Thermal insulation and mechanical properties of a specially improved insulation plaster under freezing–thawing and high-temperature conditions

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Abstract

In this study, the effects of heat preservation and the resistance to environmental conditions of ready-made insulating sludge used in the interior and exterior facades of the buildings were investigated. The insulation consists of lightweight aggregates, boron and steel fiber. Within the scope of the study, 1 L of water was mixed with 1 kg of insulating fluid as a proportion and a composite material was obtained. Thermal conductivity coefficient, resistance to high temperature, changes in ultrasound speed, resistance to frost and compressive strength tests were compared with respect to normal plaster consumption. At the same time, samples of 15 × 15 × 15 cm cube samples taken from fresh concrete were plated to be 1 and 2 cm on each surface, and the extent to which the mortar retained concrete under environmental conditions was investigated. One of the components of the insulating sludge, lightweight aggregate-derived perlite and pumice, was found to provide heat and sound insulation. The presence of boron in the components increased the binding and did not necessitate the use of cement during mortar. It has been observed that the presence of steel fibers minimizes the cracks in the mortar and increases the resistance of the mixture mortar. The unit weight of the insulation plaster mortar is about 0.5 g/cm^3 owing to the remarkably lower density of light fine particles. Polymer fibers and boron additives yield a notably low thermal conductivity of 0.13 W/mK.

Keywords: ultrasound velocity; high temperature; thermal conductivity; mixture mortar; insulation plaster

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1 INTRODUCTION

Recent global economic crises and the depletion of nonrenewable energy sources have demonstrated the significance of economical energy use. Insulation, the most significant measure for reducing costs and preventing energy losses, has now become a necessity rather than an option [1, 2]. In this sense, domestic heating accounts for the majority of energy consumption. Heating buildings is an expensive endeavor, especially during the winter months. Insulation materials, which are frequently used in buildings, offer benefits in terms of insulation but also have some disadvantages. Although the low thermal insulation coefficient of polymer-based thermal insulation materials is an advantage, their flammability is a disadvantage. One of the most researched topics is the development of insulation materials, particularly cement-binding compounds with high combustion resistance [3–6].

Plaster, which is used to achieve a smooth surface in structures, is a material appropriate for paint and other types of coatings for the cost-effective surfaces of buildings. Plasters made from water, fine sand and cement can be applied in thicknesses ranging from 1 to 8 cm, depending on the smoothness of the floor to be coated. Because cement and lime binders are employed, these

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materials are particularly cost-effective. There are several studies in the literature on the thermal insulation of buildings by reducing the heat transmission coefficient as well as the surface flatness of the plasters. Many different materials, including pumice, perlite, vermiculite, metakaolin, compressed obsidian and polypropylene fiber, are used to lower the heat transmission coefficient of plasters. According to the publications, plasters with thermal conductivity ranging from 1.5 to 0.07 W/mK are developed.

Fenoglio et al. [7] investigated perlite-based insulating plasters in terms of hydrothermal and environmental performance. The thermal conductivity values of the four plaster mixtures ranged between 0.118 and 0.059 W/mK, thus demonstrating that the perlite concentration had a significant impact on the reduction of thermal conductivity and that the embodied energy of the applied material (5 cm thickness) decreased as the perlite content increased. Moreover, the results of the measurements on the demonstration building and the hygrothermal simulations have revealed that the thermal insulating plaster is able to reduce the U value of the wall. However, an increase of 26% to 30% of the actual thermal conductivity should be considered when the material is exposed to real operating conditions.

Davraz et al. [8] examined a new organic-based thermal insulation material. A percentage of perlite and vermiculite of 25% was found to reduce thermal conductivity: 0.23 W/mK for vermiculite and 0.16 W/mK for perlite (from an initial value of 0.50 W/mK). A cement-based plaster, to which perlite and different types of pumice, such as lightweight aggregates (LWAs), polypropylene (PP) fibers, a foaming agent, adhesive polymer and lime, had been added, was investigated. The addition of these LWAs reduced thermal conductivity from an initial value of 0.87 W/mK to a value of about 0.08 W/mK. Perlite led to a greater decrease of λ than pumice, while pumice showed better compressive strength. Other studies focused on mixing mineral aggregates and fibers to improve both the mechanical and the thermal properties. Gencel *et al.* [9] developed a series of specimens made up of gypsum with vermiculite (10–20%) and PP fibers (0.5–1.0%). The results showed that vermiculite and the PP fibers contributed by decreasing the unit weight; vermiculite led to an increment in porosity but also determined a loss of the mechanical resistance; thermal conductivity was found to be influenced by the presence of vermiculite and, to a lesser extent, by PP fibers. A similar plaster, in which PP fibers were added to a mixture of gypsum and diatomite, was also studied [10].

