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PCM-TRC Slab

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Abstract

This research investigates integrating macro-encapsulated Phase Change Material within Textile Reinforced Concrete slabs to create a hybrid material that combines the structural advantages of TRC with the thermal storage capabilities of macro-encapsulated PCMs. The study encompasses these novel composite material's fabrication, characterization, and application, aiming to enhance concrete structures' energy efficiency and thermal performance. Microencapsulated PCMs, embedded within the textile reinforcements, offer a dual-functionality solution, harnessing the latent heat properties of PCMs while preserving the structural integrity of TRC. Through comprehensive experimentation and analysis, this research aims to establish the viability and effectiveness of macro-encapsulated PCM-TRC slabs in real-world construction scenarios, presenting a sustainable approach to address structural and thermal challenges in concrete construction.

***Keywords**:* Concrete; energy-efficient buildings; phase change technology; temperature control; sustainable construction

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1. INTRODUCTION

The construction industry is at a crossroads while its contributions to human progress are undeniable, the sector also faces a pressing challenge, reducing its significant energy consumption and environmental impact. Despite ongoing efforts to improve energy efficiency, a recent report revealed a sobering truth that the energy use and CO_2 emissions in buildings have reached record highs after the COVID-19 pandemic. The 2022 Global Status Report for Buildings and Construction, unveiled during COP27, paints a clear picture: the sector devoured over 34% of global energy demand and contributed roughly 37% of energy and process-related CO_2 emissions in 2021.

This calls for a paradigm shift in construction materials. We need to move beyond simply fulfilling structural requirements and actively seek materials that promote energy efficiency and sustainability (Cholostiakow et al., 2024; Al-Saidy et al., 2023). In this quest, a powerful duo has emerged which is Textile-Reinforced Concrete (TRC) and Phase Change Materials (PCMs).

Textile Reinforced Concrete (TRC) is a revolutionary material that breaks away from the limitations of traditional reinforced concrete. Imagine concrete slabs reinforced not with rigid steel bars, but with high-performance textiles like carbon or glass fibers (Li et al., 2023; Madhavi, 2024). This ingenious approach imbues TRC with several key advantages which include superior tensile strength and ductility, lightweight advantage, design Freedom, and faster construction (Zhang et al., 2023).

Phase Change Materials (PCMs) are a fascinating class of materials with a unique property which is their ability to absorb and release large amounts of thermal energy during phase transitions, typically between solid and liquid states. In the context of buildings, PCMs can be strategically integrated into construction materials to act as thermal batteries. During hot periods, PCMs absorb excess heat from the surrounding environment, helping to maintain a cooler indoor temperature. Conversely, when temperatures drop, PCMs release the stored heat, contributing to a more comfortable and stable indoor climate. This translates into several potential benefits which involve reduced reliance on HVAC systems, improved thermal comfort, and enhanced energy efficiency.

The combination of TRC and PCMs presents a groundbreaking opportunity for sustainable construction. The potential advantages of integrating these two innovative materials into building slabs are:

Structural strength with thermal regulation: TRC-PCM slabs combine the remarkable strength and design flexibility of TRC with the thermal regulation capabilities of PCMs. This creates a versatile building element that excels in both structural performance and energy efficiency.

Optimizing thermal mass: The inherent thermal mass of concrete is further enhanced by the presence of PCMs within the TRC slab. This increased thermal mass provides a buffer against rapid temperature changes, contributing to a more stable and comfortable indoor environment.

1.1. Literature review

1.1.1. material development and integration

Researchers are currently investigating methods to incorporate PCMs into various building materials like concrete, gypsum plaster, and lightweight aggregates. This integration aims to improve thermal insulation properties by absorbing and releasing heat during phase transitions. Studies by Al-Absi et al., (2022) demonstrated reduced thermal conductivity in cement render and foamed concrete with PCMs. El-Sayed et al., (2023) highlighted the potential of PCMs alongside traditional building materials for effective building cooling in hot climates. Khudhair & Farid (2021) provided a comprehensive overview of ongoing research on PCM encapsulation within various construction materials.

1.1.2. Evaluating PCM effectiveness

Several studies have been conducted to evaluate the effectiveness of PCMs in real-world applications. Cabeza et al., (2011) found no degradation in PCM performance in a concrete house-like structure even a decade after construction. Faraj et al., (2020) categorized PCM cooling applications and emphasized their role in reducing indoor temperature fluctuations and energy demand. Kumar et al., (2020) conducted a controlled experiment with test rooms to quantify the temperature drop achieved with PCM integration in building walls.

