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Original Article

Evaluation of Compressive Strength of PCM-Based Cement Mortar

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***Abstract* -** *Phase Change Materials offer the benefit of energy storage through latent heat while requiring less volume compared to alternative thermal storage materials. This study evaluates the compressive strength of cement mortar incorporating Phase Change Materials within building envelope applications. The inert mortar composition of Phase Change Materials (PCMs) facilitates the phase transition between solid and liquid states due to its inherent properties. This study utilises gypsum powder (G) combined with paraffin wax to create PCM aggregates, which serve as a replacement for fine aggregates in cement mortar. The production of gypsum-based PCM cement mortar was accomplished by combining quartz sand, gypsum, and PCM aggregates with water. This was done in order to make use of PPC cement. For the purpose of achieving the optimal needed strength properties of the mortar, an investigation was conducted into the variation in strength qualities that occurred with varied mix proportions of gypsum with PCM aggregates in relation to quartz sand.*

***Keywords* -** *Cement Mortar, Compressive strength, Energy efficiency, Gypsum, Phase Change Materials, Sustainable materials, Smart materials.*

1. Introduction

Researchers are investigating novel construction composites that can enhance thermal performance while preserving structural integrity as a result of the rising demand for environmentally friendly and energy-efficient building materials. Among these developments, Phase Change Materials (PCMs) have drawn a lot of interest because of their capacity to store and release thermal energy, which helps control indoor temperatures and lower heating and cooling energy costs. One promising method to improve building energy efficiency is incorporating PCMs into construction materials, particularly cement-based mortars. Making sure that the mechanical qualities, especially the compressive strength essential for structural applications, are not jeopardized by the addition of PCMs is a crucial integration challenge. A popular material in the building sector because of its affordability, ease of use, and appealing appearance, gypsum can be used as a matrix to add PCMs. To ascertain whether gypsum-based PCM cement mortar is feasible for use in actual construction, it is crucial to assess its compressive strength.

Additionally, because they use natural materials and help with passive thermal regulation in buildings, gypsum-based mortars combined with PCMs provide an eco-friendly solution. Even though PCMs have beneficial thermal properties, their addition to cementitious composites may change the matrix's microstructure and bonding properties, which could have an impact on mechanical performance. Thus, a methodical investigation is required to evaluate the effects of varying PCM types and concentrations on the compressive strength of cement mortars made of gypsum. In order to help develop multipurpose building materials that can satisfy structural and energy efficiency requirements, the current study compares and evaluates the compressive strength of PCM cement mortars based on gypsum. Another goal of this study is to find a framework for maximizing PCM integration without seriously sacrificing the mechanical integrity of construction elements.

2. Literature Review

In recent decades, sustainable building materials have advanced significantly due to population growth and increasing standards of living comfort. Effective utilisation of building envelope materials in structures may reduce issues related to energy consumption and environmental degradation (A.Ali, 2015). Per capita energy consumption reflects a country's standard of living and economic status; hence, nations are concentrating on enhancing their energy-producing capabilities. One way to enhance a building's energy storage capabilities is the incorporation of Phase Change Materials (PCMs) into the structural envelopes

(Brancato, 2019). Phase Change Materials (PCMs) will either conserve or deliver a certain amount of energy in accordance with their characteristics, in contrast to the energy required by the fabric material's temperature during the natural process. Even though salt hydrates and salt mixes are examples of extra mixing ingredients, paraffin waxes and PCMs are the most commonly employed combinations. Additionally, PCMs are utilised for construction exterior materials based on PCMs (A.M. Borreguero, 2010).

It is feasible to incorporate PCM into commonly used building envelope materials for eco-friendly construction. This includes things like concrete, bricks, paints, coatings, slabs, slate, floor, ceiling, wall, floor, ceiling and roofing tiles, boards, paints and coatings (R. Arivazhagan, 2019). Microencapsulated Phase Change Materials (PCMs) are included in building materials such as mortar, concrete, or gypsum during the production of bricks or plasterboards. Macro-capsules of Phase Change Materials (PCMs) are integrated within the vacant areas of buildings, such as beneath floors or above suspended ceilings. These aforementioned techniques have the nature of scientific proposals from the first way, and the next one is pretty easy to use; thermal improvement materials are based on sufficient qualities. These techniques involve the incorporation of PCM into the components of window blinds or furnishings.

