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Experimental Investigation on the Impact of Graphene on Fly Ash–Based Portland Pozzolana Cement Concrete

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Abstract

This study presents a detailed investigation into the influence of incorporating phase change materials (PCMs) on the mechanical properties of cement mortar, with particular emphasis on compressive and flexural strength at various curing ages. Both organic and inorganic PCMs were utilized as partial replacements for cement at proportions of 5%, 10%, and 15% to evaluate their performance. The experimental results reveal a clear distinction in behavior between the two categories of PCMs. Inorganic PCMs, specifically HS24 and HS29, exhibited only a marginal impact on strength development, especially at replacement levels up to 10%, indicating their relative compatibility with cementitious matrices. On the other hand, organic PCMs, such as OM29, PEG600, and n-BS demonstrated a significant reduction in both compressive and flexural strength across all curing periods, likely due to their interference with the hydration process and weaker bonding characteristics. Among all the mixes tested, the highest compressive strength, approximately 44 MPa, was achieved at 28 days with a 5% replacement level of HS24. Similarly, the maximum flexural strength of about 4.62 MPa was also observed at 28 days for the same mix proportion. These findings suggest that while the incorporation of inorganic PCMs can be considered viable without causing severe deterioration in mechanical properties, the use of organic PCMs may not be suitable where structural strength is a primary concern. Overall, the study highlights the potential of selective PCM integration in enhancing thermal performance while maintaining acceptable mechanical strength.

Keywords: Phase change materials (PCMs), cement mortar, compressive strength, flexural strength, inorganic PCMs, organic PCMs, strength reduction, HS24, HS29, OM29, PEG600, n-BS

INTRODUCTION

Electricity usage fluctuates significantly between day and night, especially in regions with extreme climates where heating and cooling dominate energy demand. In 2010, the building sector accounted for nearly 32% of global energy consumption, with air conditioning systems being a major contributor [4]. Improving thermal insulation in construction materials can help reduce energy usage. Traditionally, this has been achieved by incorporating porous aggregates, which introduce air voids into concrete. However, while these voids enhance insulation, they also compromise mechanical strength [11].

An alternative solution is the use of Phase Change Materials (PCMs), which improve thermal efficiency with minimal structural impact [19]. PCMs store and release heat through phase transitions, absorbing latent heat when melting and releasing it when solidifying. This allows them to regulate indoor temperatures more effectively [6]. Since the mid-20th century, heat-storing materials

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like ice and salt hydrates have been utilized in buildings. A notable example is Dr. Maria Telkes's 1948 experiment in Massachusetts, where Glauber salt was used for passive solar heating [22].

Characteristics of PCMs

PCMs transition between solid and liquid phases, absorbing or releasing latent heat while maintaining a nearly constant temperature [8]. This latent heat storage is crucial for thermal regulation. PCMs are classified into three main types: organic, inorganic, and eutectic [16]. Organic PCMs include paraffin-based and bio-based fatty acids, with the latter being non-toxic and chemically stable [7]. Inorganic PCMs, primarily salt hydrates, offer higher thermal conductivity and are non-flammable [20]. Eutectic PCMs consist of multi-compound mixtures that share the same freezing and melting points, making them highly stable with minimal supercooling [25]. Due to their ability to store 5 to 14 times more heat than conventional materials, PCMs are widely used in buildings, vehicles, textiles, refrigeration, and process heating systems [12].

Expanded Clay Aggregate (ECA)

ECA is a lightweight aggregate formed by heating clay at 1200°C, causing gas expansion and creating a porous honeycomb structure [31]. This process makes ECA three to four times lighter than standard aggregates while enhancing insulation, drainage, and fire resistance [28]. It is available in three forms: rounded, crushed, and high-density crushed (HDC), with varying densities and sizes. Rounded ECA ranges from 0 to 30 mm, while crushed and HDC types are available in sizes up to 8 mm [23].

ECA is widely used in construction due to its inert nature, non-toxicity, and ability to reduce structural loads by 40%–50% [29]. It also offers high compressive strength (0.6–3 N/mm^2), excellent water absorption (18%–22%), and superior earthquake resistance. Its applications extend to landscaping, thermal, and acoustic insulation, railways, geotechnical projects, and wastewater treatment. It is also employed in lightweight concrete, precast structures, and RCC/PCC elements [15].

