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Structural and Mechanical Performance Characteristics of Construction Plasters with Different Material Compositions and Advanced Geopolymerization

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ABSTRACT

Thermal performance-enhancing and weather-protective plasters for building elements are highly favoured in the construction industry. However, whilst substantial research has focused on the thermal performance characterisation of plasters, their mechanical properties still need to be explored. This study addresses exactly this gap by preparing plasters by TS EN 998-1 standard, with varying water/cement ratios of 0.8, 0.9, and 1. The plasters are formulated utilizing severe materials, including sand, perlite, and fibres. In addition, some plaster mixes are produced through geopolymerization by combining fly ash and blast furnace slag with a sodium hydroxide solution. The prepared plaster mixes underwent several mechanical and physical tests to determine the optimal configuration. These tests include flexural and compressive strengths, capillary water absorption values, adhesion strength, spreading diameter, and material weight loss under freeze-thaw conditions. The results indicate that diminishing the water/cement ratio enhances the flexural and compressive strengths of the plasters. Conversely, increasing the water/cement ratio improves the adhesion strength. The inclusion of polypropylene fibres reduces the adhesion strength, while perlite-containing plasters exhibit lower freeze-thaw losses compared to other mixes. These findings offer practical insights for improving plaster formulations, addressing real-world challenges, including material availability, cost-effectiveness, and production scalability. The study underscores the potential of geopolymerization to advance sustainable construction practices whilst identifying limitations in implementation for broader industry adoption.

Keywords: Freeze-thaw, Geopolymerization, Mechanical performance assessment, Plasters.

INTRODUCTION

Nowadays, the continuous increase in the human population triggers the increasing trend towards the construction sector (González-Torres et al., 2022). These successive increases also bring about some difficulties. For example, people want to live in a comfortable environment and need energy (Day et al., 2020). However, the existence of factors such as insufficient insulation of buildings (Cuce et al., 2024a) and the selection of materials with high thermal conductivity coefficients in windows (Cuce, 2014; Cuce, 2018; Cuce et al., 2024b) cause a delay in the formation of this comfortable environment and, therefore, constitute a significant obstacle. As a matter of fact, this situation is supported by researchers sharing energy consumption data from buildings owned by countries (Cuce et al., 2019). For example, while India's current energy consumption from buildings is at 26%, it is estimated that this will be 40% by 2040 (if it continues like this) (Christopher et al., 2023). Similarly, although this level is around 40% in the UK, it is the first country to decide to take and implement measures to reduce this level (Cuce et al., 2023). Buildings appear to be responsible for consuming 40% of the total energy when all countries are included in the assessment (Ahmed et al., 2022). Moreover, when the necessity of consuming fossil fuels in order to meet the demand for energy is added, the urgency of the situation emerges. Therefore, action should be taken to increase this awareness about buildings, take solution-oriented measures, and take precautions against this problem with energy-efficient practices in buildings immediately through encouraging practices. These applications may include the integration of an insulation application that can be compensated with the building material into the building envelope (Braulio-Gonzalo & Bovea, 2017). In this way, less energy can be used to keep the indoor environment at comfort levels in the winter months (Jia et al., 2021), and similarly, less energy costs can be incurred to keep the indoor environment cold in the summer months (Alyami, 2024). On the other hand, economic prosperity can be achieved by using less energy, reducing the harm to the environment and human health (less energy, less fossil fuel use) and a significant decrease in energy costs. While these practices should be mandatory for future projects, researchers believe that it would be more efficient to retrofit existing buildings (Cuce et al., 2024c) with an insulation option compatible with the building material (Sharma et al., 2022). The reason for this is that, in addition to the cost during building demolition (La Fleur et al., 2019), the harmful gas/dust that will be released may have negative impacts on human and environmental health (Tambovceva et al., 2020). In general, researchers are developing cost-effective (Karn, 2024) and practical insulation tools that can be used in strengthening building envelopes and future building construction. While these studies are ongoing, thermal insulation plasters have been the most popular in recent times with their low transmission coefficient, ease of applicability, and affordable cost, and researchers recommend them for interesting applications (Pedroso et al., 2023).

With climate change, harsh weather conditions, especially in winter, are frequently encountered in many countries, and when buildings are considered, the first ones to suffer from this situation are plasters (Bauer et al., 2020). Thanks to plasters, the building element is protected from fire (Ustabas et al., 2024), and sudden temperature drops, provided that plasters are modified (Savchenko & Antoniuk, 2024), playing an active role in delaying the heat-transfer phenomenon from the interior to the exterior. In addition to these benefits, plasters are also used to obtain a smooth surface (Ustabas & Cuce, 2023). Therefore, plasters are an extremely important building material in terms of their thermal, mechanical, and acoustic properties. On the other hand, the presence of cement and lime binders in plaster-making causes its cost to be low (Arandigoyen & Alvarez, 2007). Perlite, pumice, vermiculite, organic materials, … etc., are added to plasters in order to augment the mechanical and thermal performance (Maxineasa et al., 2022; Pavlík et al., 2023). By substitution, improvements can be made in terms of density and thermal resistance. In this way, a barrier effect against sudden fire can be achieved, with maintaining the indoor comfort temperature for a long time. However, since these healing materials added are lightweight aggregates, it is known that they exhibit deficient performance in terms of crack formation and propagation in sudden temperature drops (Ustabas & Cuce, 2023). Lightweight aggregates contain voids in the micro-structure, which provides thermal-insulation performance. However, this situation creates the capillarity effect. The moisture contained is subject to freezing due to temperature drop. As a result of freezing, an expansion situation is observed in the internal structure, and therefore, a loss of strength is observed in the structure. When temperatures return to normal, this ice returns to its previous form. If this cycle continues repeatedly, it causes crack formation in the structure after a while. This creates the need to investigate this variation of the subject in more detail. In this sense, researchers conduct tests in naturally long-term harsh climate conditions to reveal how plasters react to sudden temperature drops, or laboratory-based freezing and thawing tests to obtain faster solutions. In parallel, geopolymerization has emerged as a promising approach in addressing some of these challenges. It is a chemical process that involves the reaction of aluminosilicate materials with alkaline activators, resulting in the formation of geopolymers (Venkatesan et al., 2024). Moreover, this process provides an environmentally friendly alternative in the construction and materials' sectors, significantly reducing carbon emissions (Imtiaz et al., 2020). Geopolymers are known for their high strength, durability, and resistance to chemical and thermal degradation, making them an ideal substitute for traditional Portland cement (Ikotun et al., 2024). Additionally, they are produced using industrial by-products, such as fly ash, metakaolin, and ground granulated blast-furnace slag, supporting a sustainable approach to material development (Madirisha et al., 2024). The polymerization process involves the dissolution of silica and alumina in an alkaline solution, followed by the formation of a three-dimensional network structure (Feng et al., 2022). Compared to Portland cement, geopolymer production requires less energy, contributing to lower greenhouse-gas emissions (Jamieson et al., 2015). One of the key advantages of geopolymers is their versatility. They significantly reduce carbon footprints, with potential reductions of up to 80% compared to conventional cement (Duxson et al., 2007). Furthermore, they demonstrate exceptional resistance to aggressive environments, including exposure to seawater, acids, and other chemicals, which enhances their longevity in infrastructure applications (Ikotun et al., 2024). Geopolymers also exhibit high thermal stability, making them suitable for refractory and fire-resistant applications (Lahoti et al., 2019). In terms of economic benefits, the use of low-cost raw materials in geopolymer production ensures affordability while maintaining superior performance characteristics (Madirisha et al., 2024). Dhawan et al. (2024) investigated the economic and technical advantages of geopolymer concrete produced using fly ash and ground granulated blast-furnace slag compared to traditional Portland cement concrete. The study highlighted that geopolymer concrete can reduce production costs by 31.13 percent to 43.74 percent while achieving higher compressive strength. It also demonstrated that geopolymer concrete has lower water absorption rates, and the addition of micro-silica can further enhance its durability. Moreover, rapid setting times enable faster construction processes, which is a significant advantage in time-sensitive projects (Abed et al., 2024). The alkaline activators commonly used include sodium hydroxide and sodium silicate, and their precise ratios are crucial for optimizing the material's mechanical properties and durability (Anburuvel, 2023). As a result, geopolymers are increasingly adopted in both structural and non-structural applications, ranging from roadways and bridges to insulation panels and coatings. In addition, Kanagaraj et al. (2022) investigated the properties of cement-less concrete, also known as geopolymer concrete. Their review explored the chemical reactions involved in geopolymer-concrete production using industrial by-products and naturally occurring aluminosilicates. The authors highlighted the challenge of inconsistent mix designs in geopolymer-concrete production, unlike traditional cement concrete where the water-cement ratio is the primary variable. They discussed the numerous factors influencing geopolymer-concrete properties, including alkaline liquid-to-binder ratio, activator ratio, binder type, and curing methods. The study provided an overview of geopolymer chemistry, aluminosilicate sources, and micro-structural analysis under various curing conditions. Lastly, the utilization of industrial waste in geopolymer production supports circular-economy principles and reduces landfill dependency.

