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Research Article

Thermal regulation and mechanical performance of cement mortars for building thermal energy storage applications

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ABSTRACT

This study investigated the effects of microencapsulated phase change material (mPCM) with a phase transition temperature of approximately 25 °C on the physical, mechanical, thermal, and microstructural properties of cement mortars. mPCM was incorporated into mortar mixtures at 2.5%, 5%, and 7.5% of the cement weight. The results showed that mPCM decreased consistency and unit weight while increasing porosity and water absorption. The 28-day compressive strength decreased from 49.9 MPa for the reference mortar to 46.7, 44.2, and 38.8 MPa for mortars containing 2.5%, 5%, and 7.5% mPCM, respectively. The 28-day flexural strength decreased by 9.7-26.6%. SEM analyses revealed that void content and microcapsule-matrix interface discontinuities increased with increasing mPCM content. During heating-cooling cycles (0–40 °C), the maximum temperature differences between the reference mortar and the mPCM2.5, mPCM5, and mPCM7.5 mixtures were 1.1, 1.2, and 2.1 °C during heating, and 1.0, 2.0, and 2.8 °C during cooling, respectively. Increasing mPCM content enhanced the thermal buffering capacity, delayed heat transfer, and reduced internal temperature fluctuations. The findings demonstrate that mPCM-modified cement mortars have potential for thermal energy storage and indoor temperature regulation in building applications. The highest thermal buffering effect was achieved with 7.5% mPCM, but this mixture also showed the greatest reduction in mechanical strength. Overall, the study provides valuable information on the combined thermal and mechanical performance of mPCM-modified cement mortars for building thermal energy storage applications.

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1. Introduction

The dramatic increase in energy demand and the resulting intensity crises continue to be a focal point for energy in the building sector. In particular, the share of energy spent on climate control (heating-cooling) in buildings is quite critical. Therefore, minimizing indoor temperature fluctuations and reducing heat loads in sustainable architectural design has led to the dissemination of regional research (Sun et al. 2025; Yu et al. 2026). In this context, intensive studies are being conducted on passive energy storage solutions to both increase ther-

mal comfort and save energy (Cui et al. 2017; Ren et al. 2021).

Limiting thermal fluctuations in the indoor environment through passive systems is one of the most effective ways to increase efficient energy use. The methods used for thermal energy storage (TES) purpose are examined in three basic categories: sensible, latent, and thermochemical storage (Cunha et al. 2016; Jin et al. 2017). Among these methods, latent heat storage is particularly advantageous in the building sector due to its ability to absorb a large amount of energy during phase change. Phase Change Materials (PCMs) balance

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heating and cooling loads by delaying temperature changes with their latent heat capacity during melting and freezing cycles (Alakara et al. 2025a; Alkan et al. 2023).

While the integration of PCMs into building materials offers great potential for thermal management, it also introduces technical limitations. In particular, the leakage problem seen when PCM is directly incorporated into the mixture can negatively affect both the mechanical resistance and durability of the material (Li et al. 2026). To eliminate these risks, various application techniques have been developed, such as direct addition (Li et al. 2013), form stabilization (Fang et al. 2014), impregnation (Zhang et al. 2021a), and encapsulation (Xu et al. 2023). Microencapsulation is a prominent method in cement-based systems because it prevents PCM from leaking into the external environment during phase transition (Essid et al. 2019; Pilehvar et al. 2017).

The use of microencapsulated PCMs (mPCMs) in cement-based mortar and concrete systems contributes to indoor temperature stability by increasing the TES capacity of building components. In particular, when selecting mPCMs, it is critical to maximize energy storage efficiency so that the phase transition temperature is close to the ideal indoor comfort range (20–25 °C) (Zhang et al. 2025).

Although numerous studies in literature have investigated the thermal and mechanical performance of cement-based materials containing mPCM, studies that simultaneously evaluate the effects of different mPCM ratios on physical, mechanical, thermal, and microstructural properties are limited. Furthermore, studies that examine the effects of different usage ratios of a commercial mPCM with a phase change temperature of approximately 25 °C on the physical, mechanical, and thermal performance of cement mortars, along with microstructural observations, are also limited. Therefore, in this study, mortars containing mPCM at 0%, 2.5%, 5%, and 7.5% of cement weight were produced, and the effects of mPCM addition on physical, mechanical, thermal, and microstructural properties were investigated. For this purpose, spread diameter, unit weight, porosity, water absorption, flexural strength, and compressive strength tests were performed. Additionally, SEM analyses were conducted to examine the changes in mortar microstructure caused by mPCM addition. To evaluate the effects of different mPCM ratios on thermal behavior, the internal temperature changes of all mixtures were monitored in real-time in a heating-cooling chamber. Using the obtained results, the effects of mPCM content on physical, mechanical, thermal, and microstructural performance were evaluated comparatively.

2. Materials and Method

2.1. Materials

Cement mortars were produced using CEM I 42.5 R type Portland cement as the primary binder, in accordance with TS EN 197-1 (2012). Mixing water was supplied from the municipal water network. Standardized CEN sand was preferred as fine aggregate. The physical

and chemical characteristics of the Portland cement are summarized in Table 1.

Table 1. Chemical compositions and some physical properties of PC.

Chemical composition	(%)
SiO ₂	21.23
Al ₂ O ₃	5.54
Fe ₂ O ₃	3.79
CaO	62.76
MgO	1.04
Na ₂ O	0.18
K ₂ O	0.25
SO ₃	3.09
Physical properties	
Specific gravity (unitless)	3.15
Blaine fineness (cm ² /g)	3445
Loss on ignition	1.19

The mPCM used in this study is a commercial product produced by microencapsulating a paraffin-based core material with a phase transition temperature of approximately 25 °C within a polymeric shell (melamine formaldehyde). The phase change behavior and heat storage properties of mPCM were determined by differential scanning calorimetry (DSC) analyses, and the results are given in Table 2. The average particle size of the mPCM is 90 µm. The mPCM used in this study is shown in Fig. 1

