Nanoengineered sustainable concrete with recycled concrete aggregates containing phase-change material

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Abstract

This paper presents the outcomes of an experimental investigation into graphene nanoengineered sustainable concrete, utilizing porous recycled concrete aggregates (RCA) as carriers for phase-change materials (PCM). The PCM impregnated-RCA (PCM-RCA) composite was created through an immersion technique followed by carbonation using high-purity carbon dioxide. Test results reveal that the addition of 0.02% graphene significantly enhances the 28-day compressive strength of PCM-RCA concrete compared to standard RCA concrete. In terms of thermal performance, experimental tests demonstrate that graphene reinforced PCM-RCA concrete has the potential to reduce indoor peak temperatures by 4.9 °C compared to RCA concrete. The graphene nanoengineered PCM-RCA concrete emerges as an innovative and sustainable building material suitable for thermal conditioning, offering the prospect of saving thermal energy consumption.

Keywords: Recycled concrete aggregates, phase change material, graphene, compressive strength, thermal performance.

1. INTRODUCTION

The construction sector stands as one of the foremost consumers of natural resources and a notable contributor to environmental degradation, primarily due to concrete production. Conventional concrete manufacturing entails the extraction and processing of raw materials like limestone, clay, and sand, processes known for their high energy consumption and substantial CO_2 emissions (Gartner & Hirao 2015). Additionally, the demolition of concrete structures generates a considerable amount of construction and demolition (C&D) waste, posing disposal challenges and environmental concerns (de Andrade Salgado & de Andrade Silva 2022). Addressing these issues necessitates the development of sustainable concrete alternatives that not only reduce resource consumption and waste generation but also enhance the performance characteristics of concrete.

One promising approach to achieving sustainable concrete is the incorporation of recycled concrete aggregates (RCA). RCA are derived from crushed and processed concrete waste, which can partially or fully replace natural aggregates in new concrete mixes. Utilizing RCA reduces the demand for virgin aggregates, minimizes C&D waste, and promotes a circular economy within the construction sector (Purchase et al 2021). However, concrete containing RCA often suffers from reduced mechanical properties and durability due to the presence of residual mortar and the heterogeneity of the recycled materials (Abden et al 2024). To overcome these limitations, advanced materials and innovative engineering techniques are being explored. Among these, the incorporation of graphene and graphene oxide (GO) offers significant potential (Devi & Khan 2020, Dimov et al 2018, Shamsaei et al 2018). Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, exhibits exceptional mechanical, thermal, and electrical properties. When incorporated into concrete, graphene can improve the strength, toughness, and thermal conductivity of the material.

In addition to mechanical enhancements, there is growing interest in improving the thermal performance of concrete. Phase-change materials (PCMs) are substances that absorb and release thermal energy during phase transitions, typically between solid and liquid states (Abden et al 2020). By integrating PCMs into concrete, it is possible to enhance the thermal storage capacity of buildings, thereby reducing energy consumption for heating and cooling (Abden et al 2022). PCMs can be encapsulated to prevent leakage and embedded within the concrete matrix, providing a passive thermal regulation mechanism. This study focuses on the development of graphene nanoengineered sustainable concrete incorporating RCA and PCMs (GPCM-RCA concrete). The objective is to create a concrete composite that not only leverages the environmental benefits of RCA but also exhibits superior mechanical and thermal properties due to the synergistic effects of graphene and PCMs.

2. MATERIAL AND METHODS

2.1 Materials

The materials used in this study included paraffin-based wax RT 26 (RT-series®) from Rubitherm GmbH, Berlin, Germany, recycled concrete aggregate (RCA) sourced from Lower Mountains Landscape Supplies, general-purpose Portland cement, fine sand, and industrial-grade carbon dioxide (CO_2) gas with a purity of 99.9%, supplied by BOC Limited, Australia.

