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Research Article

"Experimental Investigation of Thermal Properties of Phase Change Materials Modified Concrete Cubicles for Sustainable Building Applications"

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ABSTRACT

Introduction: The growing demand for energy-efficient building solutions has sparked interest in thermal energy storage (TES) technologies, particularly Phase Change Materials (PCM) in concrete. PCMs offer exceptional capacity to absorb and release thermal energy during phase transitions, making them promising candidates for enhancing the thermal performance of building materials. While PCM integration in concrete has shown potential for improving thermal comfort and energy efficiency, comprehensive studies linking mechanical properties and thermal performance are limited.
Objectives: The mechanical properties PCM modified concrete are studied in previous research. The 10% PCM content in both type of PCMs was resulted and optimized the compressive strength of M25 grade. To evaluate the thermal properties of concrete incorporating Phase Change Materials, specifically examining the effectiveness of different PCM types and concentrations in concrete cubicles.
Methods: The thermal properties study constructed three 1m × 1m × 1m concrete cubicles: one control specimen and two incorporating 10% PCM content by concrete mass (CrodaTherm 29P and Micronal 24D). The specimens underwent a 28-day curing regime followed by 28 days of atmospheric exposure. Temperature monitoring utilized PT100 sensors positioned on exterior and interior surfaces, with data collected through an eight-channel logger over seven-day periods during winter conditions in Pune.
Results: PCM-modified concrete exhibited extended temperature lags of 14-15 hours during cooling phases compared to 12-13 hours in control specimens. The CT29P10 cubicle demonstrated temperature differentials of 1-3°C, while M24D10 showed 2-5°C variations relative to the control specimen. The thermal performance improved with plastering the cubicles.
Conclusions: PCM incorporation significantly enhances concrete's thermal mass properties while maintaining acceptable mechanical characteristics at 10% content. The study demonstrates the viability of PCM-modified concrete for improved thermal regulation in buildings, though further research on long-term durability and economic feasibility is recommended. The findings suggest potential applications in sustainable construction, particularly in regions experiencing significant temperature fluctuations.

Keywords: Phase Change Materials (PCM), thermal energy storage, concrete, thermal performance, sustainable construction, energy efficiency, building materials, thermal mass, CrodaTherm 29P, Micronal 24D.

1. INTRODUCTION

Thermal energy storage (TES) has drawn a lot of interest in the last ten years as a viable technology for reaching a low-carbon future. TES is now a vital part of lowering energy consumption and minimizing the environmental effect of buildings because to the growing demand for energy-efficient solutions worldwide. Phase Change Materials (PCM) are one of the best methods for improving TES in construction materials. PCM is a prime choice for enhancing the thermal performance of concrete and other building materials because of its exceptional capacity to absorb and release thermal energy during phase transitions, such as melting and solidifying. Making it a perfect fit for enhancing the thermal performance of building materials like concrete. Because it provides a workable way to encourage sustainability and energy efficiency in the built environment, PCM is seen as a game-changer in the field of sustainable infrastructure development. In recent years, there has been a lot of study and reporting on the use of PCM in buildings to increase thermal comfort. By controlling temperature variations, PCM improves the thermal performance of concrete and lessens the need for extra heating or cooling. With differing degrees of success, several methods for incorporating PCM into concrete—such as embedding it in bricks, panels, or blocks—have been tried. More research is necessary to address the concerns surrounding the interaction between PCM and cementitious materials, namely the impact on the mechanical qualities of the concrete. Non-contact approaches like microencapsulation have drawn interest among the different PCM incorporation techniques because they can smoothly incorporate PCM into concrete without sacrificing the structural integrity of the material. By increasing concrete's thermal efficiency without compromising its strength and durability, these developments create new opportunities for sustainable building techniques. There is little study linking the contributions of PCM concrete composites to the accomplishment of sustainable development goals, despite the increased interest in PCM-enhanced concrete. By examining the application of PCM composite concrete as a building material, paying particular attention to its mechanical and thermal characteristics, and investigating its potential to support the development of sustainable infrastructure, the current study seeks to close this gap. The demand for concrete in the construction industry had increased substantially, necessitating the exploration of methodologies to enhance its performance characteristics. Among the various approaches investigated to improve concrete properties, the incorporation of Phase Change Materials (PCM) had garnered significant attention due to its demonstrated capacity to enhance thermal performance. PCM had demonstrated effectiveness in regulating temperature fluctuations within concrete structures through its thermal energy absorption and release mechanisms, thereby contributing to improved building energy efficiency. While PCM exhibited considerable potential for enhancing the thermal properties of concrete, its impact on mechanical properties, particularly compressive strength, warranted comprehensive investigation. The introduction of PCM into concrete matrices had been observed to potentially reduce compressive strength, a critical parameter governing the durability and structural integrity of concrete structures. Consequently, determining the optimal PCM percentage for incorporation into concrete became essential to achieve enhanced thermal properties while maintaining requisite mechanical performance characteristics. Concrete structures had historically faced challenges related to temperature fluctuations, which significantly impacted their durability and service life. The incorporation of PCM presented a promising approach to improve thermal regulation in concrete structures. However, the effects of PCM incorporation on concrete's mechanical properties, specifically compressive strength, required further systematic investigation. Although previous research had examined PCM utilization in concrete, limited studies had investigated the correlation between varying PCM percentages and compressive strength. This investigation aimed to address this research gap through a comprehensive evaluation of the effects of varying PCM concentrations on the compressive strength of M25 grade concrete. The integration of PCM into concrete matrices had presented an opportunity to enhance building energy efficiency by reducing reliance on external heating and cooling systems. However, the primary challenge resided in optimizing PCM content to maintain or enhance concrete's mechanical strength properties. Through systematic investigation of the relationship between PCM percentage variations and compressive strength, this research aimed to contribute to the development of concrete materials exhibiting improved thermal performance while maintaining structural integrity. This investigation had potentially significant implications for advancing PCM utilization in sustainable and energy-efficient construction practices. In contemporary construction practices, increased emphasis had been placed on sustainable methodologies and enhanced performance of construction materials. Concrete, being among the most extensively utilized construction materials, had played a pivotal role in this endeavour. The incorporation of PCM to enhance concrete's thermal properties had emerged as a promising approach toward reducing building energy consumption. This research demonstrated particular relevance to the construction industry through its investigation of PCM's potential to enhance concrete performance and contribute to energy-efficient, sustainable building practices.