Kanagaraj et al. (2023) inspected the sustainability and mechanical properties of self-compacting lightweight geopolymer concrete made from Expanded Clay Aggregate. They conducted various physical and mechanical tests, including slump flow, compressive strength, and impact resistance, to evaluate the performance of this innovative material under different sodium hydroxide concentrations and curing conditions. Their findings revealed that using Expanded Clay Aggregate improves fresh-state properties, allowing for significant weight reduction without compromising strength, particularly with up to 50% replacement of conventional aggregates. The study highlighted the environmental benefits of geopolymer concrete over traditional cement-based concrete, particularly through life cycle assessment and environmental-impact assessment. The authors emphasized that while higher concentrations of sodium hydroxide increase mechanical performance, they also raise energy demands and carbon emissions. Furthermore, the investigation underscored the potential for using industrial by-products, such as fly ash and slag, in geopolymer-concrete production, contributing to lower environmental impacts. Overall, the research suggested that self-compacting lightweight geopolymer concrete can serve as a sustainable alternative in construction, offering significant opportunities for future research and development in this area. Li et al. (2022) investigated the freeze-thaw resistance of geopolymer mortars reinforced with modified multi-walled carbon nano-tubes and polyvinyl-alcohol fibres. Their findings showed that geopolymer mortar containing 0.10% modified multi-walled carbon nano-tubes and 2.00% polyvinyl-alcohol fibres withstands 175 freeze-thaw cycles, significantly more than the 50 cycles endured by the control sample. The study highlighted that modified multi-walled carbon nano-tubes enhance the mortar's density by reducing capillary pore percentages through nano-filling, nano-nucleation, crack arrest, and mechanical interlocking effects, while polyvinyl-alcohol fibres counteract internal stresses caused by freezing water. The research further revealed that optimal fibre content improves durability, but exceeding these levels negatively affects performance. Similarly, Yuan et al. (2020) examined the enhancement of frost resistance in slag and Class-F fly ash-based geopolymer concrete by using polypropylene fibres, polyvinyl-alcohol fibres, and steel fibres. A coupling experiment involving 20 megapascals of axial compressive stress and 125 freeze-thaw cycles demonstrates that while fibres do not prevent the initiation of micro-cracks, they suppress the propagation of cracks and reduce damage, such as surface peeling and mass loss. Polyvinyl-alcohol fibres at 0.3 percent volume are particularly effective, improving both the mechanical properties and the frost resistance. The study highlighted the importance of compressive loading in compacting concrete, reducing water penetration, and enhancing durability. However, steel fibres, due to their high elastic modulus, show inconsistent performance under compressive stress. Wang et al. (2024) explored the impact of different fibre types, lengths, and contents on the performance of red mud-slag-based geopolymers in freeze-thaw conditions. The study found that the addition of fibres, particularly polypropylene fibres at 9 mm length and 0.9% content, enhances both the flexural strength and the frost resistance of geopolymer composites. However, excessive fibre content or length leads to fibre agglomeration, reducing frost resistance. Also, SEM and XRD analyses revealed that the fibres improve the structural integrity and durability of the materials by enhancing the micro-structure and forming strong phases, such as hydrated calcium silicate and hematite. Min et al. (2022) assessed the freeze-thaw performance of one-part geopolymer pastes made from binary precursors, ground granulated blast furnace slag and fly ash, activated by sodium hydroxide or sodium metasilicate. The study found that sodium metasilicate-activated pastes exhibit better freeze-thaw resistance due to the formation of a denser structure compared to sodium hydroxide-activated pastes. As the number of freeze-thaw cycles increases or the freezing temperature decreases, porosity increases, leading to mass loss and a reduction in compressive strength. Pang et al. (2024) studied the effect of polypropylene fibres on the mechanical performance and micro-structural changes of geopolymer-cemented aeolian sand under freeze-thaw conditions. Their outcomes revealed that adding more fibres initially boosts the specimen’s cohesion, bias stress, and elastic modulus, with the best reinforcement occurring at a fibre content of 5%. However, with increased freeze-thaw cycles, the mechanical properties of specimens without fibres deteriorate faster, while those with fibre reinforcement show better durability. The fibres help maintain the integrity of the internal matrix, reducing micro-crack formation and enhancing frost resistance. Ustabas and Cuce (2023) applied various tests to mortar samples prepared using insulation plaster, one of which is the freeze-thaw test. The samples were exposed to -20°C and +20°C temperatures for certain periods, and the processes were repeated. As a result, their weight loss and compressive strength were examined. According to the test results, increasing the insulation thickness requires significant weight loss and compressive-strength resistance, and a promising insulation plaster. Santamaría-Vicario et al. (2016) performed 56 cycles of freeze-thaw tests by using different ratios of waste steel slag aggregates instead of natural aggregates. Whilst freezing is carried out between -8°C and -12°C, thawing is conducted by immersion in water between 5°C and 20°C. The results of bending and compressive-strength tests showed that the samples containing waste steel slag aggregate have high freeze-thaw resistance in the long term. Abendeh et al. (2021) aimed to provide a sustainable solution for concrete production by using recycled steel slag aggregate as a partial replacement for natural aggregate. The study investigated the effects of replacing natural aggregate with varying proportions of steel slag aggregate, ranging from 0% to 75%, on the strength and durability of concrete. The results showed that replacing 75% of fine aggregate with steel slag aggregate improves the compressive strength by approximately 12%, with the highest compressive strength recorded as 49.2 MPa when coarse aggregate is replaced. Additionally, the flexural strength increases by 13% and 15% when fine and coarse aggregates are replaced, respectively. Overall, incorporating steel slag aggregate enhances the density, reduces water permeability, and significantly improves resistance to freezing and thawing, demonstrating its potential for sustainable construction applications. Dalila and Mebarek (2022) examined the impact of waste glass powder on the freeze-thaw resistance of high-performance concrete. The study involved partial replacement of fine aggregates with waste glass powder at varying proportions (15%, 20%, 25%, and 30%) and two different particle sizes, followed by freeze-thaw testing. The results indicated that after 300 cycles, the average dynamic modulus of concrete with 0-315 μm particle size (PSA) is measured at 84.25%, whilst that of concrete with 0.315-1.25 mm particle size (PSB) stands at 71.75%. Additionally, the fine glass powder positively influences freeze-thaw resistance, with the durability factor of PSA concrete reaching 92% and that of PSB concrete reaching 61% after 300 cycles. When compared to the control concrete and concrete containing silica fume, the performance of concrete with waste glass powder was found to be sufficiently satisfactory. These findings suggest that waste glass powder can be incorporated into concrete at rates of 20%-30% without causing long-term issues. Morgado et al. (2021) conducted a study in which they measured compressive strength and weight loss after freeze-thaw tests. In this study, samples were kept at -15°C (freezer), 20°C (water) and 60°C (oven), respectively, for certain periods of time. Test results showed that as the number of cycles increases, the most significant decrease in weight loss is experienced in silica aerogel, and the best reaction against compressive strength is given by expanded polystyrene. Catalin et al. (2023) conducted a study on the evaluation of wastes originating from the construction industry by using old plaster wastes instead of aggregates in mortar in accordance with the European Union legislation and determining the effect of this method on the fresh and hardened properties of the mortar. In this study, two mortar types containing 10% and 15% waste were tested with a standard recipe (no waste) for periods of 7, 14 and 28 days. Changes in fresh-mortar properties are observed between 1% and 2.5%, and when 15% waste is utilized, compressive strength decreases by 11.09% and flexural strength declines by 22%. These findings revealed that plaster waste can be used instead of aggregate up to 15% and can be applied effectively in practice.