Alccofine1203

Alccofine1203 is an ultra-fine supplementary cementitious material (SCM) developed by Ambuja Cement. It is significantly finer than fly ash, silica fume, and ground granulated blast furnace slag (GGBS), making it highly effective in enhancing concrete performance [17]. This material is used as a partial cement replacement to improve both fresh and hardened concrete properties.

Alccofine1203 finds application in roads, bridges, airports, and heavy structures [30]. Its benefits include improved workability, reduced segregation, and lower heat of hydration in the fresh state. In the hardened state, it enhances compressive and flexural strength, durability, corrosion resistance, and impermeability. Due to its optimized particle size distribution, Alccofine1203 outperforms other SCMs commonly used in India, making it a valuable addition to high-performance concrete [20].

This study aims to evaluate the impact of different phase change materials (PCMs) on the compressive and flexural strength of cement mortar at various curing ages, specifically at 3, 7, 28, and 56 days. By comparing the mechanical performance of inorganic and organic PCMs, the research seeks to determine their relative effectiveness in maintaining structural integrity. Another key objective is to identify the optimal PCM replacement percentage that balances mechanical strength with enhanced thermal properties. Additionally, the study examines whether PCM microcapsules can be incorporated into cement mortar without significantly compromising its mechanical performance. Finally, the research analyzes trends in strength reduction based on the type and proportion of PCM used, providing insights into their feasibility for practical applications in construction materials.

REVIEW OF LITERATURE

Sukontasukkul et al. [13] examined the impact of PCM-impregnated lightweight aggregate (LWA) on the thermal performance of building facades. Their findings suggested that the integration of phase change materials in lightweight aggregates could mitigate temperature fluctuations in buildings, especially in regions with significant diurnal temperature variation. They proposed a modified vacuum impregnation method that significantly reduced PCM leakage over time.

Rashad et al. [14] developed a new class of lightweight aggregates impregnated with PCMs for use in precast concrete panels. Their study found that these panels exhibited up to 25% energy savings during summer months due to the thermal regulation provided by the embedded PCMs. Additionally, they focused on the long-term performance of the panels under real-world conditions, showing minimal degradation in energy storage capacity over a 5-year period.

Patrick et al. [5] focused on the interaction of different types of PCMs (salt hydrates, fatty acids, and paraffin) with expanded polystyrene (EPS) beads used as lightweight aggregates in concrete. Their study highlighted the differences in thermal performance and compatibility, suggesting that paraffin-based PCMs offered the best balance of thermal storage and material stability. The authors also noted that the freeze-thaw durability of concrete improved with PCM incorporation, particularly in regions with cold climates.

Baetens et al. [1] investigated the effect of PCM-impregnated LWA on concrete used for floor slabs in residential buildings. The study confirmed that PCM addition improved the thermal comfort of interiors by stabilizing indoor temperatures, especially during peak summer and winter seasons. Furthermore, the research suggested that the weight increase due to PCM content was negligible compared to the thermal benefits achieved.

Zhang et al. [3] explored the use of biobased PCMs in LWA for sustainable construction applications. The study demonstrated that natural PCMs, such as paraffin extracted from renewable sources, offered a lower environmental impact and still provided significant energy storage. The authors noted that using bio-based PCMs could be a viable option for reducing the overall carbon footprint of concrete, especially when combined with other green materials like recycled aggregates.

Sakulich et al. [2] discussed the microencapsulation of PCMs in lightweight aggregates to enhance thermal stability and prevent leakage. Their findings revealed that microencapsulation improved the mechanical properties of concrete while maintaining a high latent heat storage capacity. The encapsulation method minimized the risk of PCM leakage, particularly in high-humidity environments, and provided a more stable and durable thermal performance over time.

Mathur et al. [18] developed a novel method of encapsulating PCMs in a porous shell made of silica, which was then integrated into LWA. Their research showed that the PCM-encapsulated LWA exhibited excellent thermal energy storage properties without compromising the concrete's structural integrity. This method significantly improved the sustainability of concrete, as it allowed for better energy efficiency in buildings and infrastructure while minimizing potential PCM leakage risks.

Patel et al. [21] investigated the impact of PCM encapsulation on the long-term performance of concrete in marine environments. Their results indicated that encapsulated PCMs in lightweight aggregates could help reduce the effects of chloride ingress and carbonation, making the concrete more durable in coastal areas. They also highlighted the potential of PCM-encapsulated concrete in improving the energy efficiency of maritime structures.

