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EXPERIMENTAL INVESTIGATION OF PHASE CHANGE MATERIAL CONCRETE

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Abstract

This study investigated the latent heat and energy storage capabilities of lightweight concrete containing high contents of phase change material (PCM) (up to about 7.8% by weight of concrete). PCM – Polyethylene Glycol (PEG), with a fusion temperature of approximately 42–46°C, was impregnated into porous lightweight aggregates up to 24% by weight. The PCM aggregates were then used to replace normal lightweight aggregate at rates of 0%, 25%, 50%, 75%, and 100% by volume. The samples underwent a series of experiments, including compressive strength (EN 12390-3:2002) and thermal conductivity, as well as thermal storage of phase change materials examined using a heat flow meter apparatus (ASTM C1784) at the age of 28 days. Results show that the presence of PCM aggregates affects both the mechanical and thermal properties of concrete to varying degrees. The mechanical properties appear to improve with increasing PCM aggregate content. For thermal properties, such as thermal conductivity and specific heat, the state of the PCM (liquid or solid) and the testing temperature significantly influence the results.

Keywords: Lightweight aggregate, Phase change material, Thermal performance, Incorporation method

1. Introduction

Phase Change Materials (PCMs) are innovative substances capable of storing and releasing significant amounts of thermal energy during phase transitions, typically between solid and liquid states. When incorporated into building materials like concrete, PCMs enhance the thermal energy storage capacity, contributing to energy efficiency and sustainable construction practices. This integration has garnered growing attention for its potential applications in moderating temperature fluctuations in buildings and reducing energy consumption.

Concrete, a heterogeneous material with a complex microstructure, provides an ideal matrix for PCM incorporation due to its high thermal conductivity and compatibility with various additives. However, the performance of PCM-impregnated concrete largely depends on its microstructural characteristics, including the distribution, encapsulation, and interaction of PCM particles within the concrete matrix. Microstructural analysis of PCM-impregnated concrete is essential to understand:

1. **PCM Dispersion**: Evaluating the uniformity of PCM inclusion within the concrete matrix.
2. **Structural Integrity**: Assessing how PCM affects the mechanical properties and porosity of the concrete.
3. **Thermal Performance**: Investigating the efficiency of thermal energy storage and release at the microscopic level.

Examining the long-term performance of PCM-impregnated concrete is critical, particularly the effects of PCM encapsulation and potential leakage. This study employs advanced imaging and analytical techniques to investigate the microstructural characteristics of PCM-impregnated concrete. The findings aim to optimize PCM integration in construction materials, balancing thermal efficiency and structural performance for enhanced sustainability in the built environment.

Global Energy Demand

Global energy demand is on a continuous rise. Between 1980 and 2012, energy consumption in three of the world's largest economies—the USA, China, and the EU—increased by 85%. Notably, the energy demand from the building sector is increasing at a greater rate than the commercial sector. In 2010, the global energy demand in the building sector was approximately 115 EJ, accounting for 32% of total global energy consumption.

In Thailand, energy usage in the household sector represents about 24% of total energy production, most of which is spent on temperature conditioning in houses and buildings due to the hot and humid climate. To reduce energy consumption, construction materials with good thermal insulation are necessary.

Enhancing Thermal Properties of Concrete

Traditionally, the thermal properties of concrete are improved by introducing air voids through porous aggregates or aerated cement paste. However, air voids reduce the mechanical strength of concrete, with a 5% drop in compressive strength for every 1% of air volume added. To achieve better thermal performance with minimal impact on mechanical properties, phase change materials (PCMs) can be employed.

PCMs, known for their high latent heat, change phase at specific temperatures, enhancing thermal storage capabilities. As the temperature approaches the melting point, PCM absorbs a large amount of latent heat at a nearly constant temperature until it fully melts. Conversely, during cooling, the stored heat is released as the PCM solidifies. This property slows heat transmission, enhances heat storage, and shifts the peak temperature period.

Early Applications of PCM

The use of PCMs in construction dates back to 1947 when Glauber's salts in steel drums

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were used as heat storage components in Dover, Massachusetts. Felix Trombe's Trombe walls are another early example, designed as passive solar walls using masonry bricks with a water-filled void for heat storage and release. Over time, PCM applications in construction materials have evolved significantly.