Experimental freeze-thaw testing is essential for assessing the durability and performance of building materials, particularly for structures exposed to harsh environmental conditions. Geopolymers and plasters have become pivotal in modern construction due to their ability to enhance thermal insulation, fire resistance, and mechanical properties. However, understanding their behaviour under freeze-thaw cycles is critical to ensuring the structural integrity and longevity of these materials across diverse climates. Despite their potential, the existing literature often focuses on single-directional materials or isolated mechanical properties, limiting the scope of practical application. This narrow focus, combined with inconsistent testing methods and the lack of standardized approaches, has resulted in notable discrepancies in research outcomes, hindering the widespread adoption of these advanced materials. This study addresses these gaps by employing a comprehensive suite of mechanical and physical tests on various plaster and geopolymer mortar compositions. By integrating multiple test methods, including flexural and compressive strengths, adhesion performance, capillary water absorption, and freeze-thaw resistance, this research offers a holistic evaluation framework that mitigates the inconsistencies observed in prior studies. Furthermore, the experimental design adopts diverse sample configurations and methodologies, ensuring a robust analysis that reflects real-world conditions. These efforts aim to establish a more reliable standard for evaluating material performance while demonstrating the practical and scientific significance of comprehensive testing approaches in advancing sustainable construction practices.

MATERIALS AND METHODS

In this study, plasters of various types and compositions are produced by cement and geopolymerization methods in accordance with the TS EN 998-1 standard (Turkish Standards Institution, 2017). Within the scope of the study, a total of traditional plaster mortar and perlite plaster mortar with water/cement ratios of 0.8, 0.9 and 1, mortars produced by the geopolymer method using fly ash and blast furnace slag, fibrous plaster mortars prepared by adding polypropylene fibre into these mortars, and thermal insulation plaster. Totally, ten types of plasters are manufactured. Spreadability, flexural-compressive strength, adhesion strength, capillary water-absorption values and mass losses in the freeze-thaw environment of these plaster mortars are measured. During the production of plasters, in the first stage, the mixing materials are placed in the mixing device, which is operated for 90 seconds. To address the lightweight nature of perlite and its tendency to float during mixing, a specific mixing protocol is implemented. Initially, the fine aggregates are pre-mixed with a portion of the binding agent (cement or alkaline solution in the case of geopolymers) to create a cohesive base. This base helps anchor the perlite when it is gradually added during the mixing process. Continuous mechanical mixing ensures that the perlite is evenly distributed throughout the mixture without allowing it to segregate or float to the surface. The two-stage mixing process is repeated to guarantee uniformity in the mortar mixture. In the second stage, the materials on the edge of the container are scraped and run again for 90 seconds to prepare the mortar mixtures.

Specifically, during the preparation of cement-bonded plasters, water is first added to the mixer. Cement is then introduced and mixed for 15 seconds. Sand is added for regular mortars, while perlite is included for lightweight mortars and fibres for fibre-reinforced variants. The mixture is stirred at a high speed for 90 seconds. The mixer is then paused, and materials adhering to the sides of the mixer are scraped off, followed by additional 90 seconds of high-speed mixing to ensure uniformity. For geopolymer plasters, a 6.3 M NaOH solution is prepared in glass bottles and left to stand for 24 hours before use. During geopolymer-plaster preparation, the fly ash and ground granulated blast-furnace slag are added to the mixer first, followed by the NaOH solution. After mixing for 15 seconds, perlite and/or fibres are added, and the mixture undergoes two rounds of 90 seconds of high-speed mixing to produce a uniform plaster mortar. After preparation, mortar samples are cast in compliance with TS EN 196-1 (Turkish Standards Institution, 2016). Flexural strength is determined on three specimens, while compressive strength is measured on six fragments derived from the same series. To provide a clearer understanding of the preparation stages, Fig. (1) illustrates the step-by-step process, including mixing, casting, and curing phases. This ensures consistency and replicability in the prepared samples.

