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Thermal performance assessment of phase change material integrated cementitious composites in buildings: Experimental and numerical approach

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HIGHLIGHTS

- New kind of PCM integrated cementitious composite (PCMCB) was developed and characterized.
- Prototype experiments showed PCMCB significantly reduced indoor temperature fluctuations.
- Thermal performance of PCMCB in buildings was assessed with numerical simulations.
- Night ventilation is required to maximize the cold storage of PCM.

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ABSTRACT

This paper presents a comprehensive experimental and numerical investigation on thermal enhancement of form-stable phase change material (PCM) integrated cementitious composites, with the goal of applying as interior surface plastering mortars in building walls. The composite PCM fabricated on paraffin/hydrophobic expanded perlite (EPO) showed an apparent density and 28-day compressive strength of 1244.2 kg/m^3 and 17.9 MPa respectively, when integrated into ordinary cementitious composite at 80% volume replacement of fine aggregate. The thermal performance of PCM integrated cementitious composites was experimentally assessed using a prototype test cell made with PCM integrated cement boards (PCMCB) subjected to realistic temperature cycles. The comparison study considers two reference prototypes made with gypsum plasterboards (GPB) and ordinary cement boards (OCB). It was found that the prototype incorporated with PCMCB reduced the peak indoor temperature by up to 2.8 °C and 4.43 °C during typical summer days and summer design days respectively, compared to the GPB test cell. Numerical simulations conducted on a multi-storey office building for the application of PCMCB as interior surface plastering mortars showed that the PCMCB could significantly reduce the peak indoor temperature and diurnal temperature fluctuations. Indeed, the interior surface application of PCM has limited cold storage at night, leading to reduced latent heat storage. However, cold storage of PCM could be improved by introducing night ventilation. The combined application of PCMCB and night ventilation reduced the peak indoor operative temperature by up to 3.4 °C, as opposed to 2.5 °C for building refurbishment with PCMCB only.

1. Introduction

Buildings are one of the largest energy consumers around the world and account for approximately 30–40% of primary energy consumption, of which a substantial amount of energy is used to enhance indoor thermal comfort [1,2]. Moreover, energy consumption in this sector has risen rapidly in recent years due to increased population growth, high living standards and people spending more time indoors. Hence, energy conservation and management in buildings has become a crucial area of research.

A building's envelope is the boundary of the building thermal system and it maintains the thermal balance between energy production, consumption and storage within the building. This balance is significantly affected by external thermal solicitations, and the building envelope acts as a barrier to such external factors [3]. Envelope construction therefore plays a significant role in

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determining the heating/cooling energy demands of a building. The choice of appropriate construction methods provides an opportunity to reduce the space conditioning energy demands and to improve indoor thermal comfort. One such method is to adopt a latent heat thermal energy storage (LHTES) system operated with phase change materials (PCMs). The incorporation of LHTES system in buildings can assist in the delay and decay of indoor temperature fluctuations by storing excess solar thermal energy and releasing when the ambient temperature drops down, leading to improved indoor thermal comfort [3–5]. Latent heat storage is operated by endothermic/exothermic energy transfer during solid-liquid phase transformation of PCMs [6,7].

To date, the PCMs for TES applications have been mainly organic paraffin and fatty acids, inorganic salt hydrates and eutectic mixture of those. Among these various PCMs, organic paraffin is considered to be a promising candidate due to its inherent merits of large volumetric heat capacity, little or no phase segregation, chemical inertness and compatibility with most construction materials [8–10]. However, pure paraffin cannot be directly incorporated into construction materials (or components) due to leakage issues [2]. Therefore, PCMs, such as paraffin, are frequently used as form-stable composites that employ the impregnation of PCM into porous granular materials and incorporate composite PCM into construction materials. When form-stable PCMs are fabricated in this manner, functional PCM is retained in the pores of the supporting material, due to the capillary forces and surface tension, thus preventing the PCM leakage [11,12]. Typically used porous supporting materials include diatomite [13,14], vermiculite [12], expanded perlite [15,16], expanded graphite [17,18] and porous clay minerals [19–21].