1.1.3. Optimizing design for PCMs

To optimize the use of PCMs, it is important to consider factors like type, thickness, and placement of material for specific building components and climatic conditions. Christen et al., (2023) utilized computational simulations to assess the performance of 3D-printed concrete facades containing PCMs considering factors like seasonal temperature variations. Konstantinidou et al.,. (2018) evaluated various PCM options for building envelopes in a Mediterranean climate which aimed to optimize cooling loads and thermal comfort. Hou et al., (2022) investigated the impact of PCM location on the thermal performance of lightweight building walls under different outdoor conditions.

1.1.4. Sustainability considerations

The field of phase change materials (PCMs) is currently exploring sustainable practices. Ghani et al., (2021) and Khosh & Atapour (2024) highlighted the potential of using waste materials in PCM development to enhance its economic and environmental value. Soares et al., (2017) discussed the importance of lightweight steel-framed construction with integrated PCMs for achieving building sustainability throughout its life cycle.

1.2. Purpose of study

The primary objective of this research is to investigate and optimize the incorporation of phase change materials (PCMs) into textile-reinforced concrete (TRC) composites, to enhance the thermal performance and energy efficiency of structural elements. By evaluating the impact of PCMs on the thermal conductivity of TRC slabs, the project aims to develop a novel building material for efficient temperature.

2. METHOD AND MATERIALS

The methodology involved in fabricating PCM-TRC was systematic and focused on precise material selection, calculation, and construction techniques.

2.1. Material Used

For the concrete mix, Grade 33 Ordinary Portland Cement (OPC) and fine aggregates with a size smaller than 2 mm were used. An M20 grade cement mortar was employed for the slabs, maintaining a water-cement ratio of 0.45 to ensure effective impregnation of the textile reinforcement.

The Phase Change Material (PCM) utilized was a type known as "Bhiim PCM 25-30," characterized by its organic composition and waxy properties. This PCM exhibited a phase change temperature range of 25 to 30°C and a heat storage capacity of 160J/g. Each slab incorporated 20 pouches of 25 gm PCM, resulting in the PCM absorbing 80 kJ of heat during phase change.

2.2. Calculation for materials

Calculations for materials were meticulously performed to determine quantities. The wet quantity of the nominal mix of M20 concrete was approximately 0.018 m^3. Thus, the dry volume of concrete was calculated as 0.018 × 1.54 = 0.0277 m^3. Accordingly, the quantities of cement, sand, and aggregates were

Determined to be 7.252 kg, 12.0872 kg, and 24.174 kg, respectively. The water-cement ratio of 0.45 led to an estimated water requirement of about 3.26 liters for this mix.

2.3. Fabrication of PCM- TRC Slab

The fabrication process began by setting up the formwork to the desired dimensions of 600 mm by 600 mm by 50 mm. A thin layer of grease or oil was applied to the mold and frame surfaces to facilitate easy removal of the cured concrete slab. This layer prevented the concrete from sticking to the mold. Subsequently, five layers of concrete, each 10 mm thick, were poured into the frame, with fiber mesh applied over each layer to enhance strength and stability.

The incorporation of microencapsulated PCM was done in the middle layer (the third layer) by evenly distributing 20 pouches of 25 gm each across the surface. Care was taken to ensure the PCM pouches were securely embedded within the concrete layer to prevent movement during subsequent stages of construction.

Figure 1
Encapsulated PCM placement

Once all layers were poured and PCM pouches were placed (Figure 1), the top surface of the slab was finished using standard concrete techniques such as smoothing or troweling. The slab was then allowed to cure under controlled conditions to achieve optimal strength and durability (figure 2).

Figure 2
Casted Slab

2.4. Testing

The temperature test (figure 3)was conducted on the two slabs, with microencapsulated PCM (Phase Change Material) pouches & TRC and without microencapsulated PCM pouches & TRC slabs of the size of (600 x 600 x 50) mm. The objective of this test was to find the thermal conductivity of the slabs with and without PCM. The device used for this test was an ***Infrared Temperature Gun.*** Both slabs were placed separately in an area where they were directly exposed to the Sunlight throughout the day.

Figure 3

Temperature test

The test consisted of every hour reading from 8:30 A.M. to 4:30 P.M. of the testing temperature of the outer and inner sides of the slabs on 14 March 2024 (Table 1).