Spreadability tests are conducted for fresh mortars following TS EN 1015-3 (Turkish Standards Institution, 2000) by measuring the diameter of the mortar subjected to 15 impacts on a flow table. Freeze-thaw tests, conforming to TS EN 15177 (Turkish Standards Institution, 2011), are performed to evaluate durability under cyclic freezing and thawing conditions. Various analyses are carried out on the samples of perlite and sand materials used in the study, which are provided before the experiments start. These analyses include sieve analysis, water-absorption capacity, specific gravity, and determination of moisture content at room temperature. Sieve-analysis results are presented in Table 1. The specific weight, water absorption, and moisture content of perlite are determined as 2.13, 5.9%, and 2.4%, respectively, while those of sand are 2.41, 5.28%, and 1.59%, respectively. Furthermore, the chemical examination of the perlite utilised in this research discloses its constituent percentages, which are provided in Table 2.

Figure (1): Step-by-step representation of the specimen preparation process: a) Materials used for mortar preparation; b) Mixing phase; c) Mould prepared for casting; d) Specimens' casting in moulds

Table 1. The results of the sieve analysis of the supplied perlite and sand

Sieve mesh opening (mm)	Passing percentage (%) for	
	Perlite	Sand
8	100	100
4	98.7	92.4
2	78.2	68.8
1	46.5	37.1
0.5	26.3	13.4
0.25	15.2	4.3
Container	0	0

Fig. (2) presents the XRD analyses of cement, fly ash, ground granulated blast furnace slag, and perlite, aimed at supporting the chemical-composition data. The analyses clearly demonstrate the presence of characteristic peaks corresponding to the crystalline phases of each material. These peaks confirm the existence of the identified components within the samples and validate that no loss of material occurs during the preparation process.

In order to ascertain the flexural and compressive strengths of the mortars prepared in the mixer, prismatic mortar samples of 4x4x16 cm^3 dimensions are produced using the shaking table. During the process of placing the mortar into the mould, the mould is initially filled halfway, followed by 60 strokes. Subsequently, the remaining half of the mould is filled with mortar, and further 60 strokes are applied, thus completing the moulding process.

Table 2. Chemical analysis of outcomes of the perlite

Chemical composition (%)	Perlite	Cement	Fly ash	Blast-furnace slag
SiO_2	72.05	19.28	52.71	38.62
Al_2O_3	13.09	5.15	17.98	11.39
Fe_2O_3	1.53	3.53	12.63	0.60
MgO	0.39	1.05	4.80	7.93
CaO	1.34	64.57	4.48	35.29
Na_2O	3.91	0.45	0.75	0.31
K_2O	4.18	1.17	1.85	1.48
Others	0.18	3.33	2.79	5.38
LoI	3.0	2.80	1.49	1.10

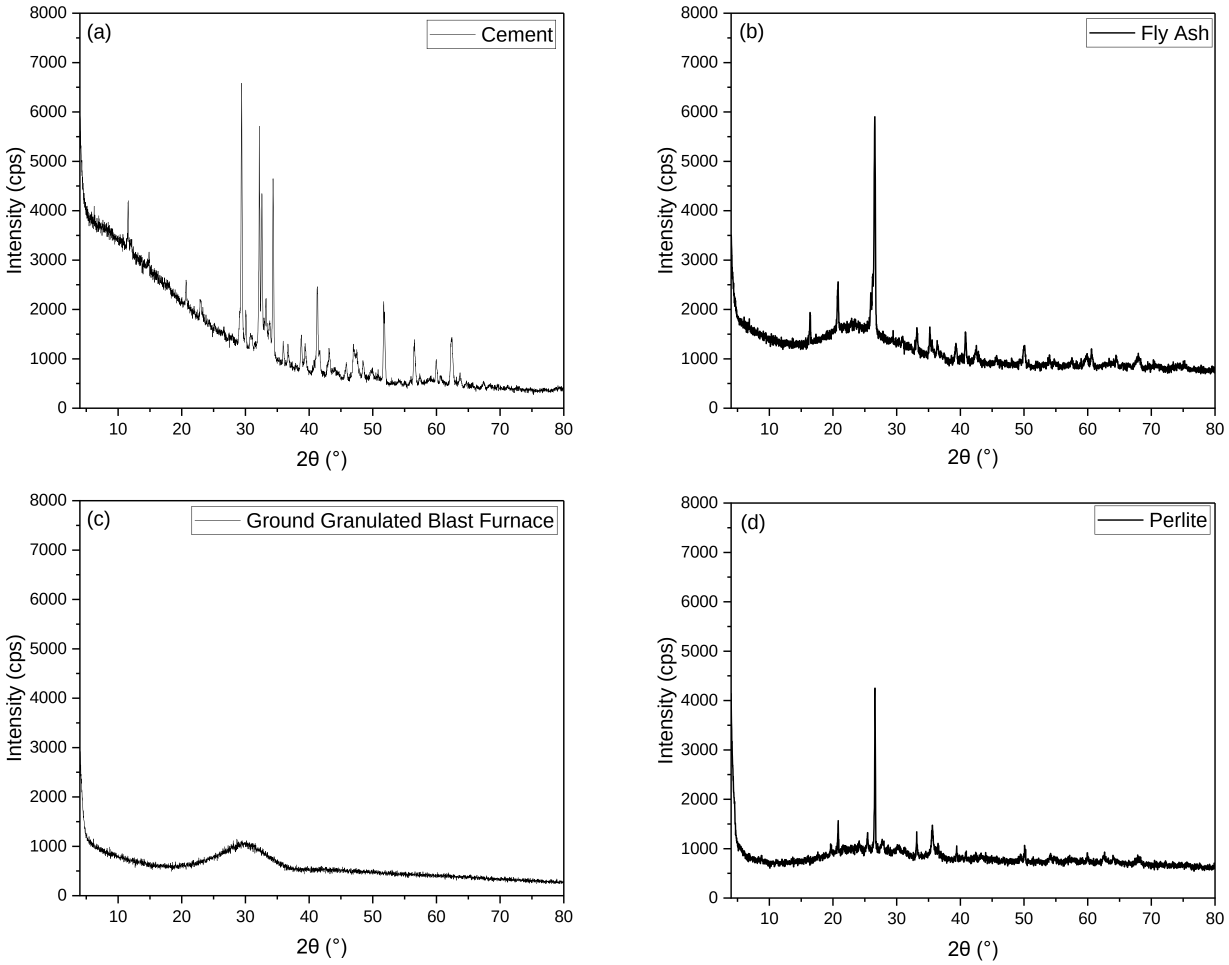


Figure (2): XRD patterns of the investigated materials: a) Cement; b) Fly ash; c) Ground granulated blast-furnace slag; d) Perlite

Glass plates are placed on moulds filled with mortar, and these moulds are kept in an air-conditioning cabinet at 20°C and 95% humidity for 24 hours. After the samples taken from the conditioning cabinet are removed from their moulds, they are left to cure for 28 days in the lime-saturated curing pool at 20°C.