2. OBJECTIVES

The present research endeavors to advance our understanding of Phase Change Materials (PCM) integration in concrete and its implications for sustainable construction practices. The investigation is driven by the pressing need to develop energy-efficient building materials that can address the growing environmental concerns while maintaining structural integrity. The following objectives have been established to guide this research:

2.1 Analysis of Thermal Properties and Performance

The primary objective of this research is to conduct a comprehensive analysis of the thermal behavior of concrete containing Phase Change Materials. This investigation aims to understand how PCM incorporation affects the concrete's ability to regulate temperature and store thermal energy. The study focuses particularly on:

a) Evaluating the thermal performance of concrete specimens containing varying percentages of PCM through systematic laboratory testing
b) Measuring and analyzing temperature differentials between exterior and interior surfaces of PCM-modified concrete under controlled conditions
c) Investigating the heat absorption and release patterns during heating and cooling cycles
d) Determining the effectiveness of PCM in extending the thermal lag time and reducing temperature fluctuations within concrete structures
e) Assessing the impact of environmental conditions on the thermal behavior of PCM-modified concrete

The thermal analysis encompasses both laboratory testing and real-world applications through the construction and monitoring of concrete cubicles. This dual approach enables a thorough understanding of PCM's effectiveness in enhancing concrete's thermal properties under actual service conditions.

2.2 Assessment of Practical Applications

The research extends beyond laboratory investigation to evaluate the practical implementation of PCM-modified concrete in building applications. This objective encompasses:

a) Construction and monitoring of full-scale concrete cubicles to assess real-world performance
b) Evaluation of PCM-modified concrete behavior under varying climatic conditions
c) Investigation of the material's effectiveness in reducing energy consumption in buildings
d) Assessment of construction challenges and practical limitations
e) Development of implementation guidelines for construction industry practitioners

This practical assessment aims to bridge the gap between laboratory research and field application, providing valuable insights for industry adoption of PCM-modified concrete.

2.3 Contribution to Sustainable Construction

The final objective focuses on evaluating the broader implications of PCM-modified concrete for sustainable construction practices. This includes:

a) Analysis of potential energy savings through passive temperature regulation
b) Assessment of the material's contribution to reducing building carbon footprint
c) Evaluation of long-term environmental benefits and lifecycle considerations
d) Investigation of economic viability and return on investment

3. METHODS

An experimental investigation had been conducted to examine the thermal properties of concrete cubicles containing phase change material. The primary objective of this study had been to evaluate the thermal behaviour of concrete cubicles incorporating optimum percentages of Phase Change Material (PCM) in comparison with reference (control) concrete specimens.

