

Improving the Thermal and Insulation Properties of Polypropylene Fiber Reinforced Concrete Facade Panels Using Phase Change Material (PCM): An Experimental Analysis

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Abstract Phase change materials (PCMs) have a high capacity to store latent heat, which makes them useful as thermal stabilizers or insulating barriers in various applications. The facade of a building is particularly important for maintaining temperature stability and minimizing energy consumption, as it acts as an envelope that protects the building from harsh weather conditions. To ensure thermal comfort inside the building, it is crucial to minimize heat loss due to differences between indoor and outdoor temperatures. The aim of this study is to reduce heat transfer between indoor and outdoor spaces. To achieve this goal, the study incorporates phase change materials (PCM) into the mortar of facade panels based on PCM's ability on retarding heat transfer and its ability to store heat. A novel experimental system was used for the study, which was created using a comparative method. It's expected that the addition of PCM will reduce the thermal conductivity coefficient of the composite material, resulting in lower energy consumption. The reference mortar used in the study was a prefabricated mixture of polypropylene fiber-reinforced concrete (PPFRC) with a constant water/cement ratio of 0.40. Samples were prepared by adding an organic microcapsule PCM with a melting temperature of 18 degrees Celsius and a diameter of 15 to 30 microns, to the reference mortar at varying rates.

The experiments conducted showed that the expected efficiency in reducing the thermal conductivity coefficient of the PPFRC mortar due to the incorporation of PCM was directly proportional to the amount of PCM used in the reference mortar. As the proportion of PCM used increased, the value of the thermal conductivity coefficient value decreased. However, increasing the ratio of PCM used resulted in a decrease in the density and compressive strength of the composite. Therefore, in this study, the proportion of PCM was determined considering the physical properties and the expected thermal conductivity value of the composite material.

Keywords Thermal Conductivity Coefficient, Thermal Comfort, Phase Change Material (PCM), Facade, Polypropylene-Fiber Reinforced Concrete (PPFRC)

1. Introduction

In the construction and manufacturing industries, technological advances have reduced the time and cost of building construction. Despite these improvements, many of the new techniques have led to the use of lightweight

materials and structures with low thermal mass. This lack of thermal mass, when combined with dynamic thermal excitation, can fail to reduce dynamic thermal load and caused an increase in thermal conductivity, energy consumption for space conditioning, and large temperature fluctuations throughout the day.

For creating environmentally friendly and efficient structures, there is a conflict between the desire to minimize environmental impact and the need to add mass to achieve heat storage. These concerns are fuelled by the effects of global climate change and rising energy costs. Since most energy loss occurs through the facade, the current project focuses on the use of phase change materials (PCM) in the exterior panels of the facade. This approach is intended to create comfortable interior conditions by reducing the temperature difference between the interior and exterior surfaces of the materials, which ultimately lowers thermal conductivity. By taking advantage of their unique thermal and storage properties, PCMs can stabilize and reduce heat transfer. Overall, this strategy aims to balance structural efficiency and thermal performance.

The concept of using PCM -improved building and finishing materials is not new. In fact, several projects were conducted in the 1970s and 1980s that were relatively successful in using various types of organic and inorganic PCMs to reduce peak loads and lower heating and cooling energy consumption. Most of these studies focused on saturating concrete, gypsum, or ceramic walls with paraffinic hydrocarbons [1].

Concrete is a widely used building material that consists of several components, namely cement, water, aggregates, and admixtures. Cement is an important component of concrete because it holds the mixture together when activated by water. To improve its thermal and insulation properties, phase change materials (PCMs) can be incorporated into concrete or mortar either as an additive or during the impregnation process.

A study was conducted to investigate the thermal conductivity of cement mortar composites with the addition of phase change material (PCM). The results showed that the incorporation of PCM into cementitious composites can lead to energy-efficient construction and the production of crack-resistant coatings [2].

Another research team compared the heat storage properties of regular concrete with those of specimens infused with phase change material (PCM), specifically with butyl stearate and paraffin PCM [3]. The team searched for suitable concrete mortars that could exhibit the thermal properties of phase change materials (PCMs) such as paraffin, butyl stearate, and dodecanol. Through experiments, they were able to study the effects of PCM dilution, concrete temperature, and alkali content during the impregnation process. Another group of researchers used the same impregnation method to incorporate sodium thiosulfate pentahydrate ($\text{Na}_2\text{S}_2\text{O}_3 \cdot 5 \text{H}_2\text{O}$) into concrete as PCM [4]. In a separate study, highly porous lightweight

aggregates were used for PCMs as carriers to evaluate their thermal storage capacity [5].

Based on the above studies, it was found that porous concrete has significant absorption capacity, which makes it a practical carrier material to avoid incongruent melting of inorganic phase change materials (PCMs) and improve structural stability over multiple thermal cycles [1]. Nevertheless, some of the PCM integration techniques discussed above have certain drawbacks, including interactions with the building structure, changes in the material matrix, and the risk of possible material leakage [6]. To prevent leakage from PCM and possible interaction with the environment, encapsulation of PCM in rigid capsule shells made of natural or synthetic polymers may be a viable solution [7]. Extensive research data shows that incorporating PCM can lead to significant improvements in building energy efficiency. Published studies have shown that the use of thermal mass in well-insulated structures can reduce energy consumption for heating and cooling residential buildings by 5 to 30% [1].

1.1. Phase Change Materials (PCM)

Phase change materials are a range of functional materials with high energy storage densities over a narrow temperature range, based on their latent heat storage capabilities [8]. PCM when applied to building facades, can help reduce indoor temperature fluctuations, minimize heating and cooling loads, and reduce energy consumption by increasing the thermal capacity of the system. A review of various projects in which PCMs have been used shows that they contribute significantly to improving the energy efficiency of the building by increasing the heat storage capacity of the building elements.

The primary classification of phase change materials (PCMs) is based on the distinction between inorganic and organic PCMs. In addition, various combinations of eutectic PCMs can be used, formed by the combination of two or more PCMs [1]. PCMs can be applied to a system in two ways: Microencapsulation and macro encapsulation. In microencapsulation, PCM can be processed independently of solids or liquids and involves small particles of solid, liquid, or gaseous particles, typically 5-10 μm in diameter, that surround the PCM core material with a tough polymer shell. These encapsulated particles can then be added to any mortar that is compatible with the shell material. Microencapsulation, on the other hand, integrates PCM into some type of packaging, such as a tube, bag, sphere, or other containers. These capsules can be used directly as heat storage devices or incorporated into building elements.

PCMs have great potential for storing both latent and sensible heat, which makes them quite advantageous. In addition, PCMs have the advantage of undergoing isothermal phase transitions. However, heat transfer during phase transitions in PCMs is quite complex due to their nonlinear nature and the different thermal and physical

properties of their liquid and solid phases [9].

The latent heat storage capability of phase change materials (PCMs) and their ability to retard heat transfer are expected to reduce heat loss due to temperature differences between indoor and outdoor environments. When the outdoor temperature exceeds the melting point of the PCM used in a facade panel, the material begins to melt and stores heat as latent energy until the outdoor temperature falls below the melting point, delaying or preventing heat transfer to the interior. Conversely, when the outside temperature falls below the melting point of the PCM, the stored heat is released, reducing the temperature difference between the interior and exterior. Due to this feature of the phase change material can acts as an insulating barrier in the system.

1.2. Phase Change Process

From a thermodynamic point of view, a change in the entropy of a phase change material (PCM) results in the absorption or release of thermal energy, commonly referred to as latent heat, which depends on the unit mass of the PCM. When thermal energy is added to the PCM, the melting process begins and bonds between molecules are broken. Most PCM consists of a mixture of liquid and solid molecules. The melting phase is an endothermic process in which the solid phase particles gain kinetic energy and heat, breaking the strong bonds between them. Eventually, the molecules rearrange themselves, leading to a change in entropy.

In contrast to the endothermic process of melting, phase change materials (PCMs) undergo an exothermic process during freezing. The transition from the liquid to the solid phase occurs as the temperature decreases, and the particles lose their kinetic energy, causing them to bind together. However, this phase change process can lead to certain problems. For example, if the temperature of PCM drops rapidly and falls below freezing, supercooling may occur. In such cases, the PCM is unstable and can quickly crystallize with minimal disturbances such as stirring or vibration [1].