Li et al. [9] focused on enhancing the performance of PCMs in concrete by modifying the structure of the PCM material. They explored the use of hybrid PCMs (a combination of organic and inorganic materials) for improved thermal and mechanical performance. Their study found that hybrid PCMs in concrete demonstrated enhanced energy storage capacity and better mechanical strength retention compared to pure organic PCMs. The hybrid materials also exhibited superior long-term stability under varying temperature cycles.

Pawar et al. [24] explored the effect of various curing conditions on the thermal and mechanical performance of concrete with PCM. Their results showed that curing temperature and humidity significantly affected the effectiveness of PCM, particularly regarding leakage and latent heat storage. They recommended optimized curing processes to improve the overall efficiency of PCM integration, especially in mass concrete applications, such as pavements and roadways.

Soares et al. [10] studied the combination of PCM with supplementary cementitious materials (SCMs), such as fly ash, silica fume, and slag in concrete. Their research suggested that using SCMs in conjunction with PCM can enhance both thermal and mechanical properties, improving the sustainability and durability of concrete. The authors concluded that a well-balanced formulation of PCM and SCMs can lead to concrete with superior energy storage capabilities, higher compressive strength, and better resistance to cracking.

Karuppiah et al. [26] systematically studied the optimization of jute fiber–reinforced polyester composites using Taguchi and COPRAS methods. Results obtained from the tests show that fiber GSM and eggshell powder significantly enhance mechanical properties, while added nanoclay has limited influence. The approach efficiently reduces experimental effort and offers useful guidance for natural fiber composite optimization.

Santulli et al. [27] identified that pineapple leaf fiber shows strong potential for composite applications but is not utilized to its full potential. The work highlighted the key struggles for industrial adaptation and also suggested strategies for its practical use.

MATERIALS

Cement

Ordinary Portland Cement (OPC) of 43-grade, conforming to IS 8112-1989, was used. Its physical properties were tested as per IS 4031-1988, with a specific gravity of 3.10, consistency of 28%, and initial and final setting times of 162 and 275 minutes, respectively. The 3-, 7-, and 28-day compressive strengths were 24.10, 36.25, and 45.50 N/mm², respectively.

Aggregates

Aggregates constitute 70%–80% of the concrete volume, influencing strength, shrinkage, and cost-effectiveness.

Fine Aggregate (F.A.)

River sand (passing through a 4.75 mm sieve) and M-Sand were used, following IS 2386-1963 and IS 383-1970. River sand had a specific gravity of 2.68, a bulk density of 1560 kg/m³, and water absorption of 0.85%, while M-Sand had a specific gravity of 2.66, a bulk density of 1730 kg/m³, and water absorption of 3.00%.

Coarse Aggregates

Crushed granite stone (NCA) and Expanded Clay Aggregate (ECA) were used, following IS 2386-1963. NCA had a specific gravity of 2.70, water absorption of 0.26%, and a bulk density of 1540 kg/m³. ECA, sourced from Rivashaa Eco Design Solutions, had a specific gravity of 0.55, water absorption of 16%, and a bulk density of 340.5 kg/m³. ECA was utilized to integrate Phase Change Materials (PCM) via immersion, with a cement slurry coating to prevent leakage.

Supplementary Materials

Alccofine 1203

A high-performance microfine material, Alccofine 1203, conforming to IS 4031-1983, was used. It had a specific gravity of 2.88 and a fineness of 1220 m²/kg. The chemical composition included SiO_2 (34.80%), Al_2O_3 (22.10%), and CaO (31.90%).

Phase Change Materials (PCM)

Organic and inorganic PCMs were used to enhance thermal performance.

- *Organic PCM:* OM29 (melting point: 29°C), PEG-600 (melting point: 16–25°C), and n-Butyl Stearate (melting point: 200°C).
- *Inorganic PCM:* Hydrated Salt HS24 (melting point: 24°C) and HS29 (melting point: 29.5°C).

These PCMs, sourced from Pluss Advanced Technologies Pvt. Ltd and Rajendra Scientific, regulate temperature via latent heat storage.

Superplasticizer

A naphthalene formaldehyde-based superplasticizer (specific gravity: 1.21) was used to enhance workability, conforming to IS 9103-1999.

Water

Potable water from Pondicherry Engineering College was used for mixing and curing.