The experimental methodology had comprised the following sequential procedures:

1. Preparation of M25 grade concrete mixture utilizing standardized proportions of cement, fine aggregate, coarse aggregate, and water.

2. Construction of three large cubicles (1m x 1m x 1m), including one control concrete specimen and two specimens incorporating CT29P and M24D with optimal 10% PCM content by concrete mass.

3. Implementation of a 28-day curing regime followed by a 28-day atmospheric exposure period to facilitate moisture removal through the drying process.

4. Installation of temperature monitoring sensors in all cubical specimens to record temperature variations following the 56-day post-casting period.

5. Collection and analysis of temperature data over a seven-day duration to evaluate PCM concrete thermal properties under diurnal winter conditions.
6. Comparative analysis of thermal performance between PCM-modified and control concrete specimens, with particular emphasis on indoor-outdoor temperature differentials of the cubical specimens

Preliminary investigations had demonstrated that through precise administration of admixture and careful calibration of PCM (Phase Change Material) percentage by cement mass, the target compressive strength for M25 grade concrete had been successfully achieved following a 28-day curing period. This optimization protocol had been fundamentally focused on establishing an equilibrium between material properties to enhance thermal efficiency while maintaining structural integrity.

For thermal performance evaluation, the 10% PCM formulation had been identified as optimal. This determination had been based on superior compressive strength characteristics and anticipated enhancement of thermal regulation properties within the concrete matrix. Consequently, the 10% PCM concrete formulation had been selected for comprehensive analyses, particularly investigating its potential applications in regions experiencing significant temperature fluctuations.

3.1 Cubicle Casting and Preparation

Three large concrete cubicles, each with dimensions of 1m x 1m x 1m and wall thickness of 150 mm, had been fabricated. One cubicle had been constructed using standard M25 grade control concrete (without PCM), while the remaining two had been enhanced with CrodaTherm 29P and Micronal 24D respectively. The casting Molds utilized had been documented in **Figure 3.1 and 3.2**. This comparative methodology had facilitated precise evaluation of thermal properties influenced by PCM incorporation.

 **Figure 3. 1 Mold used for base and room panels for cubicles.**	 **Figure 3. 2 Mold used for base and room panels for cubicles.**

Figure 3. 3 Mould used for slab panel.

3.2 Mix Design and Proportioning

The mix design and proportioning protocol had been established to ensure optimal thermal and mechanical properties of the concrete. The mix design for M25 grade concrete had been developed following standardized guidelines to achieve targeted strength and workability parameters. Mix ratios had been precisely calculated to maintain optimal proportions of cement, fine aggregate, and coarse aggregate. This methodological approach had enabled precise control over constituent proportions, ensuring reproducibility across all specimens. Modifications had been implemented to accommodate PCM's specific characteristics, optimizing both compressive strength and thermal performance of the concrete matrix.

Table 3. 1 Quantity of Material used for Cubicles

Sample	Cement (Kg/m^3)	Silica Fumes (Kg/m^3)	Fine Aggregates (Kg/m^3)	Coarse Aggregates (Kg/m^3)	PCM (Kg/m^3)	Water (Kg/m^3)
Control Concrete	293.26	15.435	825.21	1299	-	154.38
CT29P10	293.26	15.435	825.21	1299	30.87	154.38
M24D10	293.26	15.435	825.21	1299	30.87	154.38

Figure 3. 4 Mixing of PCM in concrete

Figure 3. 5 Mixing of PCM in concrete

Concrete specimens had been cast in 1m x 1m x 1m moulds: one control concrete specimen and two PCM-enhanced specimens incorporating CrodaTherm 29P and Micronal 24D respectively, as illustrated in **Figure 3.4 and Figure 3.5.** Following M25 mix design specifications, materials had been precisely measured and homogenized, with PCM incorporated at the optimal concentration of 10% by concrete mass. Minimum reinforcement had been implemented in all panels. The concrete had been placed in successive layers, each adequately compacted to ensure homogeneity. Post-casting, molds had been sealed to maintain moisture content and subjected to a 28-day curing period, followed by 28 days of atmospheric exposure in preparation for thermal performance evaluation.