2.2. Preparation and mixing process of cement mortars

Mortar mixtures were prepared in accordance with Turkish legislation (TS EN 196-1 2016). To directly determine the effects of mPCM addition on the physical, mechanical, thermal, and microstructural properties of cement mortars, the water/cement ratio was kept constant in all mixtures, and no additional chemical additives were used. In the mixing process, PC and water were mixed first. Then, sand was added and mixing was continued. mPCM was added in the final stage to minimize the risk of damage to the microcapsules by the mixer. After the addition of the microcapsules, the mixture was thoroughly mixed to ensure homogeneity. The prepared fresh mortars were poured into molds measuring 40 × 40 × 160 mm for mechanical tests and 100 × 100 × 20 mm for thermal measurements. Thermocouples were placed in the thermal test samples. After 24 hours, the samples were removed from the molds and cured in water at 20 ± 2 °C until testing after 3, 7, and 28 days. Microcapsules were added to cement mortars at 2.5%, 5%, and 7.5% by weight of cement. These ratios were selected considering the additive levels commonly used in cement-based composites in literature (Cao et al. 2019; Djamaï et al. 2019; Ren et al. 2021).

Table 2. Thermal performance characteristics of mPCM after DSC analysis.

	Initial Temperature (°C)	Final Temperature (°C)	Enthalpy (J/g)
Melting point	25.8	36.1	136.8
Freezing point	25.3	16.01	138.4

**Fig. 1.** Photograph of the mPCM used in this study.

Thus, the effects of increasing mPCM content on the physical, mechanical, thermal, and microstructural properties of the mortars could be systematically evaluated. The mixture compositions are given in Table 3. The $100 \times 100 \times 20$ mm cement mortar samples used in thermal experiments were prepared to represent the heating and cooling effects that mPCM-modified cement-based mate-

rials may be subjected to in building applications under controlled laboratory conditions, and to comparatively evaluate the thermal performance of different mixtures. Sample dimensions and experimental procedure were determined by considering similar studies in literature (Alakara et al. 2025a). The mixing, compaction, and molding process steps of the cement mortars are shown in Fig. 2.

2.3. Characterization of mortars

The consistency of the freshly prepared mortar was determined according to the TS EN 1015-3 (2000) standard. Also, some of the physical properties, like density, porosity, and water absorption, were evaluated following the procedures specified in ASTM C642-21 (2021). Experiments to determine the fresh mortar and its physical properties were performed in triplicate for each mixture, and the results were reported as average values. Mechanical performance was evaluated on prismatic specimens with dimensions of $40 \times 40 \times 160$ mm. Flexural strength tests were performed on three prismatic specimens for each mixture. The fractured fragments obtained from the flexural tests were used in compressive strength tests, and the compressive strength results were reported as the average of six measurements for each mixture. Flexural and compressive strength tests were determined in accordance with TS EN 196-1 (2016) by applying loading rates of 50 N/s and 2.4 kN/s, respectively. The fresh and hardened state properties of cement mortars were measured using the experimental equipment shown in Fig. 3.

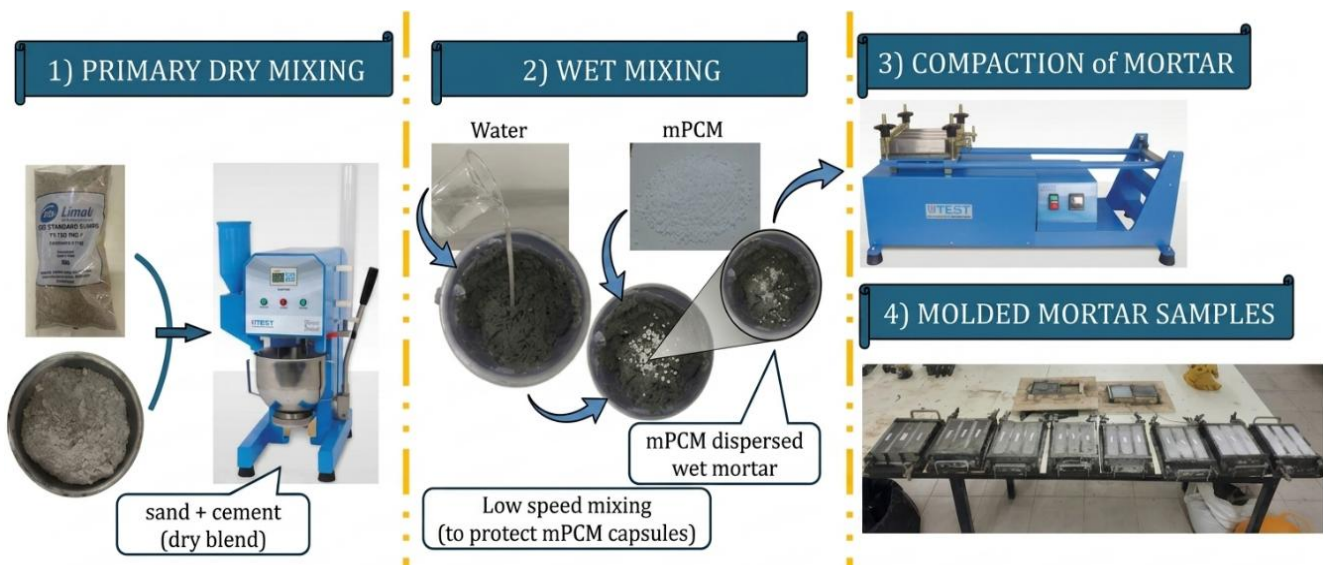
**Fig. 2.** Preparation stages, mixing sequence, and molding process of mPCM-modified cement mortar specimens.

Table 3. Quantities of materials for mortar mixtures

Sample Codes	Cement (g)	Sand (g)	Water (g)	mPCM (g)	mPCM ratio (wt.% of cement)
Ref	450	1350	225	0.0	0.0
mPCM2.5	450	1350	225	11.3	2.5
mPCM5	450	1350	225	22.5	5.0
mPCM7.5	450	1350	225	33.8	7.5



Fig. 3. Experimental test setups used for evaluating mortar properties:
(a) Flow table apparatus; (b) Archimedes balance; (c) Flexural/compressive strength testing machine.