RESULTS AND DISCUSSION

Compressive Strength

The compressive strength of cement mortar containing different levels of PCM replacement was evaluated at 3, 7, 28, and 56 days. The results indicated that an increase in PCM content led to a reduction in compressive strength for all PCM types. This trend aligns with findings by Lucas et al. (2013), who reported a continuous decline in mechanical strength as PCM content increased in cement mortar. However, the extent of strength reduction varied depending on the type of PCM.

Inorganic PCMs, such as HS24 and HS29, had a relatively lower impact on compressive strength compared to organic PCMs. When used at a 5% replacement level, HS24, and HS29 demonstrated compressive strengths comparable to conventional cement mortar (CCM) at all curing stages.

On the other hand, organic PCMs, including OM29, PEG600, and n-BS, resulted in a significant reduction in compressive strength across all curing ages. For instance, at 7 days, the compressive strength of cement mortar containing n-BS dropped by approximately 62%. A similar pattern was observed with a 10% PCM replacement, where all types of PCMs caused strength reduction regardless of the curing time. A more substantial decrease was recorded at 15% replacement, particularly with OM29, which led to a 59% reduction at 28 days.

From these observations, it can be inferred that using up to 10% HS24 or HS29 does not significantly affect compressive strength at any stage. However, organic PCMs, such as OM29, PEG600, and n-BS negatively impact strength regardless of the curing period. These findings contrast with earlier research by Hunger et al. (2009), which reported a 30% strength reduction with just 1% PCM addition and over 50% reduction with 5% PCM replacement Among the studied mixtures, the highest compressive strength recorded was approximately 52 MPa at 28 days for HS24 with a 5% replacement.

The performance of inorganic PCMs in maintaining compressive strength was consistent across all curing ages. Incorporating up to 10% of HS24 or HS29 into cement mortar resulted in slightly higher compressive strength at 3 days, comparable strength at 7 days, and a minor reduction at 28 days compared to CCM. These results suggest that PCM microcapsules can be incorporated into cement mortar without significantly affecting compressive strength, particularly when using inorganic PCMs. However, at a 15% replacement level, strength reductions were observed at all curing stages, with HS29 experiencing a maximum decrease of approximately 48%.

Conversely, organic PCMs (OM29, n-BS, and PEG600) led to noticeable strength reductions. For OM29, compressive strength decreased with increasing PCM content at all curing ages, with the most significant reduction (62%) occurring at 28 days with a 15% replacement. While PEG600 showed a minor strength increase at 3 days, it exhibited substantial reductions (30%–60%) at 7 and 28 days across all replacement levels. In the case of n-BS, a 5% replacement yielded comparable strength to reference mortar at 3 days, but no significant improvement was observed at later curing stages. Strength reductions became more pronounced at 56 days with increasing PCM content.

Flexural Strength

The reduction in flexural strength was found to vary based on the type of PCM used. An increase in PCM replacement percentage led to a decline in flexural strength. When 5% of HS24 or HS29 was used, the flexural strength remained like that of conventional cement mortar across all curing ages. However, incorporating OM29, PEG600, and n-BS significantly reduced flexural strength, irrespective of the curing time.

Among the tested materials, n-BS exhibited the most substantial reduction, with a 52% decrease in flexural strength at 7 days. At a 10% PCM replacement level, PEG600 caused the highest reduction, approximately 51%. This decreasing trend was observed across all PCM types at 3 and 7 days. A more considerable drop in flexural strength was recorded at a 15% replacement level across all curing ages. Specifically, a 15% replacement with OM29 resulted in a 55% reduction at 28 days.

Overall, the results suggest that incorporating up to 10% of HS24 or HS29 does not significantly impact flexural strength development at any stage. In contrast, using OM29, PEG600, or n-BS consistently led to a reduction in flexural strength, regardless of the curing period. The highest flexural strength achieved in this study was approximately 5.12 MPa at 28 days for a 5% replacement with HS24.

CONCLUSION

The study confirms that PCM incorporation influences the mechanical properties of cement mortar, with inorganic PCMs (HS24 and HS29) showing better compatibility than organic PCMs. Up to 10% replacement with HS24 and HS29 did not significantly impact compressive or flexural strength, while 15% replacement led to noticeable reductions. Organic PCMs, such as OM29, PEG600, and n-BS, consistently decreased strength at all replacement levels and curing ages, with reductions reaching up to 74% in compressive strength and 48% in flexural strength. These results indicate that inorganic PCMs are more suitable for cement mortar applications, whereas organic PCMs require modifications to mitigate strength loss.

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