Figure 3. 6 Casting of Cubicles

3.3 De-molding and Curing Process

Upon achieving sufficient initial strength, molds had been carefully extracted to preserve specimen integrity. Post-demolding, specimens (as depicted in Figure 5.5) had been transferred to a controlled curing environment to facilitate proper hydration and strength development. Specimens had been immersed in a water bath maintained at ambient temperature for 28 days, ensuring complete strength development. This curing regime had additionally facilitated complete integration of Phase Change Material (PCM) within the concrete matrix. Following the curing period, specimens had been subjected to 28 days of atmospheric exposure for moisture equilibration prior to thermal performance evaluation.

Figure 3. 7 De-molding of molds

3.4 Thermal Testing Apparatus and Setup

For thermal performance evaluation, specimens had been exposed to atmospheric conditions. Temperature monitoring had been accomplished using PT100 sensors positioned on both exterior and interior surfaces of each cubicle to measure atmospheric and internal temperatures respectively. Temperature measurements at both locations had been obtained using flat surface PT100 sensors. Data acquisition had been facilitated through an eight-channel data logger, enabling continuous monitoring over extended durations for each specimen. Temperature variations had been recorded at hourly intervals. The experimental protocol had been conducted over a seven-day period during winter conditions in Pune, with hourly measurements recorded for all specimens. **Figure 3.8** had illustrated the apparatus configuration during morning, afternoon, and night conditions. Detailed results and analysis had been presented in subsequent sections

Figure 3.8 Morning, afternoon and night condition of apparatus during testing.

4. RESULTS AND DISCUSSIONS:

This investigation focused on evaluating the influence of Phase Change Material (PCM) incorporation on the thermal behavior of concrete. The analytical framework had been designed to determine PCM's effectiveness in enhancing thermal efficiency, with potential implications for improved energy management in concrete structures. Through comparative analysis of temperature retention, dissipation rates, and overall heat storage characteristics between PCM-enhanced and control concrete specimens, this investigation had provided significant insights into PCM's potential applications in sustainable construction.

4.1 Indoor and Outdoor Temperature of All Cubicles without plaster in Winter Season at Pune

The comparative analysis of temperature retention, dissipation rates, and thermal storage capacity between PCM-enhanced and standard control concrete had been illustrated in **Figure 4.1 and Figure 4.2**, which had demonstrated the thermal behavior of experimental cubicles without plaster in winter season at Pune throughout diurnal cycles.

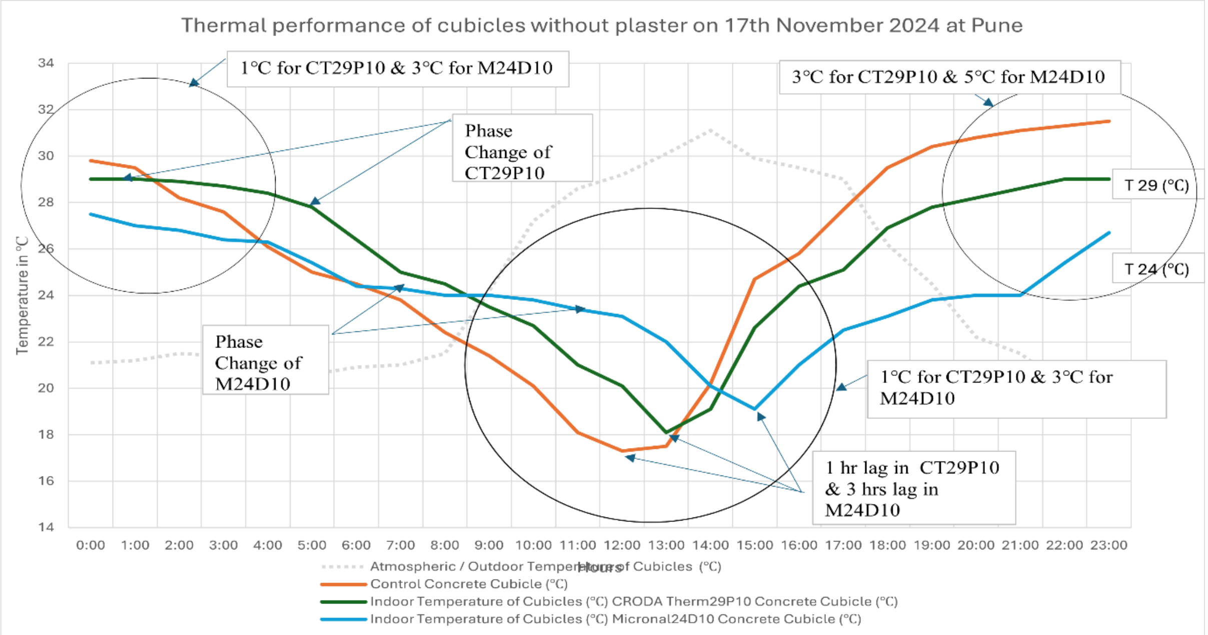

Figure *4.1* Thermal Performance of Cubicles without plaster on 17th November 2024 at Pune