In terms of reducing the amount of heat energy used in buildings and preventing issues brought on by sound insulation, wall components are more crucial than other components [11]. The material to be encased on the walls should have a very low heat transfer coefficient. If the concrete or plaster mortar used in this situation helps with insulation, it does so by using lightweight particles to lower the density and, consequently, the thermal conductivity [12–15]. Even while the plaster insulation mortar used on the outer facades of buildings in cold climate conditions supplies the building's interior thermal insulation, it is crucial for the mortar's durability to be resistant to freezing and thawing. The drawback of lightweight aggregate mortars is their high sensitivity to setting circumstances, which can considerably impact the beginning and spread of cracks [16, 17]. The insulation plaster mortar, which is not frost-resistant, will not be durable since cracks will form over time.

Increasing the resistance of construction elements to high temperatures is another objective. Construction and insulation elements that can survive high temperatures may be created, as can construction and insulation elements that will last long enough to allow for the evacuation of people or products from the building. The aggregate has a significant impact on the high-temperature effects of construction elements [18]. Insulation plaster, one of the insulation elements, must have these qualities and prevent high-temperature damage to constructional components. These factors led to the investigation of insulation plaster to provide heat and sound insulation on building walls.

Rashad [19] carried out a study to investigate whether thermal insulation plaster can be produced from cementitious materials commonly used in practice. During the study, binding was provided with the help of cement or gypsum without using any lightweight aggregate or foamer. Eight different plaster types were developed and their properties, such as thermal conductivity, porosity and compressive strength were compared with traditional cement mortar plaster. According to the results obtained, it is possible to achieve insulation plaster with low thermal conductivity and high pore number without using foamer or light aggregate. Ferrandez et al. [20] conducted a study to analyze plaster mortars produced using waste construction and demolition materials. The mechanical and physical properties of the insulation plaster prepared with three different types of aggregate, and two different types of waste materials were observed. The results obtained from the study showed that the mechanical properties of conventional plasters are lower than plaster mortars produced with waste aggregates. However, as the density of the mortars decreases thanks to the expanded polystyrene residues, their behavior against water absorption is improved and thus the thermal conductivity of the material is reduced.

These studies examine how the plaster's resistance, thermal heat transmission coefficient and water vapor permeability vary. Therefore, the most desired feature of the newly developed plaster is its affordability. The effectiveness of the insulation plaster as a heat and sound insulator, when combined with water and formed into an insulation plaster mortar and applied 1 cm to the inner surfaces of building walls and 2 cm to the exterior surfaces of building walls, was examined. In addition to saving energy, the durability of insulation plaster in buildings under various environmental circumstances was also investigated.

2 MATERIALS AND METHODS

The insulation plaster used in this research contains perlite and pumice-type light fine aggregates, boron minerals and steel fibers. The physical properties of the insulation plaster are shown in Table 1. The methylene blue test was performed on the insulation plaster, and Table 1 shows that it does not contain clay-type fine

Table 1. *The physical properties of the insulation plaster*

Material	Relative density (g/cm^3)	Water absorption (%)	Fine material ratio (%)	Fineness module	Methylene blue	Frost resistance determination using a chemical method (with sodium sulphate) (%)
Insulation plaster	1.20	28.8	14.5	1.9	0.3	1.3

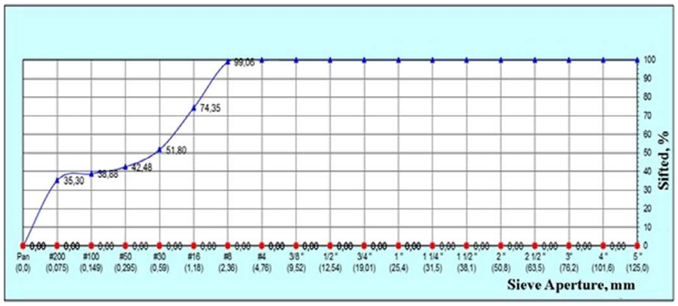


Figure 1. *Particle size distribution of insulation plaster.*

material and is stone flour. Figure 1 depicts the particle size distribution of the insulation plaster with a maximum diameter of 2.36 mm.