The building envelope material incorporating Phase Change Materials (PCMs) can effectively meet physical and thermal properties for several compelling reasons. The utilisation of microencapsulated Phase Change Materials (PCMs) prevents direct contact between the PCMs and mortar, concrete, or gypsum while also enabling the regulation of chemical stagnation within the composites and providing extra control over PCM leakage during the melting phase. The melting of PCM enhances the microstructure of porous materials, hence providing strength to PCM composites (S. Mohaine, 2016).

Moreover, it was determined that various combinations of PCMs and building envelope materials (such as gypsum, concrete, and mortar) have the potential to be beneficial when the appropriate and suitable PCMs are employed (Mankel C, 2019). PCM plastering mortar and concrete brick construction materials incorporating PCMs are designed to enhance energy efficiency due to their inherent properties while also contributing to the structural integrity and stability compared to traditional building envelope materials (S.A. Maciej, 2011).

Direct inclusion, shape stabilization, immersion, and encapsulation are some methods identified for correctly incorporating PCM into building materials. The encapsulation method is a powerful, long-lasting, thermally appropriate, leak-proof PCM integration approach. Macro encapsulation is a simple and smart way to add PCM directly to construction materials (R. Arivazhagan, 2019).

Microencapsulation is an effective technique for protecting sensitive materials from environmental adverse effects, facilitating the safe handling of active materials. The dehydrating property of gypsum at a temperature of 120°C contributes to its fire resistance (Yataganbaba A, 2017). Inorganic materials, particularly in the guise of polymers and phase change materials, serve as both cores and shells. It has been observed that encapsulated phase change materials play a significant role in enhancing the thermal conductivity of the PCM (P.K. Rathore, 2019).

Microencapsulated Phase Change Materials (MPCMs) incorporated directly with construction envelope materials such as cement mortar, brick, wallboard, and gypsum demonstrate significant benefits for buildings. The direct incorporation of wall component materials enhances the efficiency and strength properties of structures when compared to other components for integration (S.A. Memon, 2014).

A mortar specimen was prepared by Frahat to study the effect of Phase Change Materials (PCMs) and Ceramic Fine Aggregates (CFA) on mortar properties. Four mixtures contained varying PCM contents (0%, 12.5%, 25%, and 50%) with 100% natural sand. Additionally, eight mixtures used ceramic fine aggregates replacing sand at 25%, 50%, 75%, and 100% levels, combined with 25% and 50% PCM, respectively. Comprehensive test results revealed no chemical interaction between PCM and cement during hydration. Significant improvements were observed in compressive strength and thermal performance when CFA was used. Specifically, the mix with 50% PCM and 100% CFA exhibited a 37.1% increase in compressive strength, reduced temperatures by 9.5 °C, and a phase change peak shift of 115 minutes. These findings highlight the effectiveness of ceramic aggregates and PCMs in enhancing mortar performance (Frahat, 2023).

Incorporating microencapsulated Phase Change Materials (PCMs) directly into concrete has notable effects on its properties. The addition of PCM leads to a reduction in the compressive strength of concrete, mainly due to the partial rupture of microcapsules and their uneven distribution on the surface. It was observed that with 5% PCM content, the hydration temperature could be reduced by up to 28.1%, although the heating rate remains unaffected. Moreover, increasing PCM content further reduces the thermal conductivity and enhances the heat storage capacity of concrete. Overall, the integration of PCMs improves the thermal performance of concrete, contributing to energy efficiency and savings (Vargas, 2024).

Slag cement combined with microencapsulated Phase Change Materials (PCMs) is used to develop heat storage mortars for radiant floors. Mortar blocks with 0% to 15% PCM content were prepared to study their thermal and mechanical properties. Results showed that adding PCM reduces bulk density, compressive strength, and thermal conductivity by 2%, 24%, and 9% per 1% PCM added. Among the samples, SSC3 (with 1.97 wt% PCM) exhibited balanced thermal and mechanical properties, making it suitable for thermal storage layers in radiant floor heating systems (Li, 2024).