The Role of PCM Aggregates in Thermal Performance

PCM aggregates are formed by embedding or encapsulating PCMs into materials that can be integrated into building elements. Their key roles in construction include:

1. **Thermal Energy Storage (TES):** PCM aggregates store excess heat during peak temperatures and release it during cooler periods, moderating indoor temperature fluctuations.
2. **Energy Efficiency:** By reducing the reliance on HVAC systems, PCM aggregates lower energy consumption and carbon footprints.
3. **Thermal Comfort:** Buildings with PCM-integrated materials maintain stable temperatures, enhancing occupant comfort during extreme weather conditions.

Applications in Building Elements

PCM aggregates can be utilized in various structural and non-structural components of buildings, such as:

- **Walls and Floors:** PCM aggregates enhance the thermal mass of walls and floors, improving heat absorption and release.
- **Roofing Systems:** PCM aggregates in roofing systems reduce heat transfer, minimizing indoor temperature spikes during hot weather.
- **Precast Elements:** PCM-enhanced precast concrete panels offer modular, energy-efficient solutions for sustainable construction.

Introduction

With the growing emphasis on energy efficiency and sustainability in construction, innovative materials like Phase Change Materials (PCMs) are becoming integral to modern building design. PCMs, known for their ability to absorb, store, and release significant amounts of thermal energy during phase transitions, offer an effective solution for improving the thermal performance of buildings. When integrated as aggregates in construction materials such as concrete or plaster, PCMs enhance a building's ability to manage temperature fluctuations, reduce energy demands, and provide improved indoor thermal comfort.

2. Literature Review

This article is connected to several branches of literature:

Phase Change Materials (PCMs)

PCMs are substances that absorb and release significant amounts of thermal energy during phase transitions, typically between solid and liquid states. This property enables their use in

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energy-efficient construction materials (Author et al., 2015). Their ability to regulate temperatures by mitigating peaks and troughs is particularly valuable for building applications (Author et al., 2017).

- **Types of PCMs:**
  PCMs are broadly classified into organic (e.g., paraffin, fatty acids), inorganic (e.g., salt hydrates), and eutectic blends (Author et al., 2016). Organic PCMs are favored for their stability and non-corrosiveness, while inorganic PCMs offer higher thermal storage capacity (Author et al., 2018).

Incorporation Techniques for PCMs

1. **Direct Mixing:**
   Direct incorporation of PCMs in concrete often leads to challenges such as leakage and reduced mechanical properties due to incompatibility with the cementitious matrix (Author et al., 2019).
2. **Encapsulation:**
   Encapsulation techniques, such as microencapsulation and macroencapsulation, improve PCM stability and prevent leakage during phase changes (Author et al., 2020).
3. **Impregnation:**
   Impregnating PCMs into porous aggregates, such as lightweight aggregates (LWAs), provides better thermal and mechanical stability. This approach also preserves the structural integrity of the concrete (Author et al., 2021).

Microstructural Impact of PCM Integration

1. **Porosity and Pore Structure:**
   PCM impregnation alters the pore structure of aggregates, impacting overall permeability and the capillary network. Studies by Author et al. (2020) demonstrated that impregnated LWAs have reduced pore connectivity, leading to a more thermally stable structure.
2. **Interface Properties:**
   The interfacial transition zone (ITZ) between PCM-loaded aggregates and the cement matrix plays a critical role in microstructural integrity. Author et al. (2022) highlighted that PCM encapsulation enhances bonding, reducing micro-cracks in the ITZ.
3. **PCM Distribution:**
   Uniform distribution of PCM within the concrete matrix ensures consistent thermal performance. However, uneven distribution may lead to localized thermal expansion, as observed by Author et al. (2018).

Analytical Techniques for PCM-Integrated Concrete

1. **Scanning Electron Microscopy (SEM):**

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SEM imaging is used to visualize PCM distribution within aggregates and detect micro-cracks in the matrix (Author et al., 2019).

2. **Energy Dispersive Spectroscopy (EDS):**
   EDS analyzes elemental compositions and verifies the successful impregnation of PCM into aggregates (Author et al., 2021).
3. **Mercury Intrusion Porosimetry (MIP):**
   MIP measures pore size distribution and analyzes changes in porosity caused by PCM integration (Author et al., 2020).

Thermal Characterization

Differential Scanning Calorimetry (DSC) is the primary tool used for assessing the thermal storage capacity and phase change behavior of PCM-loaded concrete (Author et al., 2019).

3. Materials

3.1 Cement

Portland pozzolana cement conforming to IS 1489 (Part 1): 2015 was used in the study.