For building envelope applications, phase change materials (PCMs) typically must undergo a complete phase transition within 24 hours to achieve maximum effectiveness. Therefore, the temperature at which the PCM is installed must fluctuate within its functional temperature range, possibly even daily, to ensure that the PCM undergoes the required phase change.

2. Materials and Methods

The aim of this study was to investigate the physical and mechanical properties as well as the thermal conductivity coefficient of facade panels made of PPFRC mortar with phase change material (PCM) in different quantities. The data obtained from the experiments were analyzed using a

comparison method between the manufactured samples and a reference object placed on the experimental device. The technical properties and mix details of the reference mortar, the PCM used and the composite mortar produced in the experiments are given below.

2.1. Mortar Properties and Materials Used

The reference mix for the PPFRC mortar used in this study was obtained from the Turkish company Fibrobeton. Facade panels made from this mortar are commonly used in architecture for decorative forms with a thickness of 20-25 mm. The mixture consists of white cement as a binder, silica sand as an aggregate, special additives, randomly distributed polypropylene fibers and water with a pH of 7.3. Table 1 lists the technical properties of the PPFRC reference mortar.

Table 1. Technical Properties of PPFRC Mortar [10].

Physical properties		Unit	Quantity	
alkali resistant glass fiber ratio		weight %	2.5-3.5	
Dry Density		g/cm ³	1.7-2.1	
Compressive Strength		MPa	40-80	
Poisson Ratio		-	0,24-0,25	
Expansion limit		%	0.6-1.2	
Strength Properties	Flexural	MOR	MPa	8-20
		LOP	MPa	5-10
		Modulus of Elasticity	MPa	10-21
	Tensile	UTS	MPa	4-7
		BOP	MPa	3-5
	shearing	Out of plane	MPa	4-6
		In-plane	MPa	4-6
		Interlayer	MPa	4-6
	Impact Resistance		kJ/m ²	7-12
Water Absorption		%	8-13	
Drying Shrinkage		%	0.1-0.2	
Thermal Conductivity		W/m. K	0.9-1.5	
Coefficient of Thermal Expansion		x10 ⁻⁶ / °C	10-20	
Flammability class		-	A1 or A2	
Audio Transmission Loss (dB) (Thickness: 15 mm)		125 Hz	27	
		250 Hz	30	
		500 Hz	35	
		1000 Hz	39	
		2000 Hz	40	

Below are the technical data of the components used in

the above mortar:

2.1.1. White Cement

Çimsa Eco White Cement (CEM II /B-L 42.5R) is a type II cement with a 28-day strength of 42.5 MPa. It is classified as type B, which means it contains 21 to 35% additives, and type L, which means it has low/slow strength gain. Figure 1 shows its high whiteness, and Figure 2 presents a scanning electron microscope image (SEM).



Figure 1. Sample picture of cement used [11]

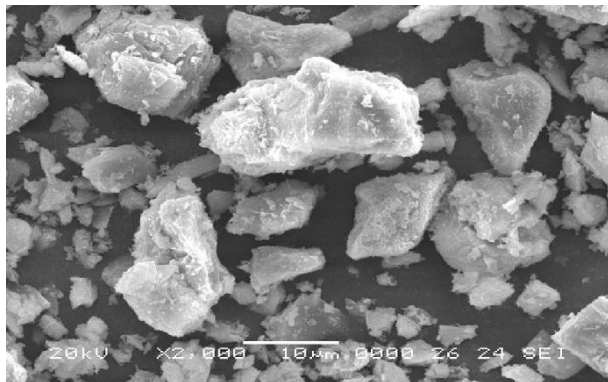


Figure 2. SEM image of cement particle [12].

The cement is environmentally friendly due to its low clinker content and its pure additive content. It offers optimal formulation possibilities for construction chemistry, precast, fiber-reinforced concrete, and gross concrete production. The advantages of Çimsa Eco White Cement include high whiteness, low CO₂ emissions, high durability, low alkali content, and high volume. Tables 2 and 3 provide detailed information on the chemical, mechanical, and physical properties of the cement [11].

Table 2. Chemical features of the cement used [11].

Features	Factory Values	Standart Limits (EN 197-1)	
		Min.	Max.
Insoluble Residue	0.12%	-	-
SiO ₂	17.50%	-	-
Al ₂ O ₃	3.30%	-	-
Fe ₂ O ₃	0.21%	-	-
CaO	63.50%	-	-
MgO	1.15%	-	-
SO ₃	2.80%	-	4.0
Ignition Loss	11.50%	-	-
Na ₂ O	0.25%	-	-
K ₂ O	0.27%	-	-
Chlorine (Cl)	0.0080%	-	-
Free CaO	1.80%	-	0.1

Table 3. Mechanical and physical features of the cement used [11].

Features	Çimsa Values	Standart Limits (EN 197-1)	
		Min.	Max.
Specific Gravity	3.00 g/cm ³	-	-
Blaine	5500 cm ² /g	-	-
Whiteness Y	86.50%	-	-
Vicat Initial Set	110 Minute	60.0	-
Vicat Final Set	135 Minute	-	-
Water Volume	28.60%	-	-
Stability (Le Chatelier)	1.0 mm	-	10.0
Residue at 45 (microns)	1.50%	-	-
Residue at 90 (microns)	0.10%	-	-
Compressive Strength (2 days)	28.0 MPa	20.0	-
Compressive Strength (7 days)	-	-	-
Compressive Strength (28 days)	48.0 MPa	42.5	62.5

2.1.2. Silica Sand

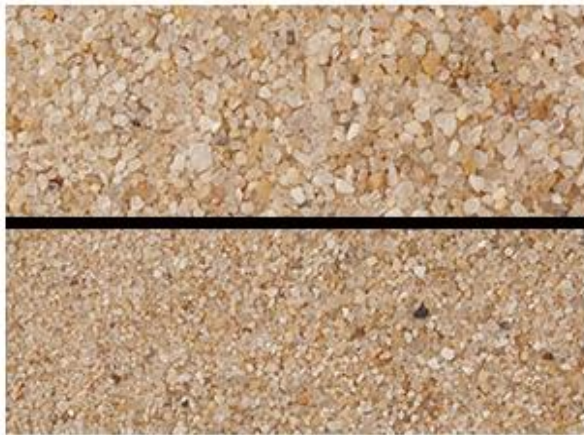
In this study, AFS 30-35 type silica sand with a fineness number of 30-35 according to the American Foundry Society (AFS) classification system was used as an aggregate. This natural mineral product has a high silica content, low volatility and a specific sieve size (see Table 4). The maximum moisture content of the silica used is 0.1%, and the clay content is between 0.1 and 0.35%. The chemical constituents and their ratios are listed in Table 5. The sand is available in light brown and bright white colors, as shown in the optical microscope image (OM) in Figure 3. It is odorless and is used in the form of granules [13].

Table 4. Sieve analysis of the silica sand used [13].

Sieve dimension (Micron)	Range %
+ 1000	0-7
710- 1000	2-12
500-710	20-40
355-500	15-45
250-355	2-25
180-250	1-10
125-180	0-2
90-125	0-1
0-90	0-7

Table 5. Chemical components of the silica sand used [13].

Components	Ratio
SiO ₂	98.6
Fe ₂ O ₃	0.13
MgO	0.03
CaO	0.01
K ₂ O	0.09
Na ₂ O	0.02
Al ₂ O ₃ etc	1.12

**Figure 3.** Sample picture of silica sand used [13].

2.1.3. Fiber

The use of micro synthetic fibers in concrete structures prevents cracks and increases safety and reliability during their service life. It is easy to use because it can be mixed

directly into the concrete, reducing the time and labor required to transport and load conventional reinforcement. The three-dimensional distribution of the micro synthetic fibers in the concrete minimizes damage from freeze-thaw cycles and chemical exposure. Polymono's high binding ability makes it a widely used product for shotcrete applications while being cost-effective and avoiding micro-cracking. In this mix, 6 mm long polypropylene fibers are randomly distributed in the concrete mortar to prevent panel cracking and breakage at low thicknesses. Table 6 presents the general properties of the fibers, while Figure 4 shows a sample view and SEM of the material [14].

Table 6. Properties of the fiber used [14].