Incorporating Phase Change Materials (PCM) into conventional cement-lime mortars significantly altered their physical, mechanical, and thermal properties. PCM addition reduced the mortar's density and strength but enhanced its heat storage capacity.

Furthermore, including lightweight aggregates and fibres improved the mortar's thermal performance, complementing the effects of PCM. The study also highlighted that the thermal behavior of PCM-modified mortars depends on both their composition and the climatic conditions they experience, indicating the importance of environmental factors in their performance. (Guardia, 2020).

The literature review highlights that incorporating innovative materials like PCMs can improve thermal efficiency, though challenges in maintaining mechanical strength remain. Further research is needed to optimize material combinations for practical applications. Based on that, this study will examine the compressive strength properties of Phase Change Material (PCM) incorporated into cement mortar, utilising various mix ratios of gypsum-based PCM and fine aggregate within cement mortar evaluated.

3. Materials and Methods

The preparation of PCM cement mortar based on gypsum required careful planning. The PCM capsules are mixed into the cement composite mortar using the direct mixing technique. Incorporating a little amount of quartz sand into the cement composite mortar is another method for replacing PCM capsules (P.K. Rathore, 2019). Various methods have been considered for incorporating PCM into gypsum-based PCM mortar; however, direct mixing and replacement techniques are employed in this study.

Gypsum-based PCM cement mortar was made with gypsum powder, paraffin wax, quartz sand, Portland Pozzolana Cement (PPC), and water. When it comes to phase transition materials, paraffin wax was utilized. Gypsum powder, which has a density of 2.64 g/cm-3, is of Type-A β-hemihydrates. 53 Grade Portland pozzolana cement was utilized. Quartz sand with a particle size of 4.75 mm is utilized to make cement mortar based on gypsum.

Need to achieve the optimal attributes of PCM situations, we initially conducted a preliminary study to understand the methodology involved in PCM design. In order to prepare PCM aggregates, paraffin wax Cn H2n +2.C is the carbon, H is hydrogen, and n is no. of molecules, molar mass equal to 785 g/mol and Gypsum powder as β- hemihydrates Type-A grade and 2.64 g/cm-3 density are going to be used. To prepare PCM aggregates, 50 grams of gypsum powder and an equal proportion of paraffin wax were utilized to create the PCM wet mix. In order to facilitate the mixing of gypsum powder and paraffin wax, the paraffin wax was melted to a fluid state at a temperature of 100°C and subsequently mixed with the gypsum powder for 1 hour in a separate container. This process facilitated the transit of the liquid paraffin into the voids of the gypsum.

The next phase was executed with precision, involving the pouring of dissolved wax onto gypsum to create small aggregates having a particle size range of 1.18–5.36 mm. The paraffin-used gypsum aggregates were maintained at ambient temperature to create surface protection and dried at the same temperature for a duration of 4 hours. In order to prevent the cases of PCM from being damaged or fractured due to internal pressure, they were placed in a self-curing arrangement. PCM gypsum-based aggregates passing through a 4.75 mm IS sieve were considered for mortar preparation. Following the preparation of PCM aggregates, various mix proportions were evaluated for the formulation of gypsum-based cement mortar, wherein the mass of quartz sand was substituted in accordance with the gypsum-based PCM aggregates at different mix ratios to investigate the compressive strength characteristics of the gypsum-based PCM cement mortar. The water-cement ratio is taken as 0.55 for all mix proportions to enhance the workability of mortar.

Every item would be helpful and kept at a suitable temperature of 27 ±3ºC. PPC cement must be mixed evenly with a trowel to prevent lumps while making dry mortar composite. Following the dry mixing of quartz sand, PPC cement was added to gypsum-based PCM aggregate, which was evenly distributed according to the design matrix. A well-mixed mortar with a calculated water content was still obtained. To facilitate the removal of test samples, the interior surfaces of iron cube molds should be lubricated with grease prior to casting the wet mortar. The wet, normal mortar and gypsum-based PCM mortar will be applied in three layers and compacted uniformly to prevent the formation of honeycombing. Gypsum-based PCM mortar was prepared according to various mix proportions. The specimens, measuring 70 mm on each side, were employed to assess the compressive strength of the mortar through rigorous testing. Specimens with varying mix proportions are prepared for testing at intervals of 7 days, 14 days, and 28 days following standard curing from the day of casting, respectively. Normal curing is applied to the samples for the strength test. The average compressive strength of normal mortar and gypsum-based PCM mortar, as assessed through these cube specimens, is utilized to determine the actual strength performance of the composite mortar.