For the mortar mixture, 1 kg of insulation plaster was added to 1 liter of water and mixed. The mixing time was approximately 5 minutes and continued until it became thick. 5 × 5 × 5 cm cube samples were taken from the mortar mixture and high-temperature resistance, ultrasound velocity (USH) and frost resistance tests were performed. The thermal conductivity coefficient was measured from the plaster mortar. Comparisons of insulation plaster mortar and normal mortars at the desired standards were made on the tests. One- and 2-cm coating on each surface of 15 × 15 × 15 cm cube samples taken from fresh concrete, high-temperature resistance, post-high temperature compressive strength, USH, frost resistance and post-frost compressive strength tests was performed. Thus, it was observed to what extent the insulation plaster mortar protects the concrete.

Figure 2 shows the insulation plaster produced from expanded perlite, a very small amount of boron mineral colemanite, polymer fiber and binder before hydration. Perlite layers expanded in the form of plates and products expanding in the form of buds on these plates are seen. The structure is in amorphous form with plenty of voids and polymer fibers in the voids.

Figure 3(a) shows the image taken from the electron microscope and Figure 3(b) shows the elements detected by EDS analysis. It has an abundance of expanded perlite microplates. An important part of the chemical composition of the insulation plaster consists of SiO_2. There are Al_2O_3, CaO and Fe_2O_3 together with silica in the chemical composition of the insulation plaster. Boron mineral cannot be detected in the spectral analysis since it is present in very low amounts in the composition of the insulation plaster.

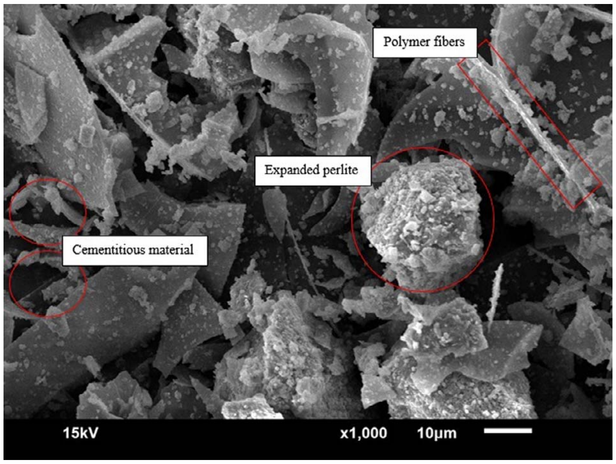
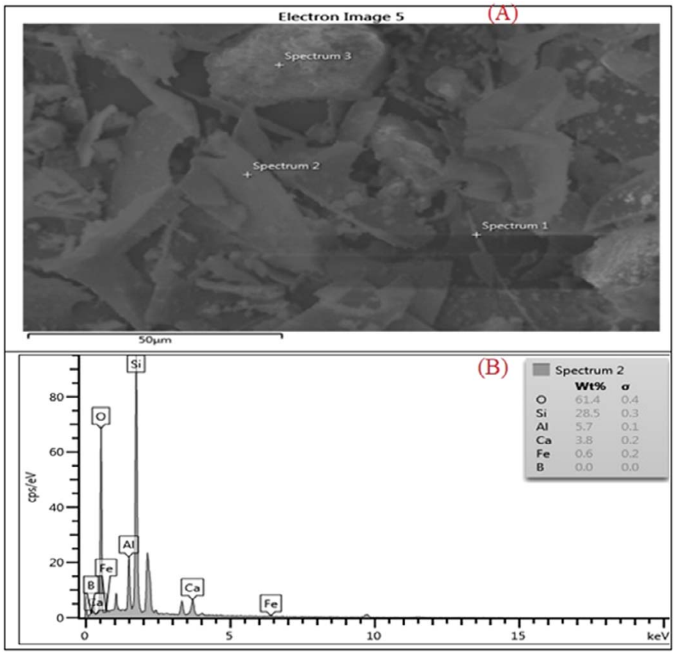


Figure 2. *The image of the thermal insulation plaster before it is hydrated.*



Spectrum 2	Wt%	σ
O	61.4	0.4
Si	28.5	0.3
Al	5.7	0.1
Ca	3.8	0.2
Fe	0.6	0.2
B	0.0	0.0

Figure 3. *(a) Electron microscope image of the insulation plaster; (b) spectral analysis of the insulation plaster.*

The tests on all samples obtained with the insulation plaster mortar were carried out over a period of 28 days under suitable curing conditions, and the experiments began using the oven-dry method.