In thermal experiments, one sample measuring $100 \times 100 \times 20$ mm was used for each mixture. For internal temperature measurements, a thermocouple was placed at the geometric center of the sample 10 mm deep from the top surface. The experiments were carried out in a programmable laboratory-type heating-cooling chamber where temperature and holding times could be controlled. The samples were tested without any insulation, and all surfaces were left exposed to environmental conditions. Heating-cooling cycles were applied twice in the temperature range of 0 – 40 °C. To ensure that the samples reached the target temperature and thermal equilibrium was achieved, they were held at the maximum and minimum temperatures for 6 hours. Temperature data were recorded every minute with an accuracy of ± 0.1 °C using a four-channel Testo 176 T4 data logger. Fig. 4 shows an image of the experimental setup and the placement of the thermocouples within the mold.

3. Results and Discussion

3.1. Consistency

The consistency of mortar mixtures was evaluated using the flow table test, and the results are presented in Fig. 5. The spread diameter of the reference mixture was determined to be 155 mm. With the addition of mPCM, a gradual decrease in flow diameter occurred, indicating a

reduction in the workability of the mortars. Compared to the reference mixture, the spread diameters of mixtures containing 2.5%, 5%, and 7.5% mPCM decreased by 3.2%, 9.7%, and 19.4%, respectively. The high R^2 value (0.9524) obtained from the regression analysis shows a strong correlation between mPCM content and spread diameter. This indicates that the addition of mPCM has a significant effect on the fresh-state properties of the mortars.

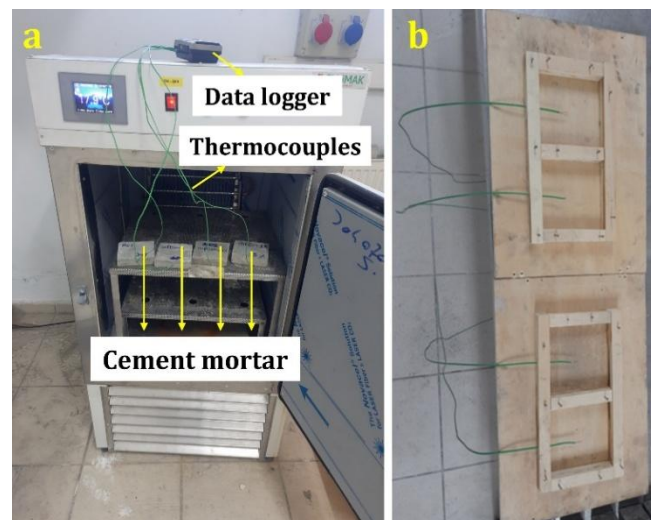


Fig. 4. Thermal performance test setup for cement mortars: (a) Climatic chamber for heating-cooling cycles; (b) Location of thermocouples inside mortar samples.

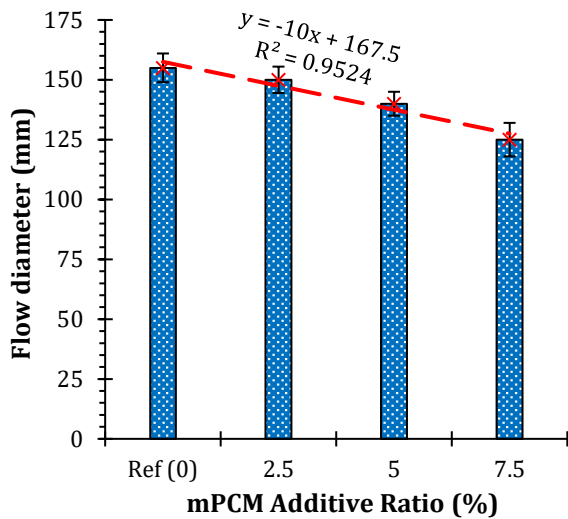


Fig. 5. Flow diameters of fresh mortar.

The workability loss observed with the addition of mPCM can be explained by the fact that microcapsules have a high specific surface area, increasing the water demand in the mixture and limiting the flowability of the cement paste (Cunha et al. 2015). Furthermore, the inclusion of mPCM as an additional fine material in the mixture increases the total solid surface area in the system, leading to a higher water demand. As a result, workability gradually decreased in mixtures prepared with a constant water/cement ratio. The more pronounced

spreading losses observed as the mPCM ratio increases indicate that this effect is dosage dependent. In addition, Zhang et al. (2021b), reported that the workability loss observed in cement mortars may also be due to electrostatic interactions between cement particles and microcapsules.

Similar results have been reported in the literature. Cunha et al. (2015) reported that the addition of 20% mPCM increased the water requirement of the mixtures, and this effect became more pronounced as the mPCM ratio increased. Similarly, Cunha et al. (2013) and Alkan et al. (2023) reported that the use of mPCM reduced the workability of cement-based composites. The results obtained in this study are consistent with these studies and show that the addition of mPCM negatively affects the fresh mortar properties. In particular, the approximately 20% spread loss observed in the mixture containing 7.5% mPCM reveals that workability can become a critical design parameter at high mPCM contents.

3.2. Unit weight, porosity, and water absorption

The unit weight, porosity, and water absorption results of cement mortars are presented in Fig. 6. Examination of the results shows that as the mPCM additive ratio increases, the unit weight decreases, while porosity and water absorption values increase. The high R^2 values (0.9083–0.9899) obtained from the regression analyses indicate strong correlations between mPCM content and the physical properties examined.