Table 1

Temperature testing values

Time Interval	Temp. (in °C) of Outer Side of Slab (with PCM)	Temp. (in °C) of Inner Side of Slab (with PCM))	Temp. (°C) of the Outer Side of the Slab (without PCM)	Temp. (in °C) of the Inner Side of the Slab (without PCM)
8:30 AM	28	22	27	21
9:30 AM	29	23.5	28.75	22.75
10:30 AM	33.5	27	32.5	26.5
11:30 AM	49.4	42.9	49.7	43.3

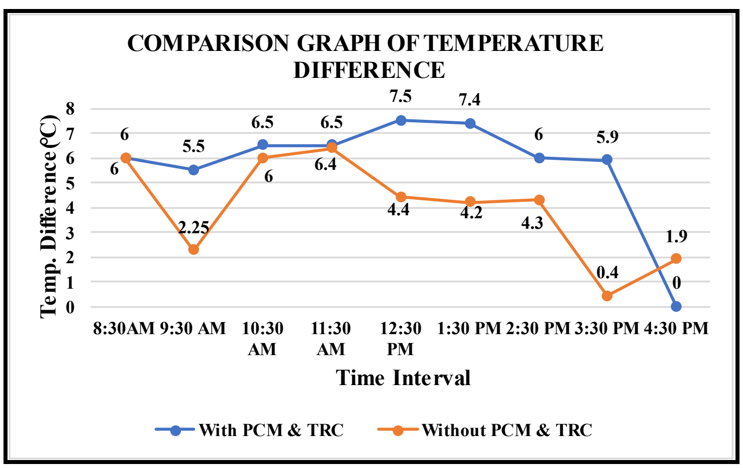
12:30 PM	56.1	48.6	54	49.6
1:30 PM	54	46.6	51.7	47.5
2:30 PM	51.4	45.4	49.5	45.2
3:30 PM	50.2	44.3	47.2	46.8
4:30 PM	43.6	43.6	44.7	42.8

3. RESULTS

After completing the testing using the sun as our main source of heat, we found an average difference of 3°C between the inner side of the slab as well as the outer side of the slab, that is, for the slab with PCM and TRC, and also for the slab without PCM and TRC.

After finding the temperature difference of both the slabs, we plotted a graph as shown below in the figure which shows that the temperature difference of the slab consisting of PCM and TRC was greater than the other slab which does not contain PCM and was not textile- reinforced (figure 4).

Figure 4
Temperature difference of both slabs



The results show that the thermal conductivity of the slab with PCM and TRC was less as the temperature difference is higher for the same than that of the slab which does not contain PCM and is not reinforced with textile. Hence, the PCM-TRC slab was found to be more effective in the case of temperature control, and better than the conventional slab.

4. DISCUSSION

The results of the testing using the sun as the primary heat source indicate a significant difference in temperature behavior between the two slabs, one containing Phase Change Material (PCM) and Textile Reinforced Concrete (TRC) and the other lacking these materials. On average, the temperature difference between the inner and outer sides of the slabs was 3°C for both the PCM-TRC slab and the conventional slab without PCM and TRC.

However, the temperature difference observed for the slab containing PCM and TRC was notably higher than that of the conventional slab. This suggests that the inclusion of PCM and TRC enhances the slab's ability to manage temperature variations, likely due to the PCM's ability to absorb and release heat during phase changes, which helps to moderate temperature fluctuations within the building structure. The higher temperature difference for the PCM-TRC slab implies that the material is effectively storing heat on the outer side and releasing it more slowly, reducing thermal fluctuations on the inner side of the slab.

The results also suggest that the thermal conductivity of the slab with PCM and TRC is lower, as evidenced by the higher temperature difference observed. A lower thermal conductivity indicates that the PCM-TRC slab is more effective at insulating and controlling the flow of heat, as it resists the transfer of heat more than the conventional slab. This result aligns with the expected behavior of PCM, which is known for its thermal storage capacity, and TRC, which contributes to the overall structural integrity and durability of the material.

In conclusion, the slab containing PCM and TRC demonstrated superior performance in temperature control compared to the conventional slab. This indicates that integrating PCM with textile-reinforced concrete provides a promising solution for improving the thermal management of building materials, offering potential benefits for energy efficiency and comfort in buildings. The results suggest that further exploration into the use of PCM-TRC slabs in construction could lead to more sustainable and thermally efficient building systems.

5. CONCLUSION

The present research sought to bridge the gap between conventional construction practices and emerging sustainable technologies. To do this, we cast micro- micro-encapsulated PCM - TRC slab to check the thermal properties of this slab and then compare this slab with the conventional concrete slab. The researchers performed the temperature test on the slabs.

It can be concluded from the testing results that the encapsulation of PCM pouches and providing textile reinforcement not only affected the structural properties but also majorly contributed to enhancing the thermal properties of the slabs. It has not adversely affected the compressive and the tensile properties of the slabs and was found to be very good in the case of thermal performance, completing the main goal of our project as the purpose of this research was to find sustainable building materials that can contribute to energy savings and indoor comfort.

Conflict of Interest: The authors declare no conflict of interest.

Ethical Approval: The study adheres to the ethical guidelines for conducting research.

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