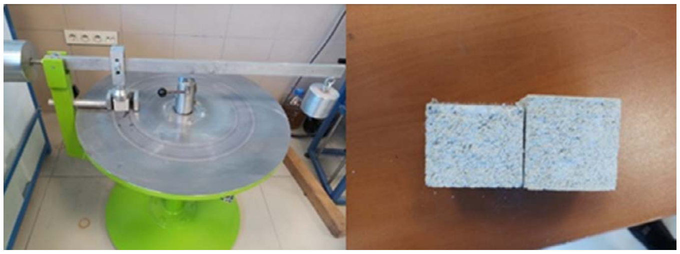


Figure 4. *First-round mortar sample wear loss.*

3 RESULTS AND DISCUSSION

The average thermal conductivity coefficient on three mortar samples made from the insulation plaster was measured to be 0.134 W/mK. The presence of pumice and perlite lightweight aggregates in the mortar resulted in an extremely low coefficient of thermal conductivity. In their study on the thermal conductivity of light mortars obtained by employing fine aggregate pumice, Widodo *et al.* [12] calculated the thermal conductivity coefficient by using the same quantity of cement and different proportions of pumice. On the other hand, in their study on the durability characteristics of high-performance foam concrete, Namsone *et al.* [14] determined that the thermal conductivity coefficient of foam concrete is in the range of 0.04 to 0.15 W/mK and claimed that it is ultra-light concrete. It was noted that the mortar employed in this study was an ultra-light insulation plaster mortar, and the thermal conductivity coefficient was extremely low when compared to conventional plaster mortars. The insulation plaster mortar sample was also floating over the water because it was a light composite material with a lower density than water, and on the seventh day, it was noticed that the sample sank into the water after becoming saturated with water.

The second round of the insulation plaster mortar abrasion test was canceled due to excessive sample loss in the first round. According to Figure 4, the first round of the Bohme experiment revealed a 0.8-cm size loss relative to the 5-cm reference sample, and the abrasion resistance of the specified insulation plaster mortar was ineffective. Table 2 states that the insulating plaster's poor compressive strength and lack of abrasion resistance are also reflected in its lack of abrasion resistance. According to Hroudova *et al.* [13], thermal insulation plaster mortars containing light particles like perlite have a lower compressive strength than conventional plaster mortar.

The insulation plaster, which was initially in the form of fine sand, was exposed to sodium sulfate solution in order to test its chemical resistance to frost. As shown in Table 1, the maximum limit value for fine aggregate is substantially below 10%, and the insulation plaster frost loss is 1.3% [21]. It was observed that insulation plaster was resistant to frost when it was in the form of fine sand. The 5 × 5 × 5 cm mortar samples made from the insulation plaster were then subjected to a freezing and thawing resistance test by performing cycles between +20°C and −20°C. As shown in Table 2, the weight loss at the end of frost is minimal, and it has been noted that neither the mortar nor the insulation plaster would be affected under frost conditions. The weight loss of the material after frost should be no more than 4%, according to TS EN 1367-1, in order for the material to be resistant to freezing and thawing [22]. In their research on lab tests and the potential of thermal insulation plasters, Maia et al. [16] adopted a heating-freezing cycle and found that there was no significant loss of resistance and no cracks in the samples.

Figure 5. *Samples of mortar-coated concrete prepared before the frost test.*

Figure 5 shows how 15 × 15 × 15 cm cubes of concrete were coated with 1 and 2 cm of mortar and then subjected to a natural frost test to determine how well the mortar protected the concrete from frost conditions. After the frost test, the mortars were cleaned from the concrete samples covered with mortar, the weights were weighed and the concrete compressive strengths were determined.

As shown in Table 3, weight and compressive strength losses following frost decreased as coating thickness increased. It was observed that as the coating thickness increased, the strength of the concrete increased and the mortar shielded the concrete from frost events in the end-frost compressive strengths.