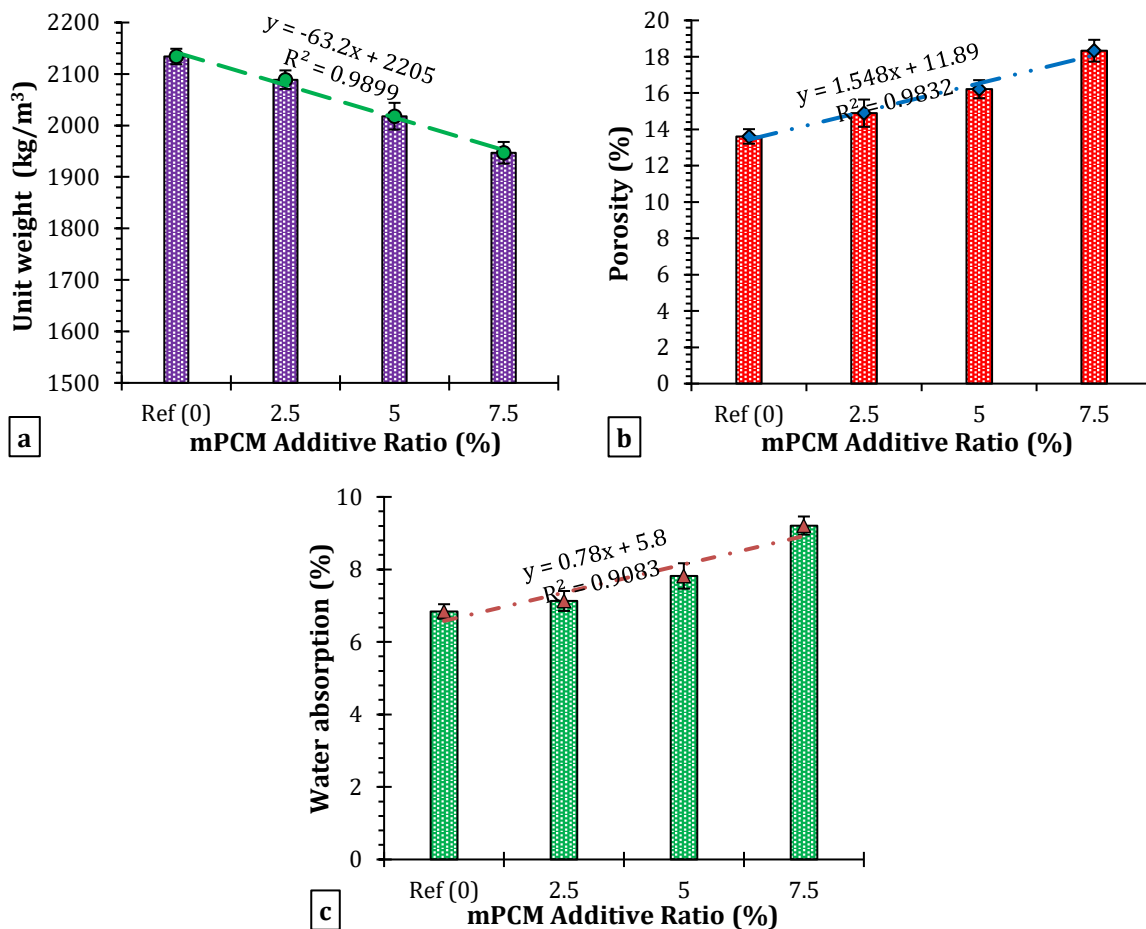


Fig. 6. (a) Unit weight; (b) Porosity; (c) Water absorption values of cement mortars.

The unit weights of the cement mortars ranged from 1947–2134 kg/m³. The unit weights of mortars containing 2.5%, 5%, and 7.5% mPCM additives decreased by 2.1%, 5.4%, and 8.8%, respectively, compared to the mortar with the Ref code. This decrease in unit weight is due to mPCM having a lower density compared to cement. The microcapsules added to the mixture reduced the amount of dense solid phase in the mortar, resulting in lower unit weight values. Similarly, Cao et al. (2017) and Cunha et al. (2015), reported that the addition of mPCM reduced the density of cement-based composites. The results obtained in this study are consistent with these studies and show that the use of mPCM contributes to the lightening of mortars.

Increasing the mPCM additive ratio resulted in significant increases in the porosity and water absorption values of the mortars. Porosity values ranged from 13.61–18.33%, and water absorption values ranged from 6.84–9.21%. Compared to the reference mixture, mixtures containing 7.5% mPCM showed approximately a 35% increase in porosity and water absorption values. This can be attributed to the fact that mPCM, due to its fine-grained structure and high specific surface area, increases the water demand of the mixture. In mixtures prepared with a constant water/cement ratio, the increased mPCM content resulted in insufficient water supply and the formation of additional voids within the matrix (Alkan et al. 2023; Illampas et al. 2021). Furthermore, it is thought that discontinuities formed in the interface regions between the

polymeric shell structure of the microcapsules and the cement matrix also contributed to the increase in porosity. This assessment is supported by the voids observed in SEM analyses and the discontinuities at the microcapsule-matrix interface.

In the literature, it is widely reported that the addition of mPCM negatively affects the porosity and water absorption properties of cement-based composites. For example, Hunger et al. (2009) reported that the porosity of concrete increased from 15.2% to approximately 20.5% with the addition of only 3% mPCM. Similar trends were observed in studies by Alakara et al. (2025a) and Cao et al. (2017). The results obtained in this study are consistent with these studies and show that the decrease in density and the increase in void volume with increasing mPCM content directly affect porosity and water absorption behavior. The significant increases observed, especially in the mixture with 7.5% mPCM additive reveal that the changes in physical properties occurring at high mPCM contents should not be ignored.

3.3. Flexural strength

The flexural strengths of cement mortars were determined on three samples for each mixture, and the results are presented in Fig. 7. Fig. 7(a) shows the flexural strength results, Fig. 7(b) shows the strength losses compared to the reference mixture, and Fig. 7(c) shows the regression relationships between mPCM content and flexural strength.