Properties	Explanation
Composition	100% virgin polypropylene
Type	Monofilament micro fiber
Impurity	First class pure polypropylene without olefin, polyamide, nylon
Cross Section	Circular
Standard	EN 14889 Part II Type 1A, ASTM C1116 Type III
Tensile Strength	467 - 548 MPa
Elastic Modulus	4048 - 5674 MPa
Elongation	20 - 25%
Specific Weight	0.91 gr/cm ³
Durability	6.5 - 7.0 gr / Denier - High Strength
Color	Transparent
Melting Point	160 °C
Number of Fibers	120 million + / kg
Surface Area	140 m ² /kg
Chemical Resistance	Alkali and acid resistance
Oxidant Resistance	Excellent
Biological Resistance	Excellent
Cement Compatibility	Excellent
Water Absorption	N/A - Hydrophobic

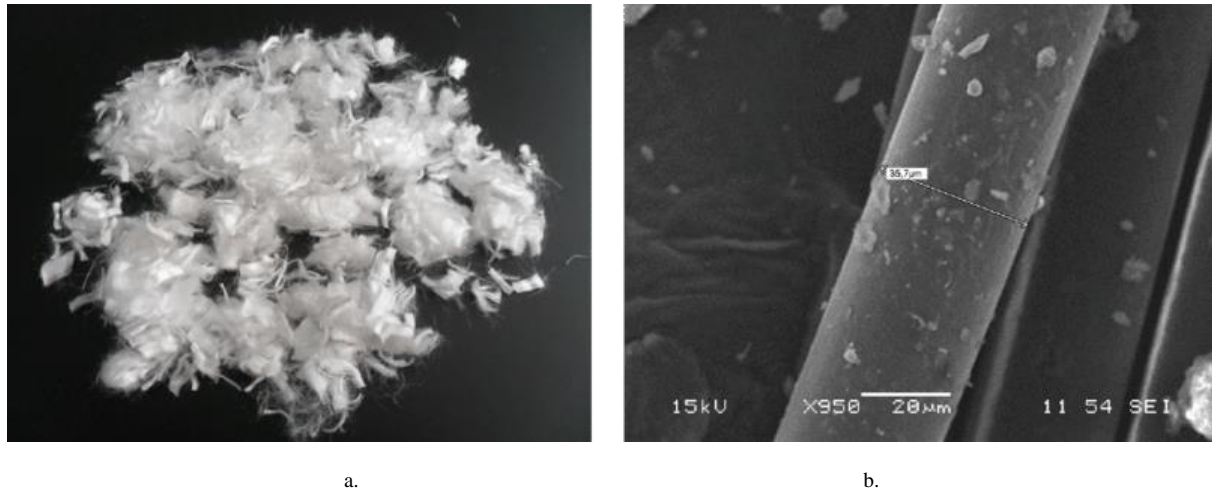


Figure 4. (a) Sample picture of Polypropylene fiber used and (b) SEM of polypropylene fiber ($\times 950$) [14], [15].

2.1.4. Additives

ACS LATEX 5® is an acrylic dispersion additive that improves the quality, adhesion, and impermeability of cement-based plasters and mortars. It improves the performance of the mortar and increases its durability. The technical data of this polymer are listed in Table 7, while Figures 5 and 6 show the SEM image and a sample view of the material. This polymer is widely used in construction due to its superior performance and reliability [16].

Table 7. Technical specifications [16].

Properties	Explanation
Structure of the Material	Modified acrylic dispersion
Color	White
Solids Ratio	0.44
Density	1,10 kg/lt
Application Floor Temperature	+ 5 °C - +35 °C
Service Temperature	- 20 °C - +80 °C

The above values are based on a temperature of 23 °C and 50% relative humidity, and the time required may vary depending on the temperature, i.e., shorter at high temperatures and longer at low temperatures [16].

Here are the advantages of this additive:

- It is able to significantly improve the quality of cement mortars during mixing.
- It contributes to the reduction of mortar shrinkage.
- It provides excellent adhesion and increased wear resistance.
- It does not cause corrosion or damage to equipment.
- It can withstand freeze and thaw cycles.
- It creates a strong and long-lasting bond.

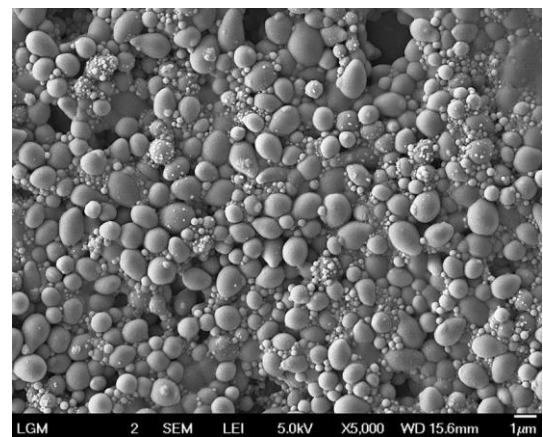


Figure 5. SEM micrograph of the polymer [17].



Figure 6. Sample picture of polymer used.

The plasticizer used in PPFRC blends is BUILDENT WR -780, a low-cost polycarboxylate ether for superplasticizers (PCE). With a solids content of 55%, it exhibits excellent water reduction and good flowability.

The product is designed with an acidic value for stability during transportation but can be easily adjusted to a neutral pH by adding caustic soda (sodium hydroxide) with technical guidance from the manufacturer. Table 8 contains the physical properties of BUILDENT WR -780, and Figures 7, 8, and 9 show the SEM image, molecular structure, and sample view of the material [18]. BUILDENT WR -780 offers several advantages, including reducing the amount of water required in the mortar, improving flowability, and stable performance during the production process. It is also non-corrosive and does not damage equipment.

Table 8. Physical properties of plasticizer used [18].

Properties	Explanation
Appearance	light brown liquid
Odor	Characteristic
Total Solid Contents, %	55% (w/w), approx
pH(undiluted)	2.5
Specific Gravity	1.11 (25 °C)
Viscosity, Brookfield Viscometer, cps	500 (25 °C)

The BUILDENT WR-780 offers several features and benefits, including:

- Strong dispersion effect and excellent water reduction
- Great fluidity and flowability
- Consistent air entrainment
- Low stickiness in concrete
- Cost-effective solution
- Suitable for self-compacting concrete with high flowability
- Ideal for precast concrete
- Increases strength and improves durability
- Low water-cement ratio resulting in high compressive strength.

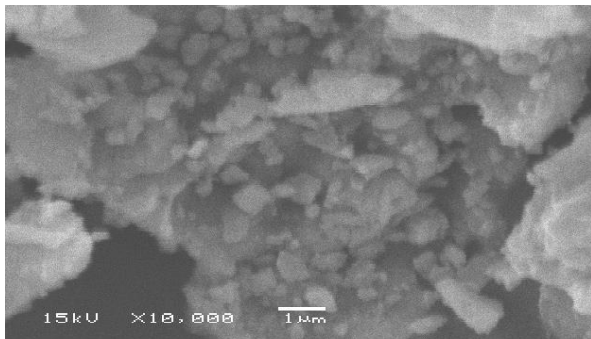


Figure 7. SEM images of PCE sample [19].

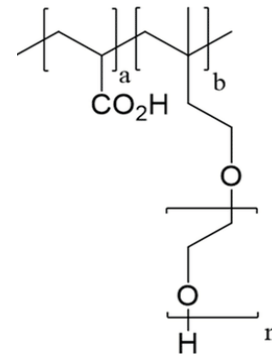


Figure 8. The molecular structure of polycarboxylate ether (PCE) superplasticizer [20].

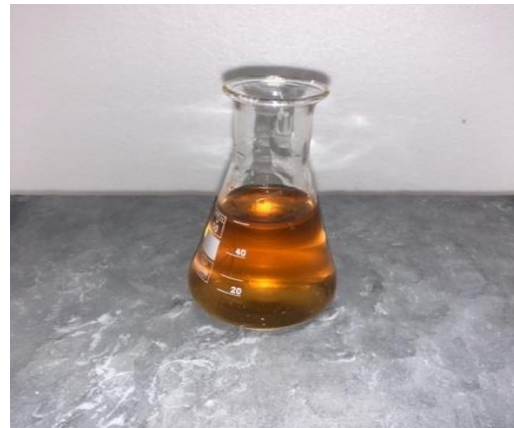


Figure 9. Sample picture of plasticizer.