As shown in Figure 6, no cracks in the mortar and concrete covered the surface of the concrete following the frost. In their study on the freeze–thaw resistance of porous aggregate and concrete, Pospichal *et al.* [17] determined that the type of concrete produced from the tested porous lightweight aggregates meets the required freeze–thaw resistance requirements of Czech standard SN 731380 and that there was no mechanical damage.

The resistance of 5 × 5 × 5 cm insulation plaster mortar samples to high temperatures of 300°C, 600°C and 900°C was examined. As demonstrated in Figure 2, expansion occurred in samples at 300°C and 600°C; however, shrinking occurred in

Table 2. *Results of natural frost tests on mortar samples*

Weight before test (g)	Weight after test (g)	Weight loss (%)	Compressive strength before test (MPa)	Compressive strength after test (MPa)
60.6	60.0	1.0	0.72	0.62

Table 3. *Results of natural frost test of concrete samples*

Sample type	Weight before test (g)	Weight after test (g)	Weight loss (%)	Compressive strength before test (MPa)	Compressive strength after test (MPa)
Ordinary	7695.1	7502.6	2.5	39.4	28.9
1 cm thick insulation	7731.5	7589.7	1.8	39.4	30.4
2 cm thick insulation	7746.7	7709.5	0.5	39.4	31.6

Figure 6. *Changes in the mortar-coated concrete sample before and after the frost test.*

Figure 7. *Variations in mortar samples after exposure to high temperature.*

samples at 900°C compared with the control samples that were not exposed to high temperatures. As shown in Figure 7, the weight loss is minimal, and there are no surface cracks in the 5 × 5 × 5 cm mortar samples exposed to a high temperature.

As indicated in Table 4, the samples lost weight as the temperatures to which they were subjected rose, and this was also apparent in the compressive strength of the samples. As the temperature increased, a drop in compressive strength was noted alongside an increase in weight loss. The presence of light fine aggregates in the insulation plaster resulted in low compressive strength and high strength losses even after 900°C high temperature. A study conducted by Bekem et al. [18] revealed that lightweight concretes produced with limestone aggregates derived from lightweight aggregates showed substantial compressive strength loss values after 800°C high temperature.

The velocity of ultrasound waves in 5 × 5 × 5 cm mortar samples before and after high temperatures were measured. As noted in Table 4, the USH losses after high temperature were smaller and even increased at 900°C, compared with the samples before the high temperature was applied. Sound insulation was provided due to the light fine aggregates in the insulation plaster. The fine aggregates contain numerous pores and voids, as seen in Figure 5. In addition, as shown in Table 1, the high water absorption values support the substantial amount of voids. As a result, it was determined that between 300°C and 60°C, it began to expand and fill the voids and that the insulation at 600°C was better than at 300°C. The voids in the fine aggregates were seen to be filled and expanded up to 600°C, and the USH increased by shrinking at 900°C and turning into a void-free structure.

15 × 15 × 15 cm cubed concrete samples were coated with insulation plaster-made mortar samples in thicknesses of 1 and 2 cm, and their effects on the concrete after exposure to high temperatures were examined. Initially, 900°C of high temperature was applied to concrete samples that had no mortar coating. The same concrete was then covered in 1 and 2 cm of mortar and heated to a high temperature of 900 °C. Following high-temperature cleaning of the mortars from the mortar-coated concrete samples, the weights were weighed and the compressive strengths were calculated. Table 5 shows that as the coating thickness in the concrete increases, the weight losses decrease. As a result, because the mortar coatings shield the concrete, it has a much higher compressive strength after being exposed to high temperatures than the uncoated samples. Because of the presence of light fine particles in the insulation plaster, it was determined that the mortar protects the concrete from high temperatures.

A 15 × 15 × 15 cm cube-shaped concrete samples, 1-cm mortar-coated concrete samples, and 2-cm mortar-coated concrete samples were analyzed before and after the USH modifications at 900 °C high temperature. As can be seen in Table 5, the concrete's USH before the test was 4.4 km/s, and according to ASTM C 597, the concrete's wave velocity falls within 3.5 to 4.5 km/s, which is considered to be good [23]. After exposure to high temperatures, it was found that the uncoated concrete sample had very substantial USH losses and that its ASTM C 597 quality had dropped from good to very poor. It was found that the coated concrete samples' concrete quality remained at a good level in accordance with the ASTM C 597 standard, where USH losses were essentially nonexistent, even after the mortars had been removed from the samples at high temperatures.