Amounts of Materials Used for Plaster

Table 3 lists the amounts of materials utilized for 1m^3 of plaster. CEM I 42.5 R-class cement and polypropylene fibre are used in the plaster mortar. The amount of fibre is added at the rate of 0.1% of the volume of the plaster mortar. Additionally, the amount of air is accepted as 3%.

Table 3. Quantity of materials required for 1 m^3 of plaster mortar (in kg)

The Ratio of Water/Cement	Cement	Water	Sand	Fibre
0.8	300	240	1341	-
0.9	300	270	1278	-
1	300	300	1373.7	-
1	300	300	1373.7	14

On the other hand, Table 4 is organized in order to inform the amounts of materials used in the mortars of plasters generated by using perlite and geopolymer.

Table 4. Materials counted in 1 m^3 of perlite and geopolymer plaster mortars (kg)

The Ratio of Water/Cement	Cement	Water	Perlite	Fibre	NaOH	Blast-furnace Slag
0.8	300	240	1341	-	-	-
0.9	300	270	1278	-	-	-
1	300	300	1214.1	-	-	-
1	300	300	1214.1	14	-	-
Fly ash: 75	-	240	1256.7	-	246	225
Fly ash: 75	-	240	1256.7	14	246	225

Geopolymer is a pretty contemporary material with a potential to replace conventional Portland cement. This material is an inorganic compound with an amorphous or semi-crystalline polymeric structure, synthesized at ambient or slightly elevated temperatures by the alkaline activation method. Geopolymers can be produced from a variety of raw materials containing reactive or amorphous silica and alumina, such as metakaolin, fly ash, mine waste, red mud and blast furnace slag. Since most of these raw materials consist of industrial waste or by-products, the production and use of waste-based geopolymers can provide significant environmental and economic benefits. Although geopolymer concrete has some challenges, such as production outside the laboratory and appropriate supply of source materials, this material offers rapid mechanical strength gain compared to traditional Portland cement, as well as low shrinkage during drying, high fire resistance, superior acid resistance, non-toxicity and ability to contain hazardous substances. It has the advantage of being effectively immobilized. It also offers additional benefits, such as significantly reducing energy consumption and greenhouse-gas emissions.

In this study, geopolymer plaster mortars are also prepared, and NaOH is substituted into the mixture. Specifically, the alkaline activator used in the geopolymer mortars has an NaOH concentration of 6.3 mol/litre. Additionally, the air content in all mortars is determined as 3%.

Experiments Conducted in the Study

Spreading Test

When the spreading values of the plaster mortars are measured, after mixing the mortar materials, the fresh mortar is filled into the standard cut-out funnel, and the mould is pulled upwards. In the manual spreading table, the spreading values of the mortars are determined by calculating the spreading diameter of the mortar on the table after 15 strokes.

Flexural and Compressive Tests

Flexural and compressive tests are applied to 4×4×16 cm^3-sized samples prepared from mortars utilized in plasters. Consequently, with these experiments, the flexural and compressive strengths of the samples are measured.

Capillary Water Absorption Test

The prepared samples, measuring 4×4×16 cm^3, are dried in an oven at 70°C for 1 day. After the dried samples are weighed and their masses are recorded, a three millimetre gap is left on the side edges of the lower surface in contact with water, and all four sides of the edges in contact with water are covered with paraffin which is an impermeable material. After the samples are coated with paraffin, they are placed in the mechanism, with the lower surfaces in direct contact with water. The samples that absorb water *via* the capillary route are weighed at 5 min, 10 min, 15 min, 20 min, 30 min, 45 min, 1 hour, 2 hours and 1-day intervals, and their masses are recorded. The capillary water-absorption coefficients (K_{cp}) of the mortars are measured in kg/(m^2.$s^{0.5}$) from the slope of the line created by linear regression between the amount of water absorbed from the unit area and the $\sqrt{t}$ values. In the capillary water-absorption coefficient calculation, it is calculated using Equation (1) (Chassagne et al., 2019).

$$K_{cp} = \frac{\Delta M}{A\sqrt{t}} \tag{1}$$

where, ΔM is the sample mass with water absorption subtracted in kg. A represents the capillary water-absorption surface area in m^2, and t symbolizes the measurement interval time in seconds.

Adhesion Strength Test

This experiment is performed with the Proceq dy-216 device. To measure the adhesion strength of plasters, a mark is left on the surface with a drill with a suitable cutting edge. Then, upon this permission, the head part of the device is placed on the plaster with adhesive, and a tensile test is performed on the device. The adhesion strength of the plaster is measured by dividing the tensile force measured by the device by the applied area.

Freeze-thaw Test

The samples seen in Fig. 3 a) are 10×20 cm briquettes plastered with the produced mortars. The side surfaces of these briquettes are coated with paraffin. The freeze-thaw experiment is carried out on briquettes with paraffin on the edges and plaster on the top, using the device shown in Fig. 3 b). With this device, a cycle is applied for 28 days at temperatures ranging from -20°C to +20°C in one day. Mass losses in the plasters are measured at the end of the experiment.

Figure (3): Freezing-thawing treatment: a) Specimens in moulds; b) Specimens in F/T chamber

RESULTS AND DISCUSSION

In this study, the mechanical and physical properties of regular plaster mortars prepared using perlite, sand, and fibre, as well as plaster mortars prepared using the geopolymer method, are examined. Perlite has large reserves in Turkey and is generally used in the construction industry to add thermal properties to the material due to its superior thermal properties. Fibers are other vital components that have many varieties and are used in cement-bonded building materials. Polypropylene fibres, which are considered most suitable, especially for plaster mortars, provide significant improvements in mechanical and thermal properties. In this study, alterations in the performance of plaster mortars and fibrous plaster mortars with different water/cement ratios are determined in detail by using different materials and methods.

The results of the tests will be examined separately under the headings of spreading test, flexural and compressive tests, capillary water-absorption test, adhesion strength test and freeze-thaw test.