2.2. Prepared Composite Mortar Mixes With PCM

A homogeneous mixture of phase change material (PCM) and PPFRC mortar was prepared to evaluate the thermal conductivity coefficients of the composite material. One sample was prepared without PCM and served as a reference, while the other samples had different PCM ratios. The addition of PCM to the mortar leads to a significant increase in water consumption. As the water-cement ratio increases, the strength, durability, waterproofing, and other mechanical properties of the mortar decrease significantly [21].

The phase change material used in this study is the commercially available PCM called NEXTEK 18D, manufactured by Microtek company. It is paraffin-based, has a melting point of 18 °C, and is microencapsulated. Microencapsulated phase change materials (MPCM) consist of two components: an outer shell and a core material. Nextek's capsule wall technology is patented and combines strength, high thermal stability, and easy dispersibility. Moreover, this shell is made of a stable, inert, transparent, and thermoplastic acrylic polymer, such as polymethyl methacrylate (PMMA) [22]. Table 9 and Figures 10 to 12 show the characterization of the microcapsule phase change material, including a field emission scanning electron microscopy (FESEM) image, MPCM microstructure, and geometry, with a sample view

of the material used in this research.

Table 9. General features of NEXTEK 18D product [21].

Appearance	White to slightly off-white color
Form	Dry Powder ($\geq 97\%$ Solid)
Capsule composition	85-90% by weight PCM 10-15% by weight polymer shell
Core material	Paraffin
Particle size (mean)	15 - 30 microns (μm)
Melting point	18 °C, 64,4 °F (± 2 °C)
Fusion heat	≥ 190 J/g
Specific Gravity	0.9
Temperature Stability	Extremely stable – less than 1% leakage when heated to 250 °C
Thermal cycle	more than one

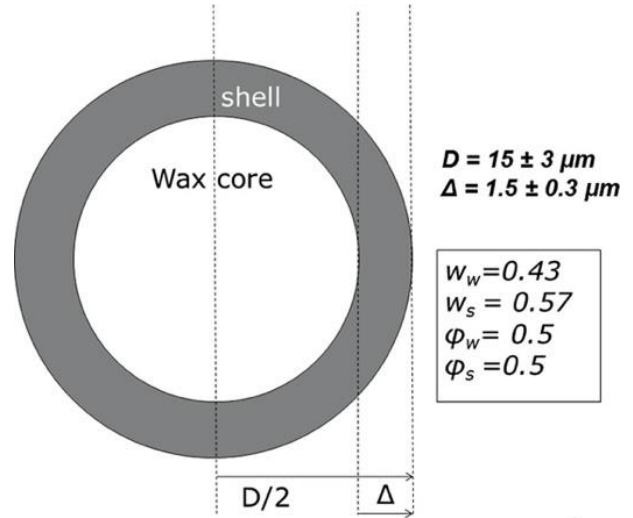


Figure 11. Average core and shell size and geometry of microcapsules [23].

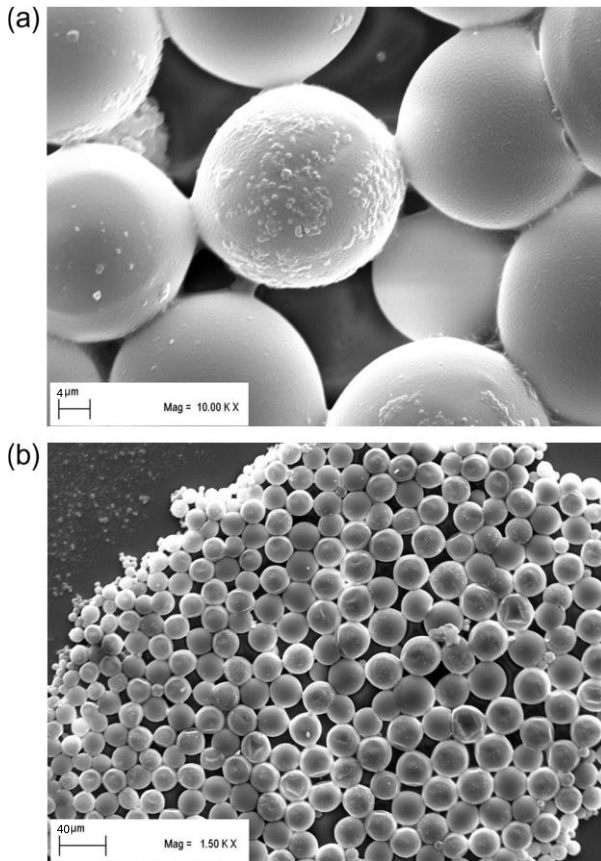


Figure 10. (a) Microstructure of the microcapsule, (b) FESEM image of MPCM [23].



Figure 12. Sample picture of PCM used.

To avoid damage when adding PCM to the mixture and to reduce water consumption, part of the mixing water is used to transform the dry PCM powder into a slurry consistency. With this method, the amount of water used for each sample is up to 67% of the volume of PCM. This method also helps to reduce the water-to-cement ratio of the samples and protect the microcapsules and paraffin inside from wear and damage.

The water-cement ratio is the ratio of water to cement per unit volume of the mortar mix. Too much water consumption can cause the concrete mix to become brittle and porous after curing, and separate sand and aggregate constituents from the cement paste, while a low water-cement ratio cause to higher strength and durability besides this issue, it leads to poor workability of mix and

making difficult to form [24]. To achieve a higher strength of the concrete, plasticizers can be used to increase the flowability of the mortar and to achieve a lower water-cement ratio. The standard range for this ratio is between 0.40 and 0.60 [25]. For this study, a water-cement ratio of 0.40 was used.

The amount of PCM that should be added to the PPFRC mortar was determined based on the total volume of the PPFRC mortar and the density of the phase change material. The specific gravity of PCM was determined to be 0.9 based on the technical data, after which the density was calculated using a formula. The increase in water requirement for the mix can be attributed to the size and density of the particles of PCM.

$$RD = \frac{\rho_{substance}}{\rho_{reference}}$$

RD = Relative Density

$\rho_{substance}$ = Density of the substance being measured

$\rho_{reference}$ = Density of the reference (water)

$$0.9 = \frac{\rho_{NEXTEK\ 18D}}{997}$$

$$\rho_{NEXTEK\ 18D} = 897.3\ \text{Kg/m}^3$$

The percentages of PCM added to PPFRC mortars, are taken as 10%, 20%, 30%, 40%, and 50% of the total volume of PPFRC mortar. To facilitate sample identification, the reference sample was designated as SREF, and the PCM -containing samples were labeled with the prefix SV (Sample by Volume) followed by a number indicating the ratio PCM.

2.3. Physical and Mechanical Properties of PCM Added Composites

The physical properties of the samples are listed in Table 10, while Figure 13 shows a comparison of the respective density values.

Table 10. Physical Properties of the Samples Used in The Experiment

Samples	Avg. Width (mm)	Avg. Thickness (mm)	Weight (gr)	Volume (cm ³)	Density (gr/cm ³)
SREF	100.98	23.01	416.80	184.17	2.26
SV10	100.95	23.16	391.67	185.29	2.11
SV20	100.97	23.18	349.42	185.49	1.88
SV30	101.00	23.20	310.23	185.78	1.67
SV40	100.99	23.19	257.42	185.65	1.39
SV50	100.97	23.02	222.90	184.21	1.21

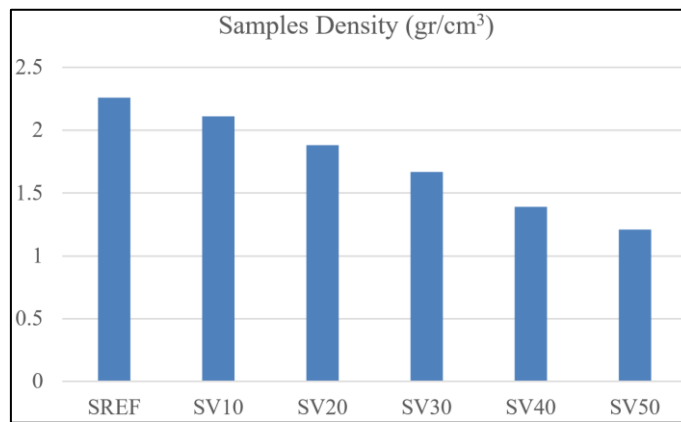


Figure 13. Density Values of The Samples.