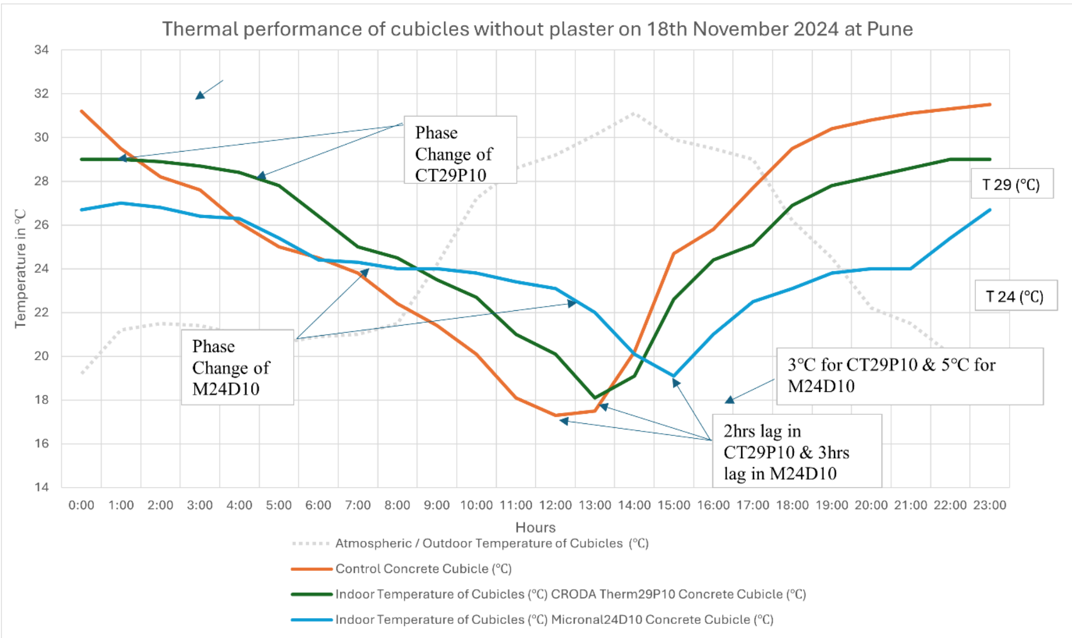

Figure 4.2 Thermal Performance of cubicles without plaster on 18th November 2024 at Pune.

Analysis of the experimental data presented in **Figure 4.1 and Figure 4.2** revealed distinct thermal behavior patterns. During the cooling phase, a temperature lag of 12 to 13 hours had been observed between outdoor and indoor temperatures in the control concrete cubicle, whereas PCM-modified concrete cubicles had exhibited an extended lag of 14 to 15 hours. The cooling phase had demonstrated a positive temperature differential of 1 to 3°C in the CT29P10 cubicle and 2 to 5°C in the M24D10 cubicle relative to the control specimen.

During the warming phase, a temperature lag of 12 to 13 hours had been observed in the control concrete specimen, while PCM-modified concrete cubicles had exhibited a reduced lag of 10 to 11 hours. The warming phase had been characterized by a negative temperature differential of 1 to 3°C in the CT29P10 cubicle and 2 to 5°C in the M24D10 cubicle compared to the control specimen.

4.2 Indoor and Outdoor Temperature of All Cubicles with Plaster in Winter Season at Pune

The comparative analysis of temperature retention, dissipation rates, and thermal storage capacity between PCM-enhanced and standard control concrete had been illustrated in **Figure 4.3 and Figure 4.4**, which had demonstrated the thermal behavior of experimental cubicles with plaster in winter season at Pune throughout diurnal cycles.