Spreading Test

Fig. (4) presents the measured spreading amounts in various plaster mortars, highlighting that the sand 1 plaster mixture exhibited the highest spreading amount. This figure also illustrates a clear trend: as the water/cement ratio in plaster mixtures increases, so does the spreading. Correspondingly, it has been observed that higher water/cement ratios enhance the workability of the plaster mixtures. Conversely, the lowest spreading amount is recorded in the perlite mixture with a water/cement ratio of 0.8. Senff et al. (2011) investigated the incorporation of perlite and vermiculite aggregates in cement mortar, conducting flexural, compressive, and spreading tests across various weights and water/cement ratios. Their findings aligned well with the results of this study, thereby supporting its accuracy. Carvalho et al. (2024) performed spreading testing on geopolymer mortar based on metakaolin and biomass fly ash in a parallel study. The outcomes of their research also corroborated this study's findings, further reinforcing the validity of this study. The presence of fibres in plaster mortars is known to reduce workability due to the increased resistance to flow. In this study, the diminishment in workability caused by fibres is addressed by optimizing the water-to-cement ratio and carefully controlling the mixing procedure. Specifically, a higher water content is used in fibrous mixtures compared to non-fibrous ones, which improves the flow and ensures adequate spreading. In addition, the mixing time is adjusted to verify uniform distribution of fibres within the mortar, thereby minimizing the clumping effect that typically hinders workability. These measures assure that the fibrous mortars achieve acceptable spreading values, as evidenced by the spreading test results presented in Table 5 and Fig. (4).

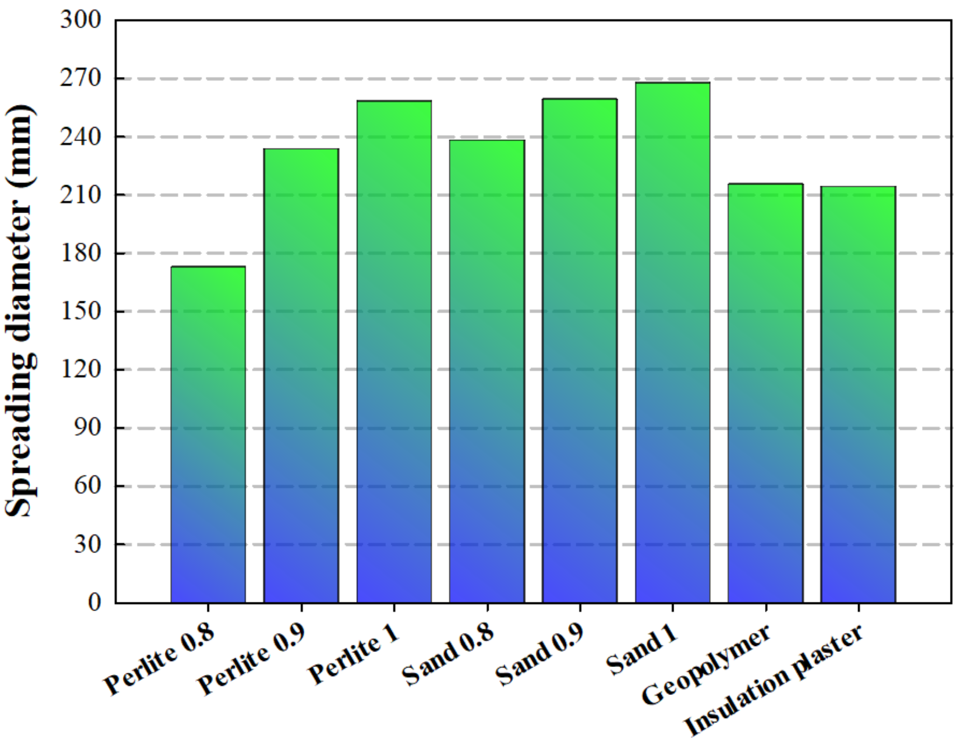


Figure (4): Spreading-diameter outcomes for each experimental sample

Detailed information regarding the spreading-diameter measurements obtained from the experiment is provided in Table 5.

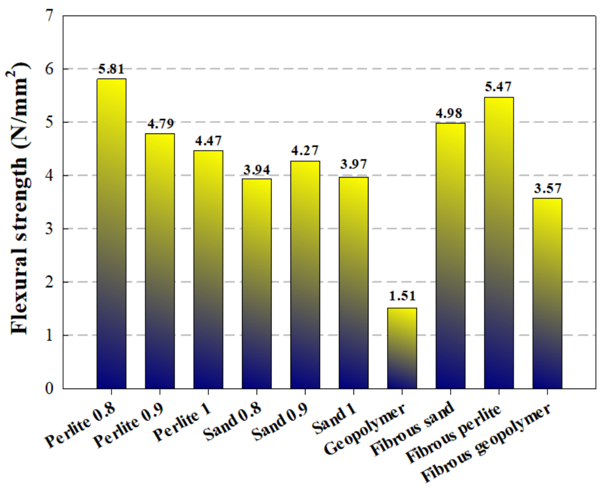
Table 5. Flow table of spreading diameter for mortars with different materials

Material	Spreading diameter (mm)
Perlite 0.8	173.5
Perlite 0.9	234
Perlite 1	258.7
Sand 0.8	238.7
Sand 0.9	259.7
Sand 1	>26
Geo-polymer	216
Insulation plaster	214.7

Flexural and Compressive Tests

Fig. 5 a) shows the flexural strength measured in plaster mortars. According to this figure, the highest flexural strength in non-fibrous plaster mortars is perceived in perlite mortars, followed by sandy mortars, with the lowest flexural strength observed in mortars produced using the geopolymer method. As the water/cement ratio of the mortar increases, a decrease in flexural strength is noted. The water/cement ratio of fibrous perlite and fibrous sand mortars is 1. When comparing the flexural strengths of fibrous perlite and fibrous sand mortars with perlite and sandy mortars having the same water/cement ratio, it is observed that the addition of fibres enhances the flexural strength of the mortar.

On the other hand, Fig.5 b) demonstrates the compressive strength of the prepared plaster mortars. As the water/cement ratio rises, a reduction in compressive strength is observed. Perlite mortars exhibit higher compressive-strength values than those of sandy mortars. Although adding fibres has given rise to a significant increase in flexural strengths of perlite, sand, and geopolymer mortars, it does not cause a noticeable change in compressive strength. In this study, it is found that the compressive strength of raw perlite mortar, which has a lower density compared to sand, is higher than that of sandy mortar. This is thought to be due to the lower consistency of the perlite mortar compared to the sandy mortar and the pozzolanic properties of the perlite used in this study. In conclusion, it is witnessed that the addition of fibres to the mortar enhances its flexural strength. Fenoglio et al. (2018) conducted a study on mechanical and thermal properties by designing plaster with lightweight aggregates, binders and additives, and found that a rise in flexural and compressive strength occurs, utilizing polypropylene fibres and lightweight aggregates together. Similar findings are found in the study of Fenoglio et al. (2018). Fibre reinforcement increases the flexural strength of plasters and the compressive strength of lightweight aggregate with high water-absorption value.