Table 11. Compressive Strength Test Results.

Samples	7 th day example1 MPa	7 th day example2 MPa	7 th day example3 MPa	Average MPa
SV10	30.01	29.34	29.62	29.66
SV20	25.89	26.20	26.01	26.03
SV30	22.01	21.65	21.41	21.69
SV40	14.47	14.42	14.58	14.49
SV50	10.21	10.02	10.30	10.18
SREF	45.32	45.55	43.17	44.68

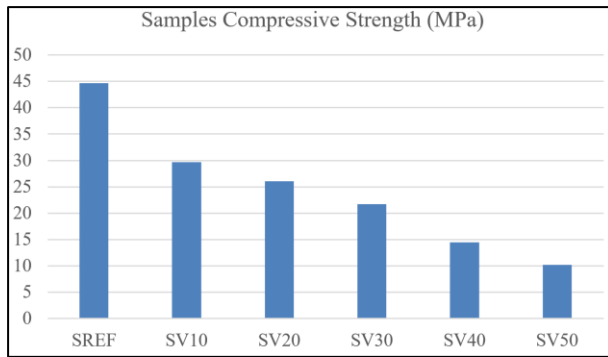


Figure 14. Average Compressive Strength of Samples

To evaluate the effect of PCM on the compressive strength of the composites, three specimens were cast from the prepared test mortars into steel molds of dimensions 40*40*40 mm. The compressive strength of the specimens was measured after seven days using a compressive strength testing device, and the results are shown in Table 11. Figure 14 shows the average compressive strength of the prepared specimens.

The average 7-day compressive strength of the polypropylene fiber reinforced concrete (PPFRC) and precast concrete facade coating mixes ranged from 20 to 34 MPa. The mixes prepared in this study, namely SV10, SV20, and SV30, also exhibited compressive strength values in this range, as described in references [26] and [27].

3. Thermal Experiment Measurements

In the present study, a scientific method, namely the comparative experiment method, is used to determine the thermal conductivity of the prepared samples. In this approach, the thermal conductivity of the test material is measured in comparison with a reference material with a certain thermal conductivity value, both under identical experimental conditions, as shown in Figure 15 [28].

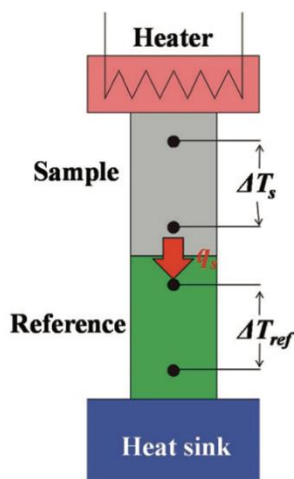


Figure 15. Comparative methods experimental setup scheme [28].

The method presented provides a way to determine the thermal conductivity value of bulk materials without having to directly measure the heat flow through the sample. Instead, a reference sample with a known thermal conductivity is used in conjunction with the sample under examination. When the system reaches an equilibrium state, the amount of heat transferred through the sample should match that of the reference sample, allowing the thermal conductivity of the sample to be determined [28]. For testing purposes, established standards such as ASTM E1225 [29] and ASTM E1530 [30] provide guidelines regarding the equipment and procedures required for the comparison method.

The steps to perform a comparison experiment between samples and a reference object to determine the thermal conductivity value of materials are as follows:

1. Sample selection: a sample and a reference object with known thermal conductivity values were selected.
2. Experimental setup: a device for measuring thermal conductivity, such as a heat flux sensor and a protected hot plate, was set up. It was ensured that the test instrument was capable of measuring temperature differences and recording data.
3. Calibration: The test device was calibrated to ensure the accuracy of temperature and thermal conductivity measurements.
4. Test Procedure: Under the same test conditions, including temperature, pressure, and humidity, the test sample and reference material were placed in the test instrument and the thermal conductivity value of the sample was measured.
5. Data collection: The data obtained was recorded during the test procedure by thermocouples placed in the hot plates which are located on the sample and reference object's surfaces, due to ensure that the measurements were accurate and reliable, the data obtained from the thermocouples were checked at an interval of 15 minutes, and the number that remained constant and did not change within 15 minutes in the thermocouple device was noted as the result.
6. Analysis of data: The data obtained were analyzed to determine the thermal conductivity value of the sample material compared to the reference object. If the heat transfer through the reference object is equal to the heat transfer through the sample and the thermal conductivity coefficient of the reference object was previously determined, the thermal conductivity coefficient of the sample can be determined.

Overall, the method of comparative experiment between specimens and a reference object is a valuable tool for determining the thermal conductivity value of materials. It provides a reliable and accurate way to compare different materials and can be used to identify materials with optimal thermal properties for specific applications.

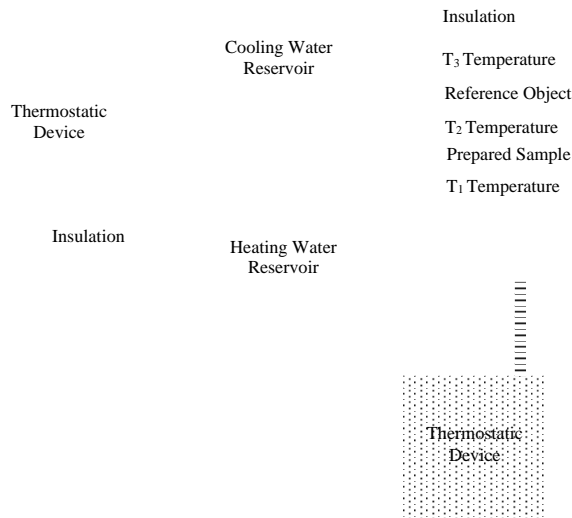


Figure 16. The Experimental Setup Details.



Figure 17. The Experimental Setup, From the Left, Thermostatic Water Bath for Temperature Control, Sample Settlement Part, Istanbul Technical University. Faculty of Mechanical Engineering, Heat Technical Laboratory.

Experiments were performed using an isolated testing device, with all specimens being the same size and 100 mm in diameter and 23 mm thick. To simulate day and night temperatures, the melting point of the MPCM was used at approximately 18 °C, with the temperature raised and lowered in a controlled manner between 14 °C and 30 °C. As shown in Figures 16 and 17, a novel experimental setup was developed with two pools of water on each side of the sample to control the temperature, while a reference object (glass) was positioned in the device to calculate the thermal conductivity values (K) of the samples by comparing the data with the thermal conductivity value. At the beginning of the experiment, the temperature on one side was set at 18 °C to simulate indoor comfort, while the temperature on the other side was gradually increased above 18 °C to 30 °C and then decreased to 14 °C. The values of surface temperature and thermal conductivity coefficient of the samples were measured at 22 °C, 26 °C, 30 °C and 14 °C and then compared with the values of the reference samples.

3.1. Output Data

To calculate the thermal conductivity coefficient, the unit of millivolts output by the thermocouples must be converted to degrees Celsius. Table 12 shows that the thermocouples used are nickel-based, so the K-type table is used for this conversion. To ensure the accuracy of the measurements, the data from three different thermocouples were collected three times at 15 minutes intervals, and the last value that remained constant for the last 15 minutes was used for further processing.

Table 12. Part of Table Type K Thermocouple Reference, Degree Celsius¹.