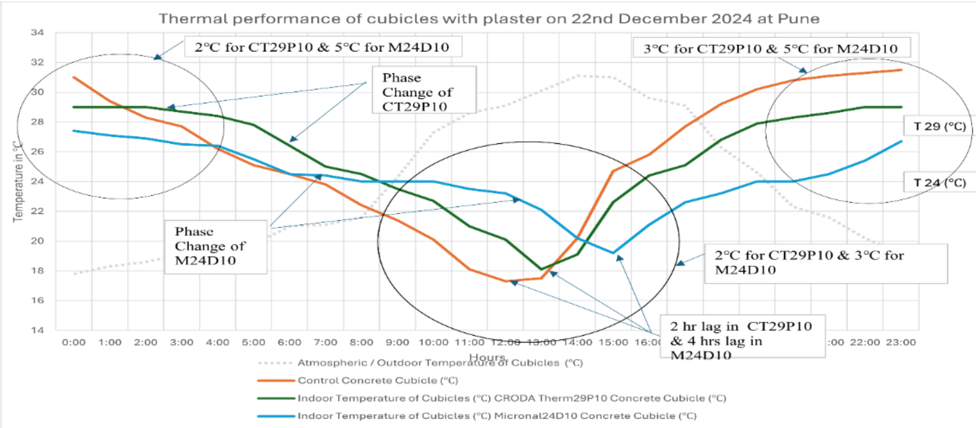

Figure 4.3 Thermal Performance of Cubicles with Plaster on 22nd December 2024 at Pune.

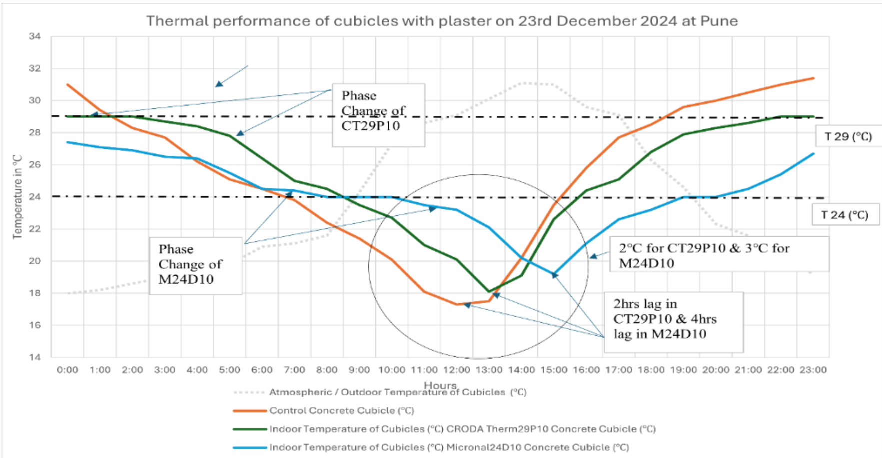

Figure 4.4 Thermal Performance of Cubicles with Plaster on 23rd December 2024 at Pune.

5. CONCLUSION

Based on comprehensive experimental analysis and investigation, the following conclusions were drawn:

5.1 Thermal Resistance and Efficacy Analysis of PCM-Modified Concrete

The experimental analysis revealed significant improvements in thermal properties of PCM-modified concrete compared to control specimens:

1. Enhanced Thermal Mass Properties: PCM incorporation significantly improved the concrete's thermal mass characteristics. Specimens containing PCM demonstrated greater temperature differentials between heat-exposed and opposite surfaces compared to control specimens.
2. Improved Heat Penetration Resistance: During the heating phase, PCM-modified concrete panels exhibited increased thermal resistance across all thicknesses, resulting in longer heat penetration times. This led to consistently higher temperature differentials between front and back surfaces.
3. Controlled Heat Release: During the cooling phase, PCM-modified concrete panels demonstrated controlled release of absorbed latent heat, maintaining enhanced temperature differentials between surfaces.

4. Significant Temperature Regulation: Temperature measurements showed consistent 3-5°C variations between control and PCM-modified concrete mixtures, indicating potential for reducing peak energy demands in buildings.

5.2 Applicability of PCM in Precast Concrete Elements

1. Precast Construction Applications: PCM-modified precast concrete walls, manufactured off-site, offer excellent thermal insulation and soundproofing properties, making them suitable for residential and commercial applications.
2. Versatile Implementation: PCM incorporation can be effectively applied to various precast concrete elements including beams, columns, walls, and floor panels, expanding its potential use across residential, commercial, and industrial construction.

5.3 Practical Implementation Considerations:

The large-scale implementation of PCM-incorporated concrete depends critically on maintaining mechanical properties while enhancing thermal performance. When properly optimized, PCM-modified concrete can significantly reduce fossil-fuel-based energy consumption in buildings.

Future Outlook:

The integration of PCMs for thermal heat storage in concrete shows promising potential for energy conservation in commercial and residential buildings. This research contributes to the sustainable development of energy-efficient building materials and construction practices. The findings suggest that PCM-modified concrete can play a vital role in meeting future sustainable construction demands while addressing energy conservation needs.

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