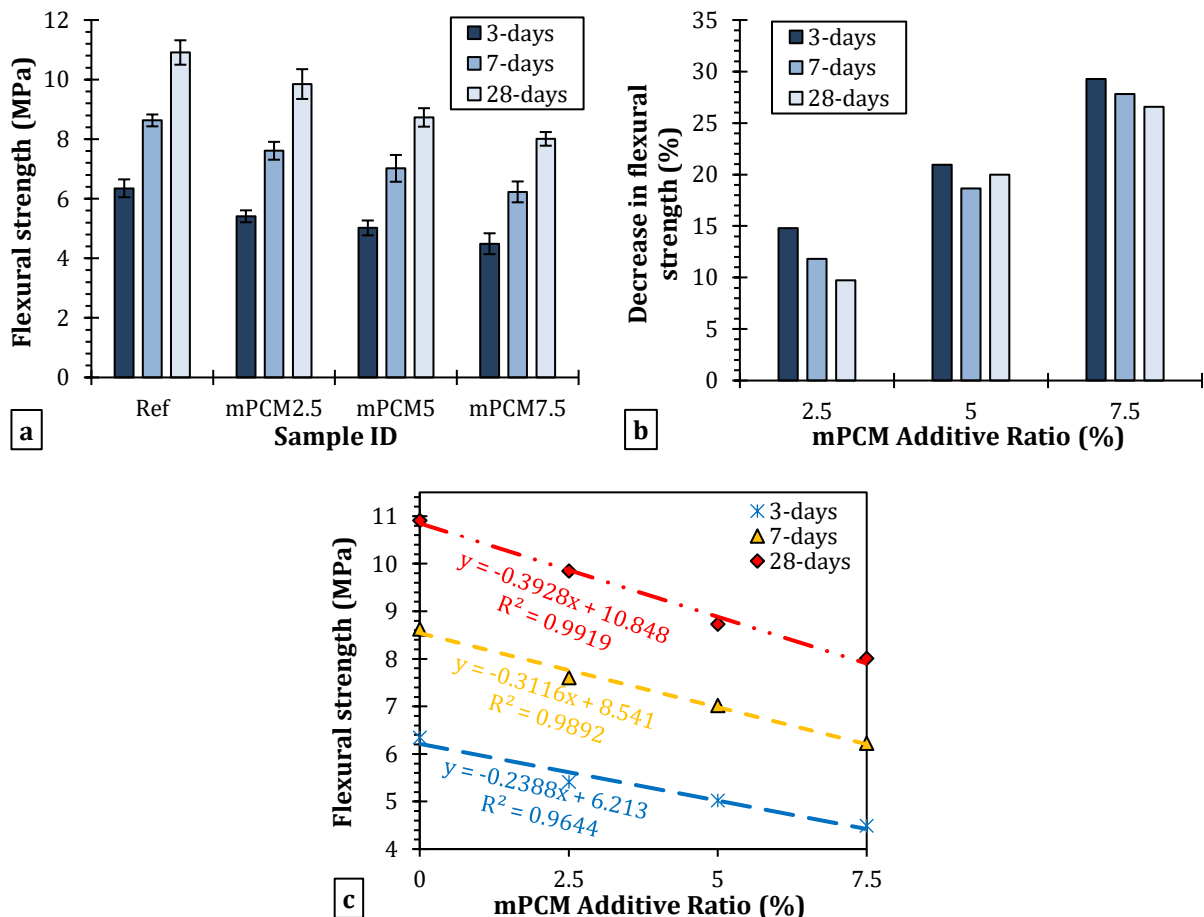


Fig. 7. (a) Flexural strength results; (b) Percentage reduction in flexural strength; (c) Regression analysis of flexural strength.

According to the results obtained, the highest flexural strength was obtained in the reference mixture at all curing times. Flexural strengths increased with increasing curing time in all mixtures depending on the progression of hydration. However, the addition of mPCM negatively affected flexural strength, and the strength loss became more pronounced as the mPCM ratio increased. Specifically, in the 28-day samples, while the flexural strength of the reference mixture was 10.9 MPa, the flexural strengths of the mixtures containing 2.5%, 5%, and 7.5% mPCM were determined as 9.9, 8.7, and 8.0 MPa, respectively. Accordingly, the percentage decrease in flexural strength compared to the reference mixture was calculated as 9.7%, 20.0%, and 26.6%, respectively. Similarly, strength losses occurred in the 3 and 7-day samples due to the addition of mPCM. The regression analyses given in Fig. 6(c) show that there are strong linear relationships between mPCM content and flexural strength. The high R^2 values obtained (0.9644–0.9919) reveal that the decrease in flexural strength is closely related to the mPCM ratio.

The observed flexural strength losses due to mPCM addition can be attributed to changes in the physical properties of the mortars. The results presented in the previous section showed that as the mPCM content increased, the unit weight decreased, while porosity and water absorption values increased. The increased void volume leads to stress concentrations under load, facilitating crack formation and crack propagation. In addition, the lower rigidity of the polymeric shell structure of microcapsules compared to cement hydration products reduces the efficiency of load transfer, negatively affecting flexural strength. Furthermore, the relatively weak structure of the interface zones (ITZ) formed between the microcapsules and the cement matrix may also contribute to strength losses. The voids and interface discontinuities around the microcapsules observed in SEM analyses support this assessment. The fact that cracks primarily start and propagate in these weak zones under load has led to more pronounced flexural strength losses as the mPCM content increases (Alakara et al. 2025b; Cui et al. 2015).

Similar results obtained in flexural strength have also been reported in the literature. Cunha et al. (2015), reported that the addition of 20% mPCM caused a decrease in flexural strength of more than 23%. Studies conducted by Aguayo et al. (2016) and Ren et al. (2021) also found that the addition of mPCM reduced flexural strength. The results obtained in this study are consistent with the aforementioned research and show that although the addition of mPCM contributes to thermal energy storage performance, careful evaluation of mechanical performance is required at high usage rates.

3.4. Compressive strength

Fig. 8(a) shows the compressive strength results of cement mortars, Fig. 8(b) shows the strength losses compared to the reference mix, and Fig. 8(c) shows the regression relationships between mPCM content and compressive strength.

The compressive strength results showed a similar trend to the flexural strength results. The highest compressive strength was obtained in the reference mixture

at all curing times, and the strength values increased in all mixtures with increasing curing time. However, the addition of mPCM negatively affected compressive strength, and the strength loss became more pronounced with increasing mPCM ratio. While the compressive strength of the reference mortar in the 28-day samples was 49.9 MPa, these values were determined as 46.7 MPa, 44.2 MPa, and 38.8 MPa in the mixtures containing 2.5%, 5%, and 7.5% mPCM, respectively. Accordingly, the reduction rates in 28-day compressive strength were calculated as 6.5%, 11.4%, and 22.2%, respectively. Similarly, significant strength losses occurred at early ages as well, and the highest reduction was observed in the 3-day mPCM7.5 mixture with 41.2%. The regression analyses given in Fig. 8(c) show that there are strong linear relationships between mPCM content and compressive strength. The high R^2 values obtained (0.9720–0.9979) reveal that the decrease in compressive strength is closely related to mPCM content.