Thermoelectric Voltage in Millivolts												
-40	-1.527	-1.564	-1.600	-1.637	-1.673	-1.709	-1.745	-1.782	-1.818	-1.854	-1.889	-40
-30	-1.156	-1.194	-1.231	-1.268	-1.305	-1.343	-1.380	-1.417	-1.453	-1.490	-1.527	-30
-20	-0.778	-0.816	-0.854	-0.892	-0.930	-0.968	-1.006	-1.043	-1.081	-1.119	-1.156	-20
-10	-0.392	-0.431	-0.470	-0.508	-0.547	-0.586	-0.624	-0.663	-0.701	-0.739	-0.778	-10
0	0.000	-0.039	-0.079	-0.118	-0.157	-0.197	-0.236	-0.275	-0.314	-0.353	-0.392	0
0	0.000	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397	0
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798	10
20	0.798	0.838	0.879	0.919	0.960	1.000	1.041	1.081	1.122	1.163	1.203	20
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.530	1.571	1.612	30
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023	40
•c	0	1	2	3	4	5	6	7	8	9	10	•c

¹ <https://www.yumpu.com/en/document/view/28040634/type-k-thermocouple-degree-celsius>

3.2. Analysis

The thermal conductivity coefficient (K) is an indicator of the insulating capacity of a material and measures the amount of heat that a material allows to pass through it due to its physical and chemical structure. A low thermal conductivity value is preferred for insulation purposes because it indicates a higher insulating capacity. To determine the thermal conductivity values of the samples, they were compared with the thermal conductivity value of the reference object (glass), using the following calculation method, since the heat passing through the sample is kept equal to the heat passing through the reference object.

$$Q_r = Q_s$$

$$Q_r = \frac{K_r}{d_r} A (T_2 - T_3)$$

$$Q_s = \frac{K_s}{d_s} A (T_1 - T_2)$$

$$\frac{K_r}{d_r} A (T_2 - T_3) = \frac{K_s}{d_s} A (T_1 - T_2)$$

Assuming that the thermal conductivity value of the reference object is 1 W/m.°C, and the measured surface area is the same as that of the samples, the given equation calculates the thermal conductivity value of the samples.

In the above equation, K_r represents the heat transfer coefficient of the reference object (glass), K_s represents the

heat transfer coefficient of the prepared sample (W/m.°C), d_r represents the thickness of the reference object and is equal to 10 mm, d_s represents the thickness of the prepared sample and is equal to 23 mm, A , represents the surface area of the reference object and the prepared samples and is equal to 7.85 mm².

4. Thermal Experimental Results

Based on the results of T_1 , T_2 , and T_3 at the indicated temperature points, the thermal conductivity value (K) and average surface temperature (T_{avg} , was calculated as the average of T_1 and T_2) of the samples were determined. These data were compared to the thermal conductivity and average surface temperature of the reference sample (SREF), and the expected decrease in thermal conductivity for the samples with phase change material (PCM) was observed.

Reviewing Table 13, it was found that the temperature T_1 was increased from 18 °C to 22 °C and a slight decrease in thermal conductivity was observed, especially for the samples with a higher percentage of PCM. This indicates that when the temperature of 22 °C was reached, the PCM just started to melt and the latent heat storage system started to activate.

The relationship between the value of thermal conductivity and T_2 is shown in Figure 18, where T_1 is held constant at 22 °C and T_3 at 18 °C.

Table 13. T_1 : 22°C– T_3 : 18°C, Experimental Results.

Samples	T_2		K (W/m. °C)	T_{avg} (°C)	$T_{avg}-T_3$ (°C)	Thermal conductivity drop rate relative to SREF sample
	MV	°C				
SREF	0.769	19.30	1.11	20.65	2.65	-
SV10	0.769	19.27	1.07	20.64	2.64	3.61%
SV20	0.769	19.25	1.05	20.63	2.63	5.81%
SV30	0.765	19.20	0.99	20.6	2.60	11.20%
SV40	0.761	19.10	0.87	20.55	2.55	21.40%
SV50	0.757	19.00	0.77	20.50	2.50	30.93%

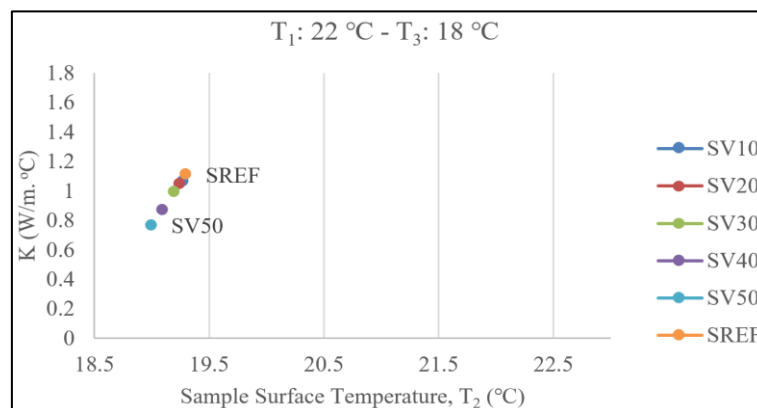


Figure 18. $T_1 = 22$ °C - $T_3 = 18$ °C, Thermal Conductivity, and T_2 Relationship.

Table 14. $T_1: 26^\circ\text{C} - T_3: 18^\circ\text{C}$, Experimental Results.

Samples	T_2		K (W/m. $^\circ\text{C}$)	T_{avg} ($^\circ\text{C}$)	$T_{\text{avg}}-T_3$ ($^\circ\text{C}$)	Thermal conductivity drop rate relative to SREF sample
	MV	$^\circ\text{C}$				
SREF	0.826	20.7	1.17	23.35	5.35	-
SV10	0.786	19.7	0.62	22.85	4.85	46.95%
SV20	0.778	19.5	0.53	22.75	4.75	54.64%
SV30	0.778	19.4	0.49	22.70	4.70	58.30%
SV40	0.769	19.3	0.45	22.65	4.65	61.86%
SV50	0.761	19.1	0.37	22.55	4.55	68.66%

Table 15. $T_1: 30^\circ\text{C} - T_3: 18^\circ\text{C}$, Experimental Results.

Samples	T_2		K (W/m. $^\circ\text{C}$)	T_{avg} ($^\circ\text{C}$)	$T_{\text{avg}}-T_3$ ($^\circ\text{C}$)	Thermal conductivity drop rate relative to SREF sample
	MV	$^\circ\text{C}$				
SREF	0.919	23.0	1.64	26.50	8.50	-
SV10	0.838	21.0	0.77	25.50	7.50	53.25%
SV20	0.826	20.7	0.67	25.35	7.35	59.28%
SV30	0.806	20.2	0.52	25.10	7.10	68.52%
SV40	0.802	20.1	0.49	25.05	7.05	70.25%
SV50	0.790	19.8	0.41	24.90	6.90	75.25%

By increasing the temperature T_1 to 26°C , there was a sudden decrease in both the surface temperature and thermal conductivity values, as shown in the analysis presented in Table 14, and when the temperature T_1 is further increased to 30°C , as shown in Table 15, this decrease continues but slows down in speed and amount. This indicates that all PCM in the samples had melted at this temperature.

The relationship between the value of thermal conductivity and T_2 is shown in Figure 19, where T_1 is held constant at 26°C and T_3 at 18°C .

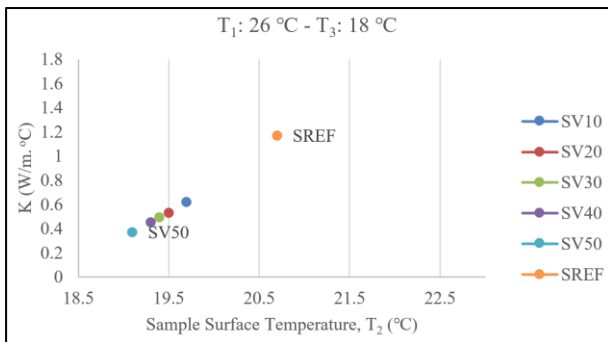


Figure 19. $T_1 = 26^\circ\text{C} - T_3 = 18^\circ\text{C}$, Thermal Conductivity, and T_2 Relationship.

The relationship between the value of thermal conductivity and T_2 is shown in Figure 20, where T_1 is held constant at 30°C and T_3 at 18°C .

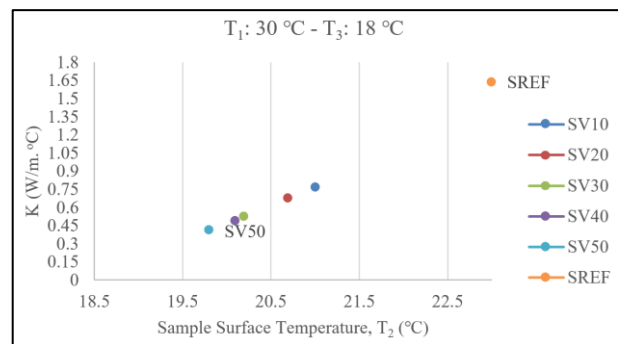


Figure 20. $T_1 = 30^\circ\text{C} - T_3 = 18^\circ\text{C}$, Thermal Conductivity, and T_2 Relationship.