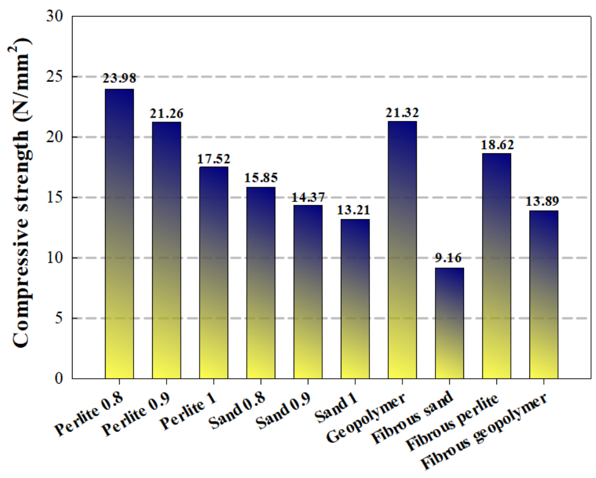


Figure (5): a) Flexural-strength results of various materials; b) Compressive-strength results of various materials

Capillary Water-absorption Test

Fig. (6) presents the linear regression equation derived from the capillary water-absorption amounts and absorption times for mortar samples per unit area. By taking the derivative of this line equation concerning x, the capillary water-absorption coefficient for the perlite 0.8 mortar is calculated. The capillary water-absorption coefficients for the other plaster mortars used in the study are also measured using this method.

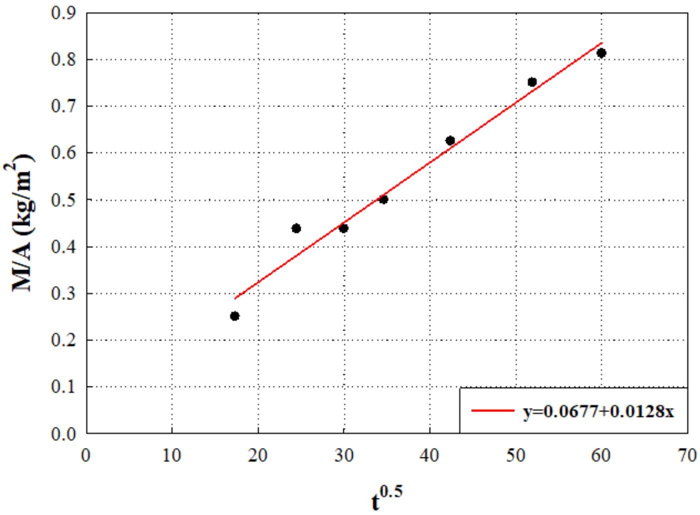


Figure (6): Analysis of capillary water-absorption coefficient of perlite 0.8 sample with the regression model

The data depicted in Fig. (7) illustrates the capillary water-absorption coefficients of plaster mortars. In accordance with these findings, the coefficients range from 0.0128 to 0.0964 kg/($m^2.s^{0.5}$). Fibrous geopolymer mortar exhibits a notably higher capillary water-absorption coefficient compared to other plaster mortars. Furthermore, elevating the water/cement ratio correlates with an increase in the capillary water-absorption coefficient of the mortars. Moreover, the inclusion of fibres in plaster mortars results in higher capillary water-absorption values. Conversely, mortars containing perlite demonstrate the lowest capillary water-absorption coefficients. This research underscores that mortars with reduced spread or consistency exhibit lower capillary water-absorption values.

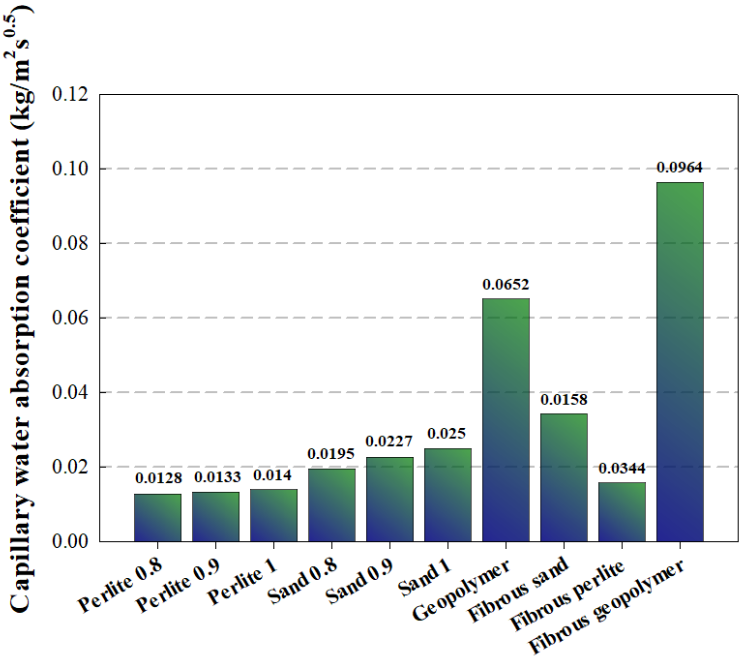


Figure (7): Capillary water-absorption coefficients measured in plaster mortars

Adhesion-strength Test

Adhesion strength is a parameter that measures the ability of a material to adhere to another material. This feature is critical for evaluating the application performance of materials, such as plaster, mortar and concrete, especially in the construction industry. Adhesion-strength testing is used to determine the adhesion capacity of materials and to build long-lasting, durable structures. The finding obtained from this study is that the adhesion strength of the prepared plaster mortars to the concrete surface can be seen in Fig. (8). It is observed that as the water/cement ratio increases, the adhesion strength reaches up to 0.68 MPa. Increasing the water/cement ratio increases the adhesion strength of high-consistency mortars with high spreading values. However, Fig. (8) shows that the addition of fibre reduces the adhesion strength of the mortars. This study shows that increased water content makes plaster adhere to the concrete surface.