Table 1. Mix Proportions of gypsum based PCM cement mortar

S.No	Type of Mix	Cement (gm)	Sand (gm)	PCM (gm)	Water (gm)	Water/ Cement
1	Nominal Mix	200	600	0	110	0.55
2	Mix with 5% PCM	200	600	30	110	0.55
3	Mix with 10% PCM	200	600	60	110	0.55
4	Mix with 15% PCM	200	600	90	110	0.55
5	Mix with 20% PCM	200	600	120	110	0.55

The Universal Testing Machine (UTM), which measures the compressive strength of cement mortar based on gypsum, has a capacity of 200KN. Samples of mortar were tested after the curing phase to determine the compressive strength in relation to the various mix amounts. The evaluation of the compressive strength test results for Gypsum-based PCM cement mortar was conducted in accordance with Indian Standard codes IS: 2250, IS: 2116, IS: 1542, and IS: 650 for cement mortar. The strength assessment adhered to Indian Standard Code IS: 4031 (Part 6), and the test was conducted in duplicate. The mean of the tested outcomes for experimental samples of gypsum-based PCM mortar was documented.

Compressive strength is the capacity of a material to withstand loads that are likely to reduce its size, as opposed to versatility, which is capable of withstanding loads that are likely to increase in size. The compressive strength test results of robust cubes provide insights into the qualities of mortar. The strength of the cubes is typically assessed according to standards after 7, 14, and 28 days for both conventional mortar and gypsum-based PCM cement mortar samples. The compressive strength of a material is the greatest load-bearing capacity at the cross-section of the surface under applied load. Compressive Strength = Maximum Load / Cross-sectional Area (Saxena R, 2019).