The decrease in compressive strength can be attributed to the changes in the physical and microstructural properties of the mortars caused by the addition of mPCM. The results presented in previous sections showed that with increasing mPCM content, the unit weight decreased, while porosity and water absorption values increased. In particular, in the mPCM7.5 mixture, an increase of approximately 35% in porosity occurred, while a decrease of approximately 22% in 28-day compressive strength was observed. This indicates that the increase in the void volume within the matrix negatively affects compressive strength by reducing the effective load-bearing cross-sectional area. Furthermore, the fact that mPCM behaves as a low-rigidity phase within the cement matrix and exhibits lower mechanical strength compared to cement hydration products also leads to the less homogeneous distribution of stresses under load. The voids around the microcapsules and matrix discontinuities observed in SEM analyses support the microstructural origin of the decrease in compressive strength, indicating that the compact structure of the mortars is disrupted. The higher strength losses observed particularly at earlier ages indicate that high mPCM contents affect matrix integrity and strength development more significantly.

Similar results have been reported in the literature. Ren et al. (2021), reported approximately 27% and 35% compressive strength loss for 5% and 10% mPCM additions, respectively. Eddhahak-Ouni et al. (2014) reported approximately 32% strength reduction with 5% mPCM use. Furthermore, studies by Pilehvar et al. (2019) and Yeon and Kim (2018) also reported that mPCM addition negatively affects compressive strength. The results obtained in this study reveal that the decrease in matrix compactness and the increase in void volume at high mPCM contents significantly affect compressive strength.

3.5. Results of cyclic heating-cooling tests on mortar samples

To evaluate the temperature behavior of mortars coded Ref., mPCM2.5, mPCM5, and mPCM7.5, they were subjected to heating-cooling cycles in a temperature

range of 0 °C to 40 °C. The samples were held for 6 hours at the lowest and highest temperatures determined during the cycle. Fig. 9 shows the graph of the internal tem-

perature changes of cement mortar samples with dimensions of 100 mm × 100 mm × 20 mm during two consecutive heating-cooling cycles.

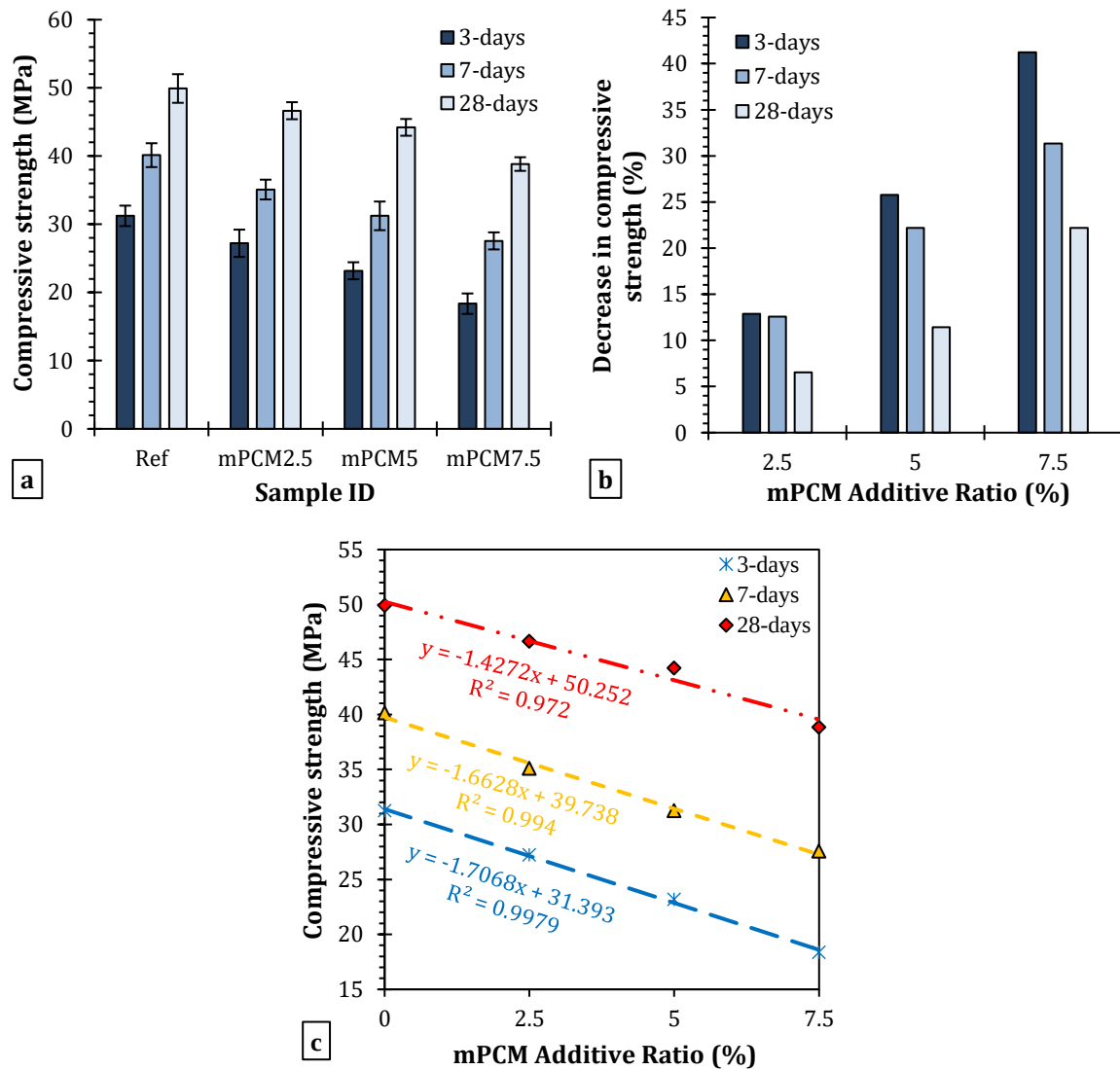


Fig. 8. (a) Compressive strength results; (b) Percentage reduction in compressive strength; (c) Regression analysis of compressive strength.