Table 4. *Ultrasound velocity test results of mortar samples*

Temp. (°C)	Weight before test (g)	Weight after test (g)	Weight loss (%)	USH before test (km/s)	USH after test (km/s)	Comp. strength before test (MPa)	Comp. strength after test (MPa)
300	61.948	58.987	4.7	1.139	0.726	0.72	0.35
600	63.587	58.318	8.3	1.198	1.125	0.72	0.31
900	62.813	52.366	16.6	1.125	1.558	0.72	0.25

Table 5. *Ultrasound velocity test results of concrete samples*

Sample type	Weight before test (g)	Weight after test (g)	Weight loss	USH before test (km/s)	USH after test (km/s)	Comp. strength before test (MPa)	Comp. strength after test (MPa)
Ordinary	7689.0	6945.3	9.7	4.400	0.395	39.4	6.4
1 cm thick insulation	7720.0	7009.7	9.2	4.400	4.085	39.4	11.5
2 cm thick insulation	7749.6	7332.0	5.4	4.400	4.355	39.4	15.9

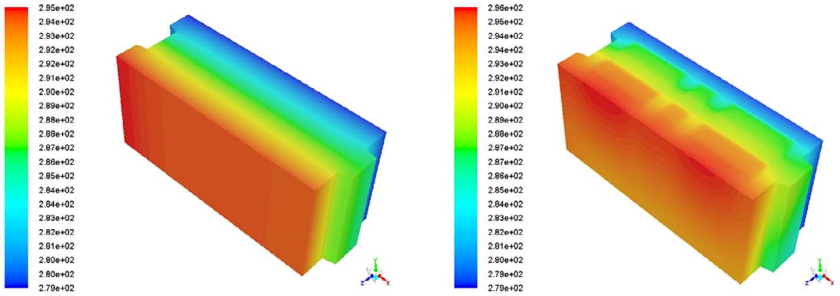


Figure 8. *CFD model of facade elements integrated with insulation plaster: the briquette without hollows (on the left) and with hollows (on the right).*

The novel insulation plaster was also analyzed through Computational Fluid Dynamics (CFD) software ANSYS FLUENT to get an understanding of its role in thermal insulation performance when it is integrated into conventional facade elements. As shown in Figure 8, for conventional briquette samples with and without hollows, CFD modeling was carried out with 1-cm-thick insulation plaster on both sides, and the thermal management feature of the insulation plaster was evaluated by considering the temperature gradient across the building element. It is clear from the static contours of temperature that the insulation plaster is capable of providing extra thermal resistance to the body with a lightweight design. In further works, it is aimed to investigate its potential impact on the U-value of the building elements at different thicknesses.

4 CONCLUSION

The following characteristic results were achieved in this study:

1. The use of insulation plaster on the interior and exterior of the buildings will protect them from high temperatures due to the low thermal conductivity coefficient of the insulation plaster mortar.
2. Due to the insulation plaster's resistance to high temperatures, the concrete is very effectively protected by the insulation plaster mortar and the coated concrete is stronger than the uncoated concrete.
3. The presence of light aggregate-based perlite and pumice in the insulation plaster mortar accounts for the high ultrasonic speeds. As a result, it is anticipated that utilizing it on building facades will significantly improve building sound insulation.
4. The insulation plaster mortar was found to be frost resistant, with no fractures or crumbling in the test samples after the frost.
5. The unit weight of the insulation plaster mortar is roughly 0.5 g/cm^3 due to the low relative density of light fine particles in the insulation plaster. It can be used practically because it is a relatively lightweight substance. When compared with standard plaster mortar, the usage of the mentioned insulation plaster mortar in structures reduces the loads.
6. The novel thermal insulation plaster can provide remarkably high thermal resistance to the building envelope. Polymer fibers and boron additives yield a promising thermal conductivity of 0.13 W/mK.
7. Because of the binding property of the boron mineral, no cement was required in the preparation of the insulation

plaster mortar. So, it has become practical to prepare plaster mortar.

8. High-temperature and end-frost tests have shown that the other component, steel fibers, prevents cracks from developing in the insulation plaster mortar.

AUTHOR CONTRIBUTIONS

Ilker Ustabas: Formal analysis, Writing – original draft, Writing – review & editing, Conceptualization, methodology.
Erdem Cuce: Supervision, Formal analysis, Writing – original draft, Writing – review & editing, Conceptualization, methodology.

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