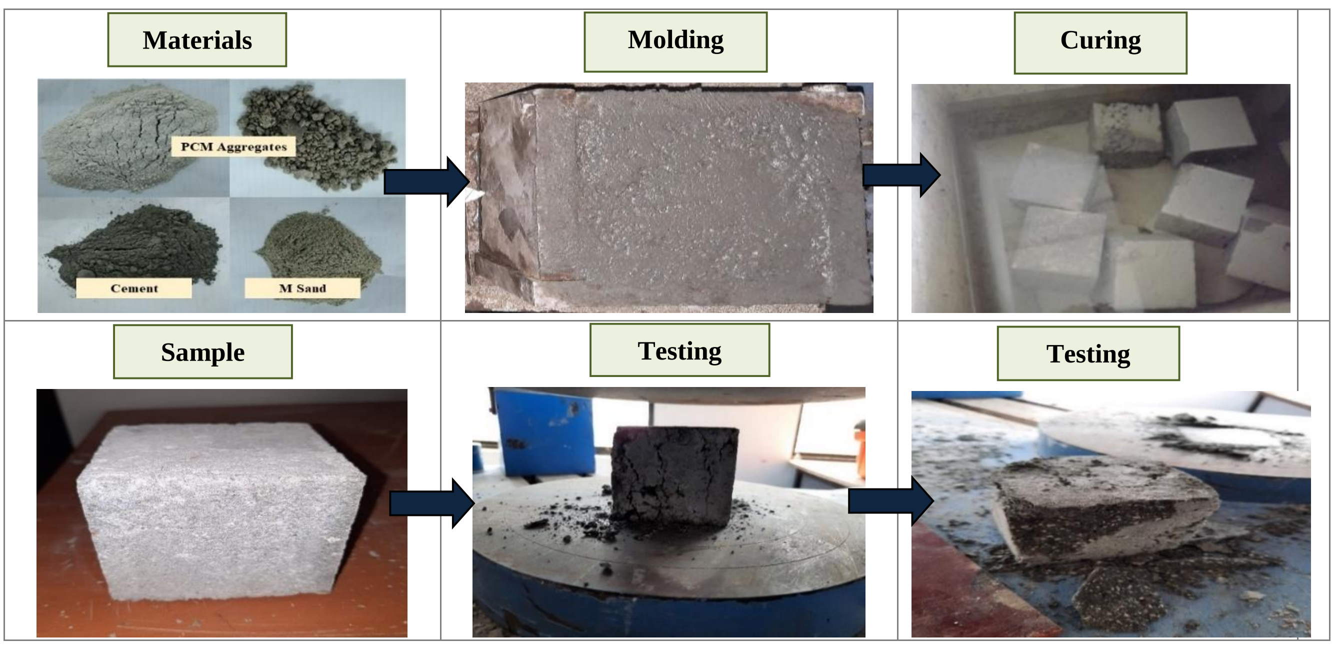

Fig. 1 Materials and testing

4. Results and Discussion

Compressive strength evaluation results for normal cement mortar and gypsum-based PCM cement mortar specimens are mentioned in Table 2; the strength behaviors were increased with respect to the curing days prolonged. The compressive strength ranges from 1800-2800 psi (13 N/mm^2 to 20 N/mm^2) according to the standard codes referred. It is best suited for substructures such as masonry foundations, retaining walls, sewers, manholes, etc. Based on the compressive strength test results of the samples from Mix-2 to Mix-4, they have reasonable compressive strength with respect to all other mix proportions related to standards. A 31% comprehensive strength improvement was observed after 14 to 28 days in samples, according to the variation in strength test results with respect to the quantity fraction of the incorporated gypsum-based PCM available into the mortar was observed. The curing duration influences the strength achievement of the composite mortar. In the encapsulated PCM within the mortar design matrix, the pore structure appears to be enhanced because porosity decreased, thereby enhancing the expandable gypsum in strength.

Table 2. Compressive strength of samples

Sl.No	Mix Proportion PCM added in %	Sample	7 Days N/mm2	14 Days N/mm2	28 Days N/mm2
1	0% of PCM Aggregates	Sample-1	14.67	17.59	21.12
		Sample-2	14.58	17.62	20.14
		Sample-3	14.63	17.61	20.63
2	5% of PCM Aggregates	Sample-1	12.89	14.89	15.38
		Sample-2	13.76	14.79	17.29
		Sample-3	13.32	14.84	16.34
3	10% of PCM Aggregates	Sample-1	11.25	12.85	12.57
		Sample-2	13.24	11.82	12.32
		Sample-3	12.24	12.34	12.45
4	15% of PCM Aggregates	Sample-1	11.32	10.13	10.81
		Sample-2	9.23	11.17	10.85
		Sample-3	10.27	10.65	10.83
5	20% of PCM Aggregates	Sample-1	7.51	8.32	9.75
		Sample-2	9.25	7.04	8.68
		Sample-3	8.38	7.68	9.22

The concentration of gypsum with PCM aggregates in the design matrix, which reflects the tensile properties of the gypsum-based PCM composite mortar, is also partially influenced by the curing duration. The gypsum-based PCM mortar samples exhibited a significant increase in strength toward the 28th day. The comprehensive strength variation in the design mix matrix is influenced by the curing temperature of gypsum-based PCM mortar. It can be observed that the phase change characteristics of PCMs, such as the transition from liquid to solid and vice versa, did not affect the strength across different design matrices of gypsum-based PCM mortar.

