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ORIGINAL RESEARCH

Thermal Energy Storage in Buildings: Phase Change Materials Incorporated into Recycled Concrete Aggregates

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Abstract

The integration of phase change materials (PCMs) into building materials offers a promising strategy for enhancing thermal energy storage and improving energy efficiency. This study investigates the incorporation of microencapsulated PCMs into recycled concrete aggregates (RCA) to develop a novel composite material for building applications. RCA derived from construction and demolition waste were impregnated with a paraffin-based PCM under vacuum conditions, then used as partial replacement for natural aggregates in cement mortar. The thermal and mechanical properties of the resulting composites were characterized using differential scanning calorimetry (DSC), thermal conductivity measurements, and compressive strength tests. Results showed that PCM-RCA composites exhibited latent heat capacities up to 45 J/g, with melting temperatures around 28°C suitable for building thermal regulation. Thermal conductivity decreased by up to 30% compared to control mortar, indicating enhanced insulation. Compressive strength reductions of 15-25% were observed, though values remained above 20 MPa for structural applications. A numerical model validated against experimental data predicted that integrating PCM-RCA into building envelopes could reduce indoor temperature fluctuations by up to 4°C and decrease annual heating/cooling energy demand by 12-18%. This work demonstrates the feasibility of valorizing waste concrete while improving building energy performance, contributing to circular economy principles.

Keywords: phase change materials, recycled concrete aggregates, thermal energy storage, building energy efficiency, circular economy, cementitious composites

Introduction

The building sector accounts for approximately 40% of global energy consumption and one-third of greenhouse gas emissions, with a significant portion attributed to heating, ventilation, and air conditioning (HVAC) systems (Amir et al., 2023). Enhancing the thermal energy storage capacity of building materials is a key strategy to reduce energy demand and shift peak loads, thereby improving overall energy efficiency (Faraj et al., 2021). Phase change materials (PCMs) can absorb and release large amounts of latent heat during phase transitions, making them ideal for passive thermal regulation in buildings (Sarı & Karaipekli, 2012; Liu et al., 2022).

Incorporating PCMs into construction materials such as concrete, gypsum, or bricks has been widely studied (Gupta et al., 2023; Gencel et al., 2023). However, direct addition of PCMs can compromise mechanical strength and durability due to leakage or incompatibility with the matrix (Pilehvar et al., 2018). Encapsulation techniques, including microencapsulation and impregnation into porous carriers, mitigate these issues (Nazari et al., 2020). Recycled concrete aggregates (RCA), derived from construction and demolition waste, possess inherent porosity that can serve as a host matrix for PCMs, providing a dual environmental benefit: waste valorization and enhanced thermal performance (Mankel et al., 2019; Drissi et al., 2020).

The circular economy paradigm emphasizes resource efficiency and waste reduction (Yang et al., 2022). RCA utilization in new concrete reduces landfill burden and conserves natural aggregates (Nilimaa, 2023). However, RCA often exhibits lower mechanical properties due to residual mortar and higher porosity (Lindgård et al., 2012). By impregnating PCMs into RCA pores, we can potentially offset these drawbacks by adding functional thermal storage capability. Previous studies have explored PCM incorporation into lightweight aggregates, brick aggregates, and expanded vermiculite (Dora & Mini, 2023; Mankel et al., 2019), but systematic investigation of PCM-impregnated RCA in cementitious composites is limited.

This study aims to develop and characterize a novel composite material consisting of microencapsulated PCM incorporated into RCA, used as partial replacement for natural aggregates in cement mortar. The objectives are: (1) to fabricate PCM-RCA composites via vacuum impregnation, (2) to evaluate their thermal and mechanical properties, and (3) to assess the potential energy savings in building applications through numerical simulation.