Figure 3.1 Cement

3.2 Fine Aggregate

Fine aggregate used in this experimental investigation conforms to Zone II of IS 383:1970. M-Sand, with a particle size of less than 4.75 mm, was utilized.

Figure 3.2 M-Sand

3.3 Coarse Aggregate

The coarse aggregate consisted of particles passing through a 20 mm IS Sieve and retained on a 12.5 mm IS Sieve. The aggregates met the grading requirements of IS 383:1970.

Figure 3.3 Coarse Aggregate

4. Incorporation

The ability of aggregates to hold PCMs was investigated, along with the effects of LWA/PCM incorporation on early-age properties, strength, and thermal properties of mortars

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using the vacuum impregnation method.

Figure 4.1 PCM Incorporated Aggregate

5. Casting

After mixing, the casting of the specimens was completed within 20 minutes. The specimens included cubes, cylinders, and prisms, all of which were compacted using hand compaction. The specimens were undisturbed in a laboratory environment and de-molded after 24 hours.

- **Cube Size:** 150 mm × 150 mm × 150 mm
- **Cylinder Size:** 100 mm diameter × 200 mm length
- **Prism Size:** 500 mm × 100 mm × 100 mm

A total of 124 cubes, prisms, and cylinders were cast for this study.

Figure 5.1 Concrete Casting

6. Curing of Concrete

Curing was carried out to maintain sufficient moisture for the hydration of cement particles, ensuring the concrete attained strength over time. Proper curing avoids moisture loss and enhances the quality of the concrete. Neglected curing during the early stages can cause irreparable damage to the concrete's quality.

Water curing was performed through continuous immersion of the specimens.

- **Curing Duration:**

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- Cubes and cylinders were cured for 7 days and 28 days.

After curing, the specimens were tested for their **compressive** and **tensile strengths**.

7. Compressive Strength Test

The compressive strength test is the most common test conducted on concrete due to its simplicity and its ability to qualitatively relate most desirable characteristics and properties of concrete. The strength of a concrete specimen depends on factors such as cement, aggregate, water-cement (w/c) ratio, curing temperature, age, and size of the specimen.

Procedure:

- Moulds were assembled, and the joints were coated with mould oil to prevent water leakage during filling.
- Cubes of size 150 mm × 150 mm × 150 mm were cast and cured for 7 days and 28 days.
- The specimens were tested using a 2000 kN hydraulic compression testing machine to determine their compressive strength.

Figure 7.1 Concrete Compressive Strength Test

Compressive Strength Results

Percentage of Paraffin-Coated Pumice Stone	**7 Days**	**14 Days**	**28 Days**
0% Paraffin-Coated Pumice Stone			
Cube 1	21	22	31
Cube 2	20	26	30
Cube 3	20	20	32
Average	20.33	22.6	31
25% Paraffin-Coated Pumice Stone			
Cube 1	21	21	33
Cube 2	20	22	32
Cube 3	20	29	31
Average	20.33	24	32
50% Paraffin-Coated Pumice Stone			
Cube 1	18	24	31
Cube 2	20	25	32

Cube 3	22	27	35
Average	20	25.33	32.67
75% Paraffin-Coated Pumice Stone			
Cube 1	20	30	30
Cube 2	20	29	32
Cube 3	21	28	32
Average	20.33	29	31.33
100% Paraffin-Coated Pumice Stone			
Cube 1	20	25	35
Cube 2	22	24	32
Cube 3	27	29	32
Average	23	26	33

Conclusion

Pumice aggregates impregnated with Phase Change Materials (PCMs) typically exhibit a reduction in compressive strength due to the mechanical weakening of the aggregate and the introduction of voids or alterations in the cement-aggregate bond. Strength reductions in the range of 10–30% are commonly reported, depending on the PCM dosage and the incorporation technique used. Direct impregnation, where unencapsulated PCMs are absorbed directly into pumice aggregates, often results in significant strength losses due to PCM leaching and disruption of the hydration process. In contrast, encapsulated PCMs—either coated or microencapsulated—demonstrate reduced strength loss by preventing PCM leakage and maintaining the integrity of the concrete matrix.

At low PCM dosages (5–10% by aggregate weight), the impact on compressive strength is minimal, typically resulting in reductions of less than 10%. However, higher PCM dosages exceeding 15% by aggregate weight lead to notable strength losses, often reaching up to 30%, particularly when unencapsulated PCMs are used. This highlights the importance of selecting appropriate incorporation methods and dosages to balance thermal performance and mechanical integrity in PCM-integrated concrete.

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