From Table 16, the difference between the average temperature and the value of T_3 was negative when the temperature of T_1 decreased from 30°C to 14°C , which was due to a change in the direction of heat transfer. When the temperature of T_1 dropped below the melting point of the phase change material, the solidification process (discharge) began instead of the melting phase (charge), resulting in the release of previously stored heat and the

formation of a second Q in the system. As a result, the average temperature of the samples increased, which helps to maintain the internal temperature and prevent heat loss. Therefore, the phase change material can act as a heat barrier and regulator.

The thermal conductivity coefficient cannot be calculated with the current formula because the surface temperature (T_2) of the SV30, SV40, and SV50 specimens is higher than the T_3 value. However, despite this limitation, a positive effect on the reduction of heat transfer in the system is observed when the average temperature and the surface temperature are increased compared to the reference sample (SREF) for these three samples.

To calculate the thermal conductivity values of SV30, SV40, and SV50 specimens, a second reference object, such as glass, on the opposite side of the specimens must be

included in the experimental setup. This allows the calculation of the thermal conductivity coefficient for two different Q_s , which can then be compared to evaluate the differences between Q and thermal conductivity values. However, this issue was not addressed in this study and a new experimental setup will need to be developed for future research to further explore this topic.

Figure 21 shows the relationship between T_2 and thermal conductivity values for a system subjected to a discharge process when the temperature dropped from 30 °C to 14 °C (with T_1 at 14 °C and T_3 at 18 °C). It was noted that the current experimental system and conditions did not allow the calculation of the thermal conductivity values of SV30, SV40, and SV50, as explained earlier.

Table 16. T_1 : 14°C– T_3 : 18°C, Experimental Results.

Samples	T_2		K (W/m. °C)	T_{avg} (°C)	$T_{avg}-T_3$ (°C)	Thermal conductivity drop rate relative to SREF sample
	MV	°C				
SREF	0.669	16.8	0.99	15.40	-2.60	-
SV10	0.693	17.4	0.41	15.70	-2.30	59.00%
SV20	0.709	17.8	0.12	15.90	-2.10	87.77%
SV30	0.721	18.1	N/A	16.05	-1.95	105.66%
SV40	0.725	18.2	N/A	16.10	-1.90	111.06%
SV50	0.733	18.4	N/A	16.20	-1.80	121.12%

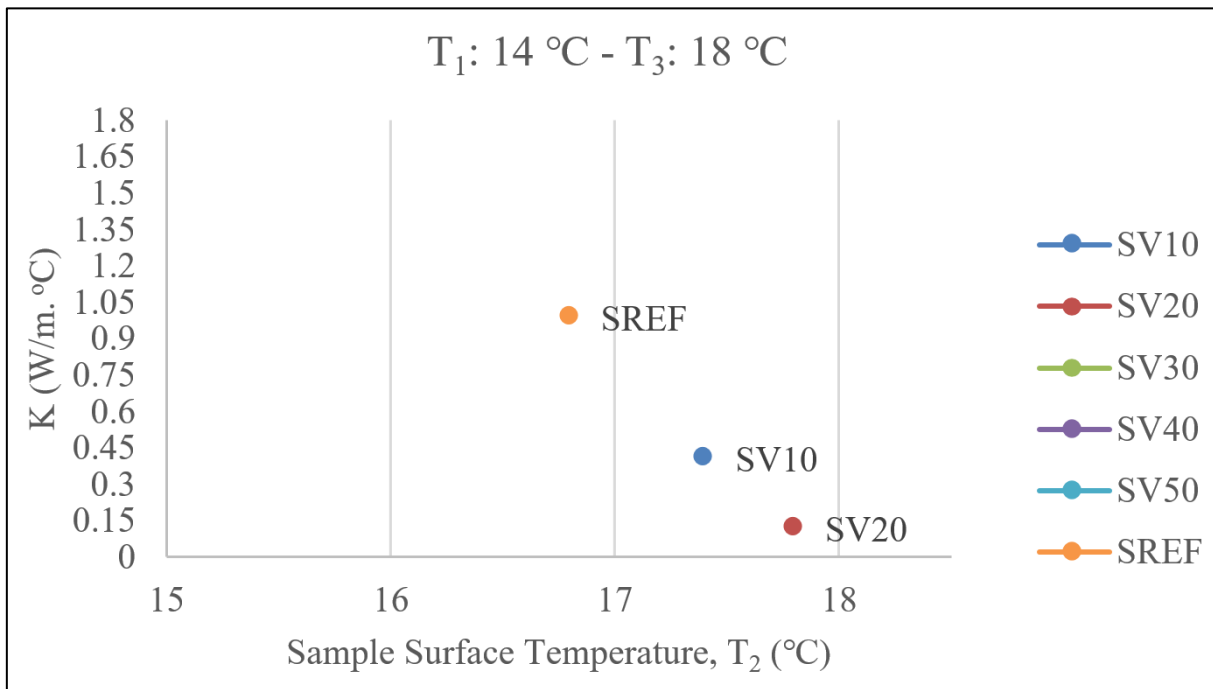
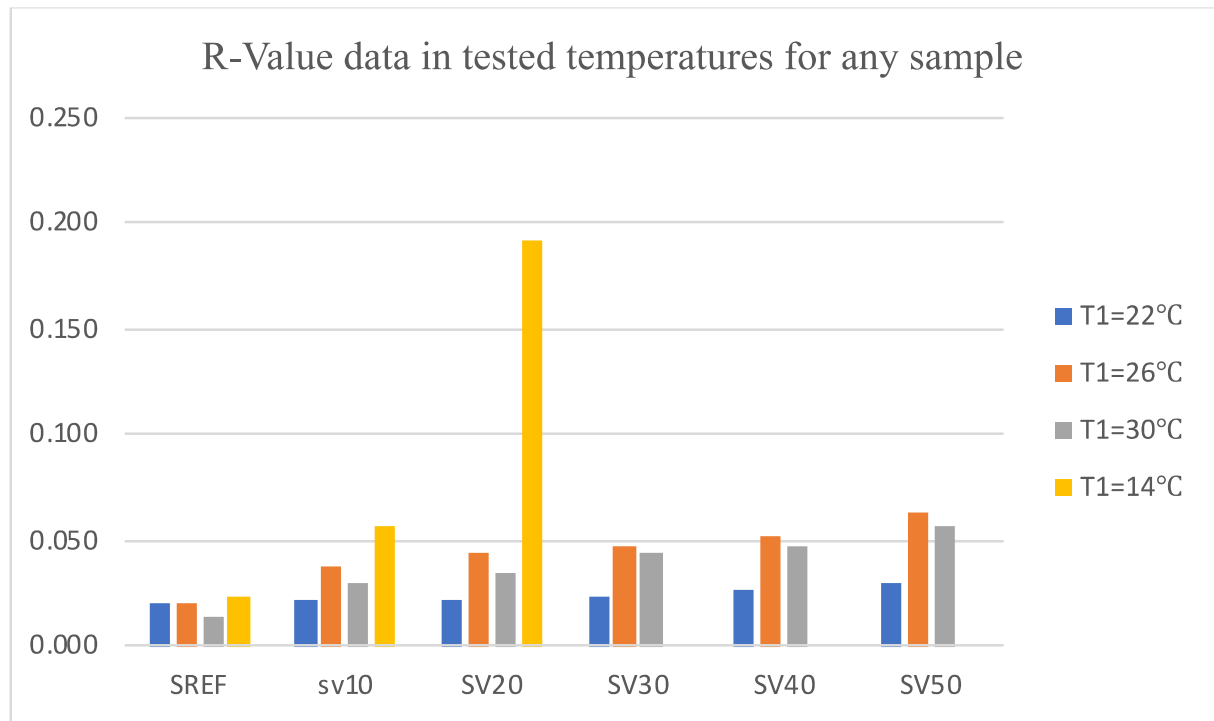


Figure 21. $T_1= 14$ °C - $T_3 = 18$ °C, Thermal Conductivity, and T_2 Relationship.