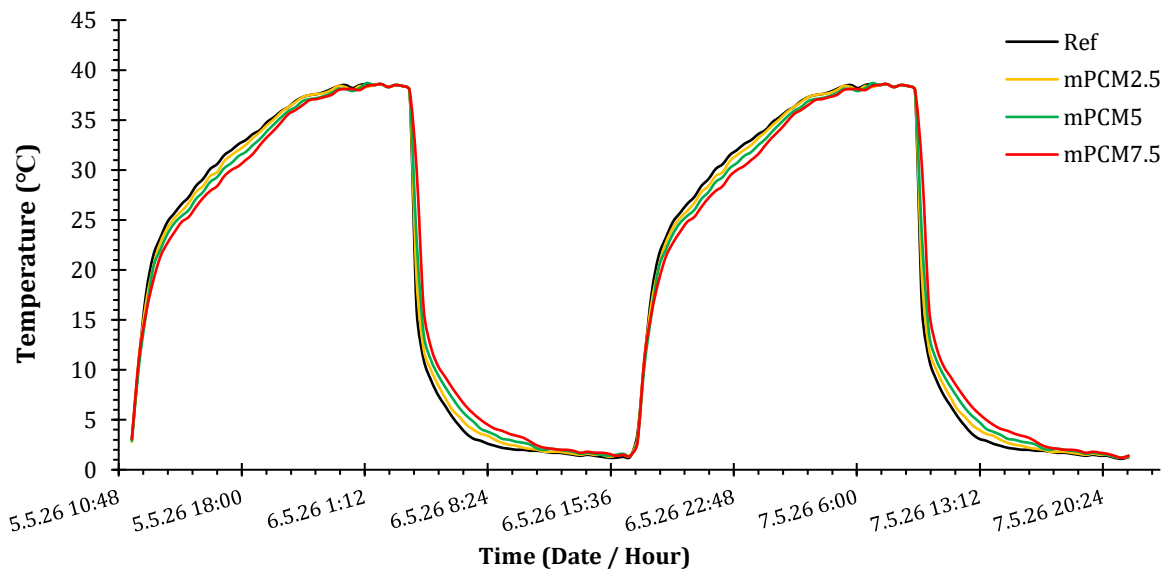


Fig. 9. Internal temperature measurements of mortars after the heating-cooling cycle.

All samples showed similar temperature change trends throughout the cycles. However, it was observed that mPCM-modified mortars heated and cooled more slowly compared to the reference sample. While the reference sample showed a faster temperature increase during the heating phase, the temperature increase in mPCM-modified samples occurred more slowly. This can be explained by mPCM storing some of the heat energy as latent heat during the phase change. Thus, the rate of temperature increase decreases, and a more stable temperature development occurs within the mortar. During the cooling phase, it was observed that mPCM-modified mortars maintained higher temperatures for a longer period compared to the reference sample. This behavior is due to the gradual release of the energy stored during the phase change in the heating process. In conclusion, the addition of mPCM reduced the rate of temperature decrease and increased the thermal inertia of the mortars.

When different mPCM ratios are compared, it is observed that the thermal buffering effect becomes more pronounced with increasing additive ratio. The maximum temperature differences between the reference sample and the mPCM2.5, mPCM5, and mPCM7.5 mixtures during the heating phase were determined to be 1.1, 1.2, and 2.1 °C, respectively. Similarly, the maximum temperature differences during the cooling phase were measured as 1.0, 2.0, and 2.8 °C, respectively. The results show that increasing the mPCM ratio increases the heat storage capacity of the mortars and delays temperature changes more effectively. The higher temperature differ-

ences observed in the mPCM7.5 mixture, in particular, reveal that this mixture exhibits the most significant thermal regulation performance throughout the cycle.

Although the observed internal temperature differences appear limited in absolute terms, temperature buffering effects of approximately 1–3 °C are considered significant for passive thermal energy storage applications (Ren et al. 2021; Wang et al. 2022; Xiong et al. 2021). However, the thermal benefits provided by the addition of mPCM should be evaluated together with the changes in physical and mechanical properties. In this study, while it was observed that internal temperature fluctuations decreased with increasing mPCM content, certain levels of decreases occurred in physical and mechanical properties. Therefore, the practical applicability of mPCM-modified mortars should be evaluated depending on the intended use and performance requirements. While thermal improvements obtained in non-load-bearing structural elements where thermal comfort and energy efficiency are prioritized may provide advantages, the effects of mPCM use in applications requiring high mechanical performance should be evaluated more carefully.

3.6. Microstructural characterization

SEM analysis was performed to evaluate the effects of mPCM addition on the microstructure of cement mortars. Microstructural investigations were carried out on mortars coded Ref and mPCM7.5, which has the highest mPCM content. SEM images are presented in Fig. 10.