2.2 Preparation of graphene solution from graphite powder

The graphene solution was prepared via high-shear liquid phase exfoliation of graphite powder using polycarboxylate as a stabilizer. Graphite flakes at an initial concentration of 0.02 wt% were exfoliated in water for 3 hours at 5000 rpm using a Silverson L5M shear mixer.

2.3 Compressive strength test

The compressive strength of both RCA and GPCM-RCA composite concrete was evaluated. Ordinary Portland cement, fine sand, and aggregate were mixed in a ratio of 1:2:2.7. A 0.02 wt% graphene solution was gradually added to this cement, sand, and aggregate mixture. The resulting mixture was then poured into 100 × 100 × 100 mm cube molds and vibrated for 2 minutes to ensure proper compaction. The ratio of the graphene solution to cement was maintained at 0.45. After 24 hours, the cubes were demolded and submerged in water at 25°C until one day before testing. The compressive strength was measured on the 28th day using a Universal Testing Machine (UTM) at a loading rate of 0.5 mm/min. This method ensured standardized preparation and testing conditions to accurately determine the compressive strength of the concrete samples.

2.4 Thermal performance test

The experimental setup consisted of two identical test chambers, each measuring 390 × 340 × 300 mm, designed to study the effect of phase change materials (PCM) on the thermal performance improvement of recycled concrete. These chambers were constructed using expanded polystyrene (EP) covered with flexible aluminum foil. Concrete samples were strategically placed on the top section of the chambers. The thermal performance of the concrete was examined over a 24-hour period. Temperature fluctuations within the chambers were measured using T-type thermocouples positioned at the center of each chamber. A PCE-T 1200 model data logger was employed to continuously record these temperature measurements at 60-second intervals.

3. RESULTS AND DISCUSSION

3.1 Compressive strength

Compressive strength is a key mechanical property of concrete, given its primary use in compression. The technique of evaluating the compressive strength of concrete cubes is commonly employed to determine the mechanical properties of concrete. The mechanical characteristics of graphene-reinforced PCM–RCA (GPCM-RCA) concrete after 28 days is depicted in Figure 1. As indicated in Figure 1, the compressive strength of GPCM–RCA concrete significantly surpasses that of standard RCA concrete. In particular, the peak strength of GPCM–RCA concrete reaches around 45.9 MPa, a 38.3% increase compared to the 33.2 MPa compressive strength of RCA concrete. This considerable strength enhancement suggests that GPCM–RCA concrete is highly suitable for real-world building construction applications.

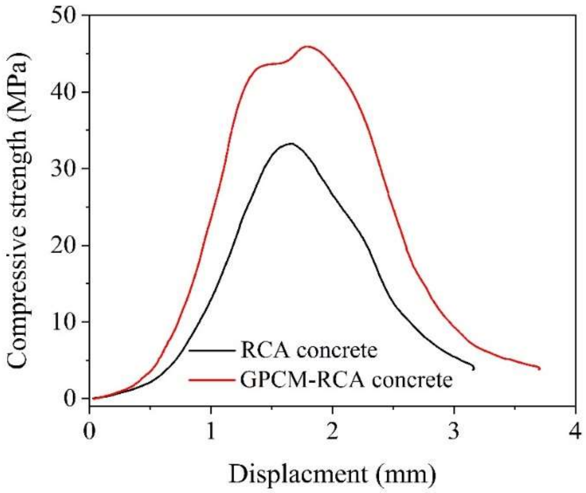

Figure 1. Compressive strength for RCA and GPCM–RCA concrete

3.2 Thermal performance

To evaluate the effectiveness of GPCM–RCA concrete for building thermal regulation, comparative tests were conducted with RCA concrete that did not contain PCM. These tests spanned a continuous 24-hour period, encompassing both daytime and nighttime conditions. The test setup is shown in Figure 2a. Throughout the duration of the tests, a linear increase in indoor air temperature was observed across all test cases (Figure 2b). However, a notable phenomenon occurred when the temperature reached the melting point of the PCM. At this juncture, the PCM began to store heat energy in the form of latent heat, effectively decelerating the rate of indoor air temperature increase. This thermal buffering effect was evident in the GPCM–RCA concrete samples.