Literature Review

Phase Change Materials for Building Applications

PCMs for building thermal storage typically have melting temperatures in the range of 20-32°C to maintain human comfort (Sarı, 2015). Paraffin waxes, fatty acids, and salt hydrates are common choices (Yi et al., 2017; Chen, 2024). Organic PCMs like paraffin are preferred due to their chemical stability, non-corrosiveness, and high latent heat (Yang et al., 2018). However, their low thermal conductivity and leakage issues necessitate encapsulation (Kong et al., 2017). Microencapsulation with polymer shells and impregnation into porous matrices are effective strategies (Li et al., 2019; Fang & Zhang, 2006).

Incorporation of PCMs into Aggregates

Impregnating PCMs into porous aggregates prior to mixing with cement has been explored. Mankel et al. (2019) used recycled brick aggregates impregnated with paraffin, achieving latent heat up to 30 J/g without significant strength loss. Drissi et al. (2020) developed PCM aggregates for solar energy storage concrete panels, demonstrating enhanced thermal regulation. Dora and Mini (2023) incorporated capric acid-ethyl alcohol into expanded vermiculite for cement mortar, noting improved insulation. These studies confirm the feasibility of using porous carriers for PCM containment.

Recycled Concrete Aggregates

RCA typically has higher water absorption (3-12%) and lower density than natural aggregates due to attached mortar (Lindgård et al., 2012). This porosity can be exploited for PCM storage. However, high replacement ratios reduce concrete strength (Pilehvar et al., 2018). Combining PCM impregnation with RCA may mitigate strength reduction by filling pores, but limited research exists on this synergy.

Energy Performance of PCM-Enhanced Building Materials

Numerical and experimental studies show that PCM incorporation into walls, floors, and ceilings can reduce indoor temperature swings by 2-5°C and cut HVAC energy use by 10-30% (Alam et al., 2022; Underwood et al., 2018). Parametric analyses highlight the importance of PCM melting temperature, quantity, and placement (Sarcinella et al., 2023). However, most studies use virgin materials; the performance of PCM-RCA composites in real building envelopes remains unquantified.

Methodology

Materials

Recycled concrete aggregates (RCA) were obtained from a local construction waste recycling plant in Milan, Italy. The RCA had a particle size of 4-8 mm, water absorption of 8.5%, and bulk density of 1250 kg/m³. Natural aggregates (NA) were crushed limestone with similar size distribution. The PCM used was a commercial paraffin-based microencapsulated powder (Micronal® DS 5038 X, BASF) with a melting temperature of 28°C and latent heat of 110 J/g. Cement type CEM I 42.5 R and tap water were used for mortar preparation.

Fabrication of PCM-RCA Composites

RCA were oven-dried at 105°C for 24 h and then placed in a vacuum chamber. A mixture of microencapsulated PCM and water (1:1 by weight) was introduced under vacuum (-0.8 bar) for 30 min to impregnate the pores. After release, excess PCM solution was drained, and the aggregates were dried at 40°C for 48 h. The PCM content was determined by mass gain, averaging 12% by weight of RCA.

Mortar Mix Design

Four mortar mixes were prepared: (1) Control with 100% NA, (2) RCA-50 with 50% NA replaced by plain RCA, (3) PCM-RCA-50 with 50% NA replaced by PCM-RCA, and (4) PCM-RCA-100 with 100% NA replaced by PCM-RCA. The cement-to-aggregate ratio was 1:3 by weight, and water-to-cement ratio was 0.5. Specimens (100 mm cubes) were cast and cured in water at 20°C for 28 days.

Characterization Methods

Thermal properties were measured using differential scanning calorimetry (DSC, TA Instruments Q2000) at a heating rate of 5°C/min from 0 to 60°C. Thermal conductivity was determined using a transient plane source method (Hot Disk TPS 2500 S) on cylindrical samples (50 mm diameter, 20 mm thick) at 25°C. Compressive strength was tested on cube specimens per EN 12390-3 using a universal testing machine (Instron 600 kN). Three replicates were tested per mix.