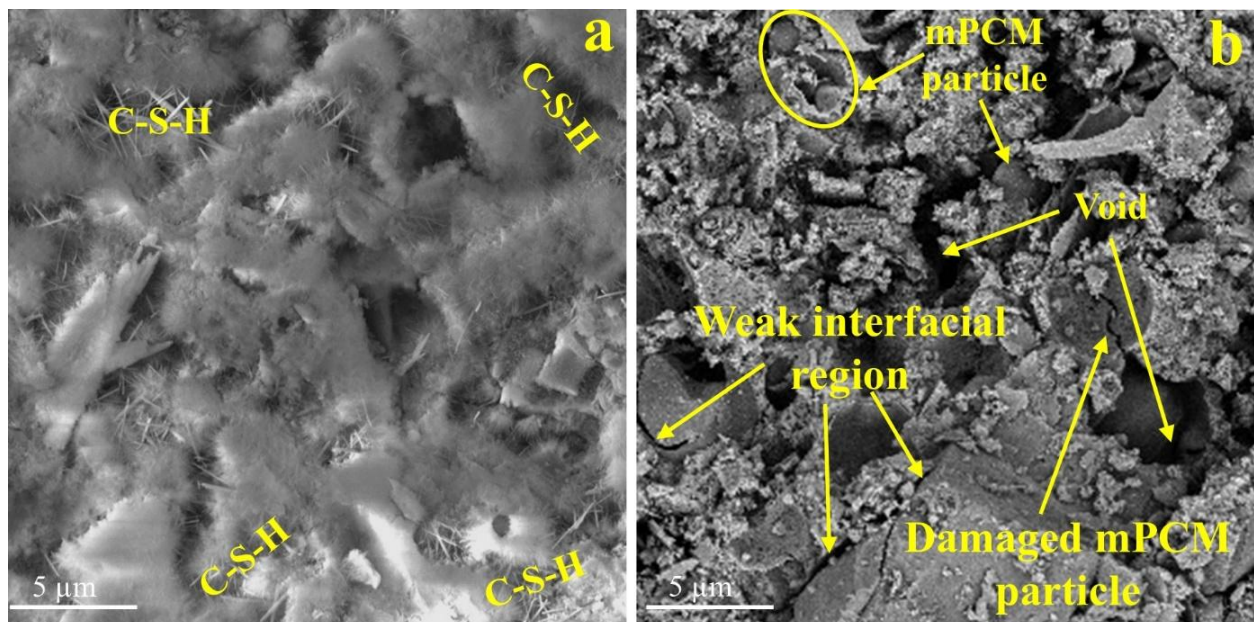


Fig. 10. SEM images of cement mortar samples coded (a) Ref and (b) mPCM7.5.

When the microstructure of the reference mortar is examined in Fig. 10(a), it is observed that the hydration products are well bound to each other, forming a dense and compact matrix structure. While fibrous and needle-like hydration products are commonly observed within the matrix, it is noteworthy that the amount of voids is lower compared to the mPCM-added mortar. The conti-

nunity of the hydration products and the limited voids indicate that the reference mixture has a denser microstructure. This can be considered one of the main reasons why the reference sample exhibits higher compressive and flexural strength. In contrast, in the mortar sample containing 7.5% mPCM, significant microstructural changes are observed in Fig. 10(b). First, the matrix

structure appears to have become more irregular and heterogeneous compared to the reference mixture. The presence of numerous spherical and hemispherical structures in the image indicates that microcapsules are distributed throughout the matrix. However, cracks and deformations are observed on the surfaces of some microcapsules, suggesting that the capsule shells may have been partially damaged during the mixing process or sample preparation. In addition, void formations and weak interfacial regions around the microcapsules are noticeable. This situation indicates that the adhesion between the cement paste and the microcapsule surface is not strong enough. The lower rigidity of the microcapsules compared to the matrix, and the resulting void formation around them, negatively impact the load transfer mechanism. Consequently, matrix continuity is disrupted, and weak regions where stress concentrations can occur are created (Alkan et al. 2023; Djamai et al. 2019).

In general, SEM images reveal that the addition of mPCM increases porosity in the mortar microstructure, reduces matrix integrity, and creates weak regions at the cement paste-microcapsule interface. These microstructural changes can be considered the fundamental factors explaining the mechanical strength losses observed in mPCM-added samples.

4. Conclusions

This study revealed how the addition of an mPCM admixture with a phase transition temperature of around 25 °C at concentrations of 2.5%, 5.0%, and 7.5% altered the physical, mechanical, thermal and microstructural properties of cement mortars. The following results were obtained within the scope of the study:

- The addition of mPCM reduced the consistency of the mortar, resulting in a 3.2%–19.4% decrease in flow diameter compared to the reference mix. The decrease in consistency became more pronounced as the mPCM content increased.
- Increasing the mPCM content reduced the unit weight of the mortars by 2.1–8.8% while simultaneously increasing porosity and water absorption. These changes indicate that the addition of mPCM alters the pore structure of the cement matrix.
- Compared to the reference mortar, the 3, 7, and 28-day flexural strengths decreased by 14.8%–29.3%, 11.8%–27.8%, and 9.7%–26.6% with increasing mPCM content, respectively.
- A similar trend was observed for compressive strength. Although strength losses increased with increasing mPCM content, mortars containing 2.5% and 5% mPCM maintained 28-day compressive strengths above 42.5 MPa. The compressive strength of the mPCM7.5 mixture decreased by 41.2%, 31.3%, and 22.2% on days 3, 7, and 28, respectively, compared to the reference sample.
- SEM observations revealed that increasing mPCM content led to the formation of additional voids and interfacial discontinuities around the microcapsules. These microstructural changes were consistent with

the observed decreases in physical and mechanical performance.

- Thermal cycling tests showed that the addition of mPCM improved the thermal regulation ability of the mortars. The maximum temperature differences between the reference mortar and the mPCM2.5, mPCM5, and mPCM7.5 mixtures reached 1.1, 1.2, and 2.1 °C during heating and 1.0, 2.0, and 2.8 °C during cooling, respectively; indicating that the thermal buffering performance increased with increasing mPCM content.

In summary, the addition of mPCM to cement mortars improved the thermal performance of the mortars by reducing internal temperature fluctuations and delaying heat transfer. However, increasing mPCM content resulted in certain decreases in consistency, unit weight, and mechanical strength values. SEM analyses showed that these changes were related to voids and interfacial discontinuities formed around microcapsules. The results reveal that mPCM-modified cement mortars have significant potential, especially in building applications where thermal comfort and energy efficiency are paramount. Although the highest thermal buffering effect was obtained in the mixture containing 7.5% mPCM, this mixture also showed the highest mechanical strength losses. Therefore, the balance between thermal and mechanical performance should be considered when using mPCM. In particular, mPCM-modified mortars can contribute to increased energy efficiency in non-load-bearing structural elements, interior partition walls, and building envelope applications.

This study is limited to performance evaluations on the material scale. Future studies are proposed to evaluate building-scale energy performance under different climatic conditions using numerical simulations and to investigate the long-term durability properties of mPCM-modified mortars, such as freeze-thaw resistance, sulfate effect, and chloride penetration.

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Conflict of Interest

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Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

The author declares sole responsibility for all aspects of the study, including conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing of the original draft, and writing, review, and editing of the manuscript.

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