Table 17. Thermal Resistance Values of Samples.

Samples	R-value (m ² °C/W) (T ₁ : 22 °C)	R-value (m ² °C/W) (T ₁ : 26 °C)	R-value (m ² °C/W) (T ₁ : 30 °C)	R-value (m ² °C/W) (T ₁ : 14 °C)
SREF	0.021	0.020	0.014	0.023
SV10	0.021	0.037	0.030	0.056
SV20	0.022	0.043	0.034	0.192
SV30	0.023	0.047	0.044	N/A
SV40	0.026	0.051	0.047	N/A
SV50	0.030	0.062	0.056	N/A

**Figure 22.** R-Value Comparison of The Prepared Samples

To evaluate insulation performance, the thermal resistance value (R) must be calculated. Thermal resistance is a physical property and is calculated by dividing the two main characteristics of the insulation material, the thickness (d) and the thermal conductivity value (K). Table 17 and Figure 22 show the R-value of the samples at the desired temperatures.

$$R = \frac{d}{K}$$

5. Discussion

Based on the experimental data, it can be concluded that the addition of PCM to PPFRC mortar leads to a significant reduction in the thermal conductivity coefficient of the composite.

The function of PCM is essentially to maintain a constant temperature when the ambient temperature exceeds the melting point of the material. During this process, PCM melts and absorbs energy in the form of latent heat until all the material is melted, which is called the charging process. Conversely, when the temperature drops to the melting point of the material, the PCM solidifies and releases the stored heat to the environment, which is called the discharge process.

Table 18 contains a comparison of the thermal conductivity of samples containing PCM with a reference sample at different temperatures during the charging and discharging phases. The results show that PCM is capable of retarding heat transfer to a large extent. In addition, Figure 23 shows the rate of reduction in thermal conductivity of the samples compared to the reference sample.

Table 18. Thermal Conductivity Coefficient (K) Comparison of the Composite Samples

Samples	Thermal conductivity drop rate compare to SREF (Reference Sample)			
	22 °C	26 °C	30 °C	14 °C
SREF	-	-	-	-
SV10	3.61%	46.95%	53.25%	59.00%
SV20	5.81%	54.64%	59.28%	87.77%
SV30	11.20%	58.30%	68.52%	N/A
SV40	21.40%	61.86%	70.25%	N/A
SV50	30.93%	68.66%	75.25%	N/A

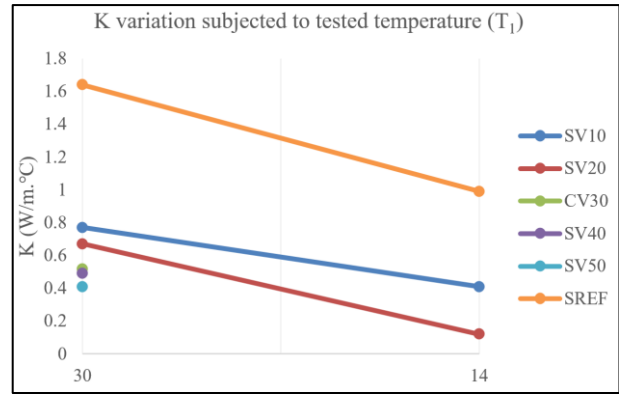


Figure 25. Thermal Conductivity and T_1 Relationship for Discharging Process.

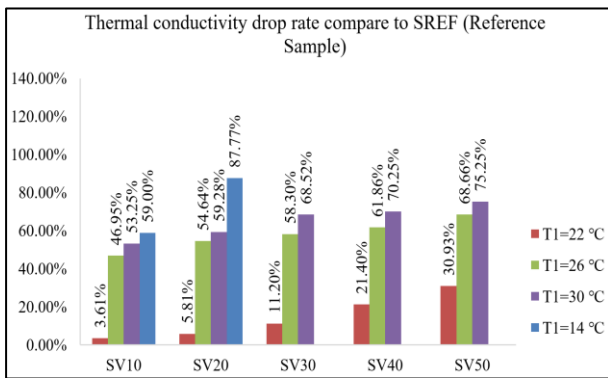


Figure 23. Thermal Conductivity Coefficient Drop Rate Compare to SREF

Figures 24 and 25 illustrate the effects of incorporating phase change material into PPFRC mortar on thermal conductivity values during both the loading and unloading processes.

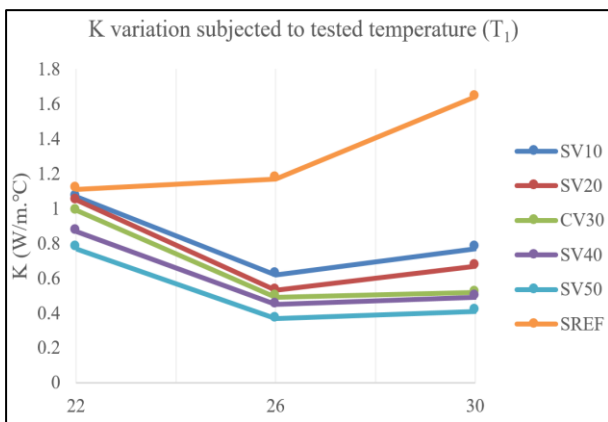


Figure 24. Thermal Conductivity and T_1 Relationship for Charging Process.

6. Conclusions

Global climate change and the energy consumption crisis have prompted researchers to explore new energy sources and find ways to use existing energy more efficiently. All materials undergo a phase transition in response to temperature changes, but there are different mechanisms for energy exchange during this process. Energy exchange can be divided into two groups: The first group involves the physical sensation of temperature increase or decrease, called sensible heat storage. The second group involves the storage of latent heat energy, in which the internal temperature remains constant without any sensation of temperature difference during the temperature rise or fall. Phase change materials fall into the second group because they act as a regulator at certain temperature points and store heat at their melting point during melting. If these materials are incorporated into the exterior facade of a building, they could effectively reduce temperature differences during melting and solidification due to their high latent heat of fusion.

To ensure that a PCM system operates efficiently over an extended period of time, phase change should be continuous and occur at least once a day. Therefore, PCM should be carefully selected from the appropriate group and have a suitable melting point based on the region and climate of the application.

Since the greatest energy waste in buildings comes from the building envelope and the facade, this study focused to reduce the thermal conductivity value of the facade panels by using phase change materials. Microcapsules of paraffin-based organic groups were used as PCM added to existing PPFRC mortars in different proportions of 10%, 20%, 30%, 40%, and 50%.

The results show that when the ambient temperature rises above the melting point of the phase change material (18 °C), in this study up to 30 °C, the PCM starts to melt and stores the excess energy as latent heat, resulting in a small temperature rise. This process reduces the temperature difference between the two sides of the composite sample, resulting in a decrease in the thermal conductivity coefficient. On the other hand, if the ambient temperature drops below the melting point of PCM (18 °C), to 14 °C, PCM starts to solidify and releases the stored heat to the environment. This leads to a decrease in the temperature difference between the two sides of the composite sample and a corresponding decrease in the thermal conductivity coefficient.

As a result, the reduction in thermal conductivity was directly proportional to the amount of PCM used in the primary mortar. However, as the amount of PCM increases, the density and compressive strength of the composite material decrease. Therefore, to achieve the desired mechanical and physical properties of the composite material, including a compressive strength between 20 MPa and 34 MPa, it is recommended to use PCM in a volume ratio of 20 to 30% of the PPFRC mortar. This range of use of PCM provides optimum efficiency in reducing the thermal conductivity coefficient around the melting point temperature of the phase change materials.

The review of numerous studies on the application of PCM in construction has shown that there is considerable potential for future research. Therefore, this study presents a brief compilation of potential areas for future research that includes:

- Develop a selection method for PCM based on the climatic conditions of different regions. For example, in this study, the climate of Istanbul was considered, where temperatures vary from 4°C to 29°C throughout the year and the average temperature is about 18 degrees. Therefore, a phase change material with a melting point of 18 was used.
- Investigation of the advantages of using eutectic PCMs in mixed climates.
- Investigate the use of PCMs with different melting temperatures that can operate more effectively at different temperatures.
- Study of the improvement effects of the use of PCM in the hydration process of concrete and the limitation of shrinkage.

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