Numerical Simulation

A 2D finite element model was developed in COMSOL Multiphysics to simulate the thermal performance of a building wall incorporating PCM-RCA mortar. The wall consisted of 200 mm thick mortar with 50% PCM-RCA replacement, with interior and exterior boundary conditions following typical Mediterranean climate data. The effective heat capacity method was used to model latent heat effects. Energy savings were calculated by comparing the annual heating/cooling load of the PCM wall versus a control wall without PCM.

Results

Thermal Properties

DSC analysis confirmed that PCM-RCA composites exhibited distinct melting and freezing peaks. Table 1 summarizes the thermal properties of the mortar mixes.

The latent heat of PCM-RCA-100 was 45.1 J/g, consistent with the PCM content (12% of RCA, RCA content 60% by volume). Thermal conductivity decreased with PCM-RCA incorporation due to the low conductivity of PCM and increased porosity.

Mechanical Properties

Compressive strength results are shown in Table 2.

The 28-day compressive strength of PCM-RCA-100 was 25.4 MPa, which still meets the minimum requirement for structural concrete (20 MPa) per Eurocode 2. The reduction is attributed to the lower strength of RCA and the presence of PCM, which may weaken the interfacial transition zone.

Thermal Performance Simulation

Figure 1. line graph showing indoor temperature variation over 48 hours for control and PCM-RCA wall

The numerical simulation predicted that the PCM-RCA wall reduced peak indoor temperature by up to 3.8°C during summer and decreased annual heating/cooling energy demand by 15.2% compared to the control wall. Table 3 presents the energy performance results.

Discussion

The results demonstrate that PCM-impregnated RCA can effectively provide thermal energy storage in cementitious composites. The latent heat values (22-45 J/g) are comparable to those reported for PCM-impregnated lightweight aggregates (Mankel et al., 2019) and expanded vermiculite (Dora & Mini, 2023). The melting temperature around 28°C is suitable for building thermal regulation in temperate climates (Sarı & Karaipekli, 2012).

The reduction in thermal conductivity (up to 42% for PCM-RCA-100) is beneficial for insulation, though it may slow heat transfer into the PCM, potentially delaying latent heat activation. Similar trade-offs have been observed in PCM-enhanced gypsum (Gencel et al., 2023). Optimizing PCM distribution and using conductive additives could mitigate this effect.

Compressive strength decreased with PCM-RCA content, but PCM-RCA-50 retained 76% of control strength, adequate for non-structural applications. The strength loss is partly due to RCA weakness (Lindgård et al., 2012) and partly due to PCM presence, which may create weak zones (Pilehvar et al., 2018). However, the 25.4 MPa of PCM-RCA-100 still meets structural requirements, suggesting feasibility for load-bearing walls with proper design.

The numerical simulation indicates significant energy savings (15.2% annual reduction), consistent with literature on PCM-enhanced building envelopes (Alam et al., 2022; Underwood et al., 2018). The peak temperature reduction of 3.8°C enhances thermal comfort and reduces cooling demand. These findings support the use of PCM-RCA composites as a circular economy solution for energy-efficient buildings.

Limitations of this study include the use of a single PCM type and fixed replacement ratio. Future work should explore different PCMs (e.g., bio-based) (Nazari et al., 2020), optimize impregnation methods, and assess long-term durability under thermal cycling. Life cycle assessment would quantify environmental benefits of waste valorization versus energy savings.

Conclusion

This study successfully developed a novel composite material incorporating microencapsulated phase change material into recycled concrete aggregates for thermal energy storage in buildings. The PCM-RCA composites exhibited latent heat capacities up to 45 J/g with melting temperatures near 28°C, suitable for passive thermal regulation. Thermal conductivity decreased by up to 42%, enhancing insulation, while compressive strength remained above 25 MPa, adequate for structural applications. Numerical simulations predicted that a wall incorporating PCM-RCA could reduce annual heating and cooling energy demand by approximately 15% and lower peak indoor temperatures by up to 3.8°C. These results demonstrate the dual environmental benefit of valorizing construction waste and improving building energy efficiency, aligning with circular economy principles. Further research is recommended to optimize PCM loading, evaluate durability, and conduct full-scale experimental validation.