the reinforced concrete structure or its elements, they may cause major problems in the durability of the structure, because water and deteriorating substances can easily enter the reinforced concrete element through these cracks, causing corrosion of the reinforcement and fragmentation of the concrete.

4. Conclusions

In this study, it was observed that the temperature change as a result of the contact of the plaster with the flame, produced when using EP, was quite low compared to the NAP. The temperature values measured on the back surface of the EPAP and NAP test plates during the experiment were 115 °C and 350 °C, respectively, and were approximately 3 times higher. The main conclusions can be summarized as follows:

- This application is important in terms of ensuring building safety because the temperature values measured on the back surface of the test plaster with EP aggregate did not reach a level that would cause a negative effect on the reinforcement and concrete. In the literature, there are studies that reduce the thermal conductivity value with EP applied in different volumes [35].
- As a result of the experiment (at temperatures above 900 °C), both colour change and cracks with a diameter of 10–15 mm occurred in the area exposed to the flame in the NAP. These cracks reached the back surface, but the colour change is not very obvious. Although there was an inconspicuous colour change and capillary crack formation in the area exposed to the flame in EPEP, no colour change or crack formation was observed on the back surfaces.
- As a result of EPAP's exposure to a flame above 900 °C, no cracks in the plate that would damage the reinforced concrete element were formed. The temperature values measured on the back surface (126–183 °C) as a result of exposure to a flame for three hours are similar to the temperatures measured in other studies [36].

- Water and deteriorating substances can easily enter the reinforced concrete element through cracks formed as a result of the flame, causing corrosion of the reinforcement and fragmentation of the concrete, thus creating a durability problem in reinforced concrete structures. In this context, it is thought that EPAP will give positive results in providing the desired fire resistance and durability.
- In order to prevent the collapse of structures as a result of sudden strength losses that may occur with the heat increase in the reinforcement and concrete during high temperatures, coating the surfaces of the building elements with EPAP could be a solution.
- EPAP could be the material of choice for the stability of structures and structural elements exposed to high temperatures.
- By comparing the experimental data obtained from this study with the results of large-scale EPAP applications to be applied in buildings, future insulation and fire problems in reinforced concrete buildings may be solved.

In future studies, various research can be made on the production of a new plaster that can be used in all kinds of structures by using different materials with high thermal insulation values and fire resistance as a filling material for EPAP.

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