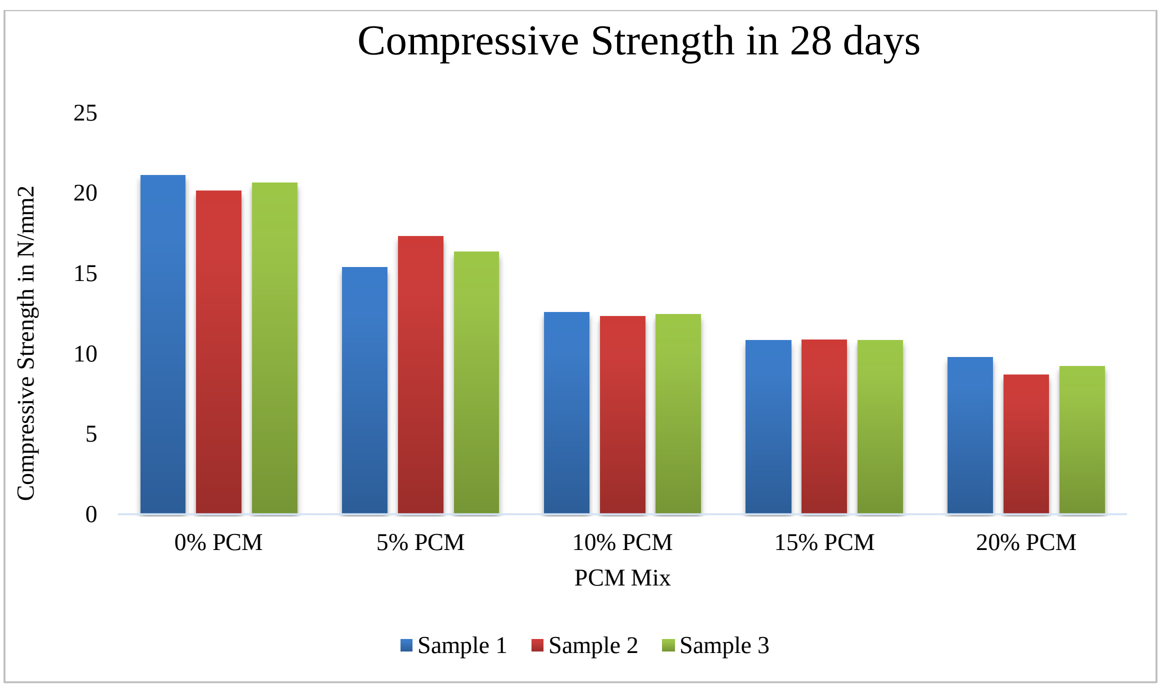

Fig. 2 Strength variations of different mix proportions of gypsum-based PCM cement mortar

Direct integration is the technique that needs the least amount of effort when it comes to fluid and powder mode. The addition of PCMs to building envelope materials, such as gypsum, mortar, and concrete, is a basic process that occurs during the manufacturing process. However, direct mixing is likely to be the most straightforward method due to the fact that it does not require a significant amount of additional equipment. Direct mixing may result in spillage failures, allowing the PCM to leak from the material framework and leading to contradictions with the encapsulation itself. The primary concern regarding phase change materials is their limited application duration in buildings; consequently, additional testing is necessary to assess their long-term durability. Phase change materials encounter several challenges during their phase transitions, including phase segregation, leakage during the melting stage, and issues related to corrosiveness. To address these issues, PCMs are encapsulated. This approach can mitigate the environmental impact on PCMs. This contributes to the prolonged use of PCMs. During the phase transition of PCMs, capsules play a crucial role in managing the volume changes of PCM composites.

5. Conclusion

This research offered an experimental method for gypsum-based PCM cement mortar, which was satisfactorily tested for use in constructing building envelope materials. For the purpose of this investigation, a gypsum-based PCM cement mortar was created by encapsulating gypsum powder, quartz sand, PPC cement, and water with paraffin wax, which served as the PCM, according to the results of the experimental evaluation of the compressive strength of gypsum-based PCM cement mortar, which was examined using a variety of design matrices. After all is said and done, the following points are highlighted from the outcomes of the experimental study.

- As the percentage of Phase Change Material (PCM) aggregates increases, the compressive strength of the concrete samples decreases at all curing ages (7, 14, and 28 days).
- The control mix (0% PCM) exhibits the highest compressive strength, reaching an average of approximately 21.12 N/mm² at 28 days.
- A noticeable decline in compressive strength is observed as PCM content increases, with a reduction from 21.12 N/mm² (0% PCM) to 9.75 N/mm² (20% PCM) at 28 days.
- The 5% PCM mix shows moderate strength retention (15.38–17.29 N/mm² at 28 days), suggesting a possible balance between thermal benefits and structural integrity.
- At 15% and 20% PCM, compressive strength falls significantly, making these proportions unsuitable for structural applications where strength is a primary concern.
- The reduction in strength is evident from the early stages (7 and 14 days), indicating that PCM inclusion affects both early age and long-term strength gain.
- PCM incorporation in concrete should be optimized, likely below 10%, to balance mechanical performance and thermal advantages, ensuring structural reliability.

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