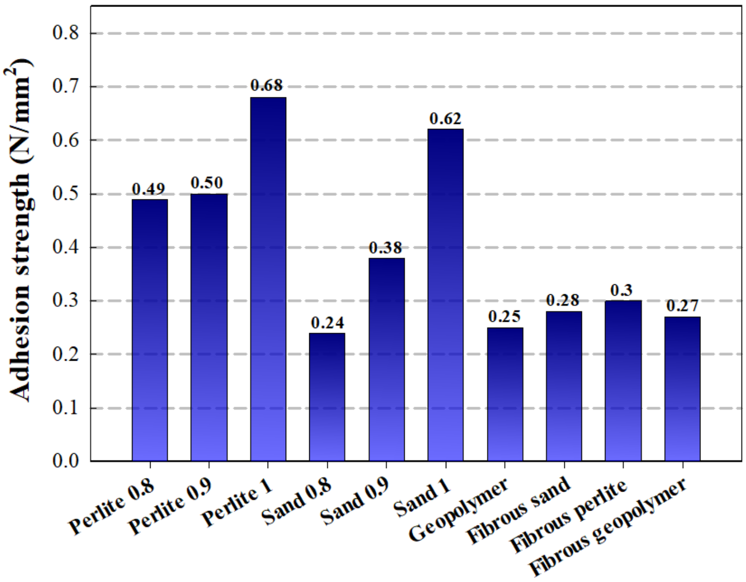


Figure (8): Adhesion strength of plaster mortars

Freeze-thaw Test

The freeze-thaw test is a method that measures the resistance of materials to the cycle of freezing and re-thawing at low temperatures. This test is specifically used to evaluate the resistance of building materials to outdoor conditions. When materials are subjected to a freeze-thaw cycle, the stresses created by the expansion and contraction of water can weaken the materials' structure and reduce their durability. Hence, the freeze-thaw resistance of building materials is a critical parameter for building long-lasting and safe structures. Fig. (9) shows the material loss rate per unit area due to the freeze-thaw test of the prepared plaster mortars. In this study, the highest flexural-compressive strength and freeze-thaw resistance are determined in perlite 0.8 plaster mortar. The literature states that there is a relationship between flexural-compressive strength and freeze-thaw resistance. However, in this study, the plaster mortar prepared by the geopolymerization method has a below-standard flexural-compressive strength, whilst the freeze-thaw resistance is the lowest. This demonstrates that plaster mortars with geopolymerization can be used in situations where they are not exposed to the freeze-thaw cycle, but require high strength. The perlite-based plaster mortar studied here demonstrates the promising potential for thermal insulation and protection of reinforced-concrete elements exposed to high temperatures (Cuce et al., 2023; Ustabas et al., 2024). While these findings underscore the technical feasibility of these materials, their incorporation into real-world construction workflows also depends on addressing practical challenges, such as training construction professionals on their application, ensuring material availability. Furthermore, regulatory adjustments may be necessary to fully legitimize these materials for widespread use. Portland cement-based plaster mortars are widely recognized for their ability to improve the surface of concrete elements and offer protection against carbonation processes, further contributing to their utility in existing construction workflows.

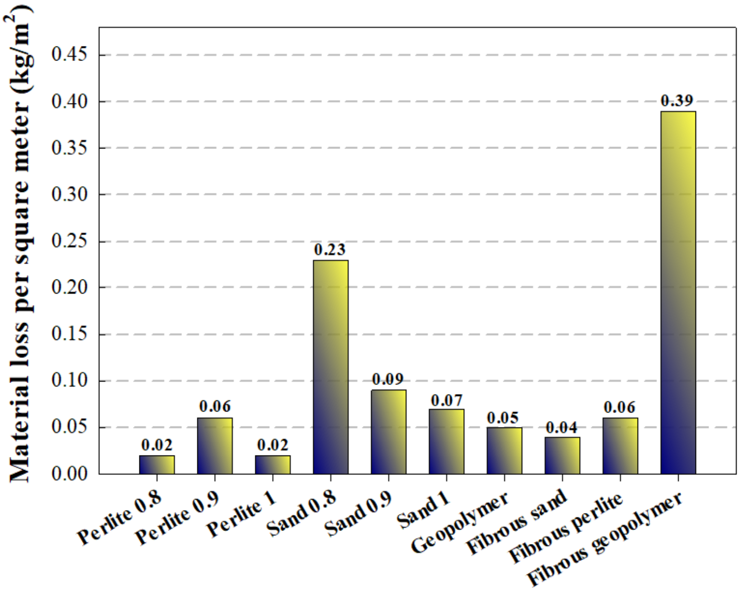


Figure (9): Freeze-thaw test outcomes

CONCLUSIONS

In this study, various types and compositions of plasters are produced using cement and geopolymerization methods in accordance with the TS EN 998-1 standard. The scope of the research included traditional plaster mortar and perlite plaster mortar with water/cement ratios of 0.8, 0.9, and 1. Additionally, mortars produced using the geopolymer method with fly ash and blast-furnace slag, fibrous plaster mortars incorporating polypropylene fibre, and thermal insulation plaster are examined. In total, ten different types of plasters are manufactured. The study investigates the spreadability, flexural and compressive strengths, adhesion strength, capillary water-absorption values, and mass losses of these plaster mortars under freeze-thaw conditions. The findings of this study provide practical insights for engineers and architects into designing durable and energy-efficient building materials. These findings can directly guide material selection and production strategies in construction projects, enabling improved performance and cost-efficiency in real-world applications. For example, the enhanced freeze-thaw resistance of perlite-based plasters offers a viable solution for structures in cold climates. By demonstrating the superior freeze-thaw resistance of perlite-based plasters and the potential of geopolymer plasters, this research offers solutions for enhancing the resilience of building envelopes in extreme climates. The integration of these materials into construction projects can reduce maintenance costs, extend the lifecycle of buildings, and improve occupant comfort. Moreover, this study highlights the role of geopolymer plasters as a sustainable alternative to traditional Portland cement-based materials. However, the integration of such innovative materials into existing construction workflows requires a comprehensive assessment of compatibility with current industry practices and regulatory standards. These considerations are critical for the large-scale adoption of sustainable alternatives, like geopolymer plasters. The use of industrial by-products, such as fly ash and blast-furnace slag, not only reduces landfill waste, but also significantly lowers carbon emissions associated with construction materials. This approach aligns with global sustainability goals, promoting the integration of low-carbon materials into mainstream construction practices. Nevertheless, for these materials to achieve broad adoption, it is imperative to evaluate their compatibility with existing regulatory frameworks and construction workflows. Policymakers and industry stakeholders should prioritize developing guidelines and standards that accommodate such innovative materials, ensuring a smooth transition to sustainable construction practices. As a consequence, the conclusions obtained from this study are determined as follows:

- It is observed that the compressive strength of mortars with a low water/cement ratio is higher. Additionally, the addition of fibre to plaster mortars increases their flexural strength, but does not affect their compressive strength.

- Increasing the water/cement ratio of the mortar raises its consistency, which elevates its adhesion strength. However, adding propylene fibre to the plaster mortar reduces the adhesion strength.
- It has been stated that the capillary water-absorption values of mortars produced by the geopolymerization method are higher than those of perlite and sand mortars.
- As the water/cement ratio of the mortars amplifies, the amount of material removed from the unit area diminishes.
- In samples produced by the fibrous geopolymerization method, freeze-thaw caused the most material loss.
- Perlite samples have the most minor material loss per unit area in the freeze-thaw environment. This is because the porous structure of perlite enlarges the performance of plasters in the freeze-thaw environment.
- The devices employed allow for the measurement of only the spreading strength of the insulation plaster, with the compressive and adhesion strengths remaining unmeasured.

Perlite aggregate, abundant in Turkey, yields beneficial effects on mechanical properties when incorporated into plaster mortars. However, escalating perlite aggregate volumes may entail a risk of diminishing mechanical properties. The study unmistakably reveals perlite's enhancement of bending-compressive strength and rupture strength. Consequently, various fibre types can be introduced to perlite aggregate to bolster plaster mortar's mechanical attributes. Moreover, plaster development through geopolymerization, using fly ash and blast-furnace slag alongside varying perlite ratios, is feasible. Future plans include thermal characterization measurement of the produced plasters and exploring their contribution to building energy efficiency.

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