As a result, the peak indoor air temperature attained with the GPCM–RCA concrete was significantly lower compared to the RCA concrete without PCM (Figure 2b). Specifically, the peak temperature of GPCM–RCA concrete was approximately 4.9 °C lower than that of the RCA concrete without PCM (Figure 2b). This substantial reduction in peak temperature demonstrates the effectiveness of PCM in enhancing the thermal regulation properties of the concrete.

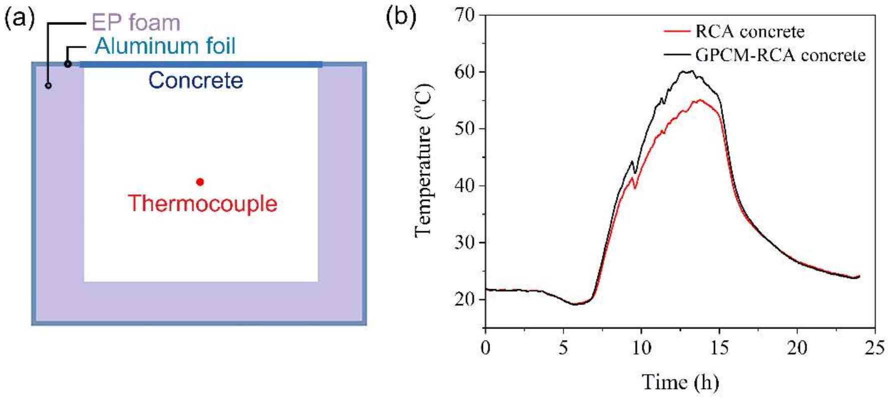

Figure 2. (a) Experimental configuration for monitoring the thermal performance of 25 mm thick GPCM–RCA concrete, (b) T_{in} (internal temperature) curves of RCA and GPCM–RCA concrete

These findings indicate that GPCM–RCA concrete is a promising solution for building thermal management, offering significant benefits in terms of enhanced energy efficiency and improved indoor comfort levels. The integration of PCM into the concrete matrix not only mitigates peak temperature increases but also contributes to a more stable indoor thermal environment. This reduced thermal fluctuation can decrease the reliance on additional cooling and heating systems, thereby improving overall energy efficiency. Moreover, the use of graphene further improves the mechanical properties and durability of the concrete, making it a robust material for construction. The dual functionality of GPCM–RCA concrete in providing both structural support and superior thermal regulation positions it as a viable and sustainable material for modern building applications. The incorporation of recycled materials also aligns with sustainable construction practices, promoting environmental conservation and waste reduction.

In summary, the study's results underscore the potential of graphene-reinforced PCM–RCA concrete as an innovative material for energy-efficient building design. Its ability to regulate indoor temperatures effectively, coupled with its structural benefits, makes it a strong candidate for widespread adoption in the construction industry.

4. CONCLUSIONS

In conclusion, this study underscores the potential of graphene nanoengineered PCM–RCA concrete as a sustainable building material. The addition of 0.02% graphene led to a notable 38.3% increase in the 28-day compressive strength of PCM–RCA concrete, reaching around 45.9 MPa. This enhancement positions GPCM–RCA concrete as a robust option for real-world construction applications. Furthermore, our thermal performance tests reveal a notable reduction of approximately 4.9 °C in peak indoor air temperature compared to standard RCA concrete. This demonstrates the efficacy of PCM in enhancing thermal regulation, offering energy efficiency and improved indoor comfort. Overall, the integration of graphene and PCM into RCA concrete presents a promising solution for sustainable construction practices. Further research is needed to optimize this composite material for broader adoption in the construction industry, contributing to environmental conservation and resource efficiency.

5. ACKNOWLEDGMENTS

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