Recent studies have shown that the incorporation of form-stable PCM into construction materials, such as cementitious composites, could lead to increased thermal energy storage performance due to large energy storage capacity and improved thermal conductivity. For instance, Xu and Li [13,22] developed new thermal energy storage cement-based composites (TESC) by incorporating paraffin/diatomite form-stable PCM into cement based materials. TESC developed by integrating 30wt% of form-stable PCM showed a significant improvement in thermal performance while maintaining adequate mechanical properties. However, the paraffin investigated here has a phase transition temperature of 41.1 °C, limiting its applications to building exterior surfaces such as roof tiles. Nevertheless, undesired adverse effects have been reported when low melting temperature form-stable PCMs are integrated into cementitious composites. For example, Li et al. [14] fabricated paraffin/diatomite PCM composite with the phase transition temperature of 21 °C for building interior surface applications. The authors observed a significant amount of PCM leakage when such form-stable PCM is integrated into cement mortars, leading to incompatibility issues with cementitious materials. In another study [23], the feasibility of integrating a commercial grade form-stable PCM into cementitious composite was investigated by the same team and they reported that the direct incorporation of form-stable PCM into cementitious composites would lead to instability or PCM leakage and hence, surface coatings are necessary to prevent such leakage. More recently, Ramakrishnan et al. [16] successfully overcame these issues by developing a novel form-stable PCM composite based on paraffin and hydrophobic expanded perlite composite, which can be directly incorporated into cementitious composite without the leakage issues, thanks to the hydrophobic surface property of this expanded perlite.

Incorporation of PCMs into building materials and components for the purpose of indoor climate control have also been extensively studied with the aid of experimental, analytical and numerical approaches. PCMs incorporated into wallboards [24,25], tiles [26], bricks [27] and concrete [28–30] have been considered as effective applications in reducing the indoor temperature fluctuations and heating/cooling energy demands. For instance, Athienitis et al. [31] investigated the thermal performance of a PCM integrated gypsum wallboard through a full-scale test room in Montreal CA. The PCM wallboard containing 25 wt% of paraffin showed a reduction in peak indoor temperature of 4 °C compared to the reference test room. Sari et al. [32] also experimentally studied the performance enhancement of PCM wallboard in a small test room for the application of passive solar buildings. The authors reported a reduction of 2 °C and 1.3 °C for inner surface temperature and indoor air temperature respectively, for PCM integrated wallboard compared to ordinary gypsum wallboard. Other experimental studies on the thermal performance of PCM in concrete floors showed that concrete floors containing PCM reduce the maximum floor temperature by up to 16 ± 2% and increase the minimum temperatures by up to 7 ± 3% [29].

In addition, the use of PCM integrated cement mortars or plastering mortars has been recently reported as a potential technology to improve building energy efficiency [33–35]. This application method is more versatile than other traditional methods as it has a relatively high surface to depth ratio, a large amount of PCM can be accommodated and this method can be used in existing buildings as an energy refurbishment approach. Sa et al. [36] investigated the thermal performance enhancement of PCM integrated plastering mortars with the aid of experimental and numerical approaches. The pilot scale experiment of this research showed a 2 °C reduction in the peak indoor temperature, while numerical studies assisted in optimizing the thermo-physical properties of PCM-enhanced plastering mortars. Kheradmand et al. [37,38] also examined the thermal behavior of plastering mortars containing hybrid micro-encapsulated PCM as a potential application to the interior surface of building walls. Their study showed a maximum reduction of peak indoor temperature by 1.5 K and increase in minimum temperature of 2.6 K for the prototype test room experiments.

Although several studies reported that the PCM integrated cement mortars could be a potential technology to improve indoor thermal comfort, most of the studies were based on commercially available microencapsulated PCMs. These microencapsulated PCMs do not only incur a high cost, but they are also detrimental to the cement matrix. This is particularly due to the soft polymeric shells encapsulating the PCM, which can be damaged and destroyed during mixing. Furthermore, the high pH environment in the cement matrix also deteriorates the polymeric shells of micro-encapsulated PCMs, resulting in a large amount of leakage. Some previous studies reporting the adverse effects of micro-encapsulated PCM in cementitious composites can be found in Refs [15,28].

The aim of the present study was to assess the thermal performance of buildings with a new PCM integrated cementitious composites applied as interior surface coatings in building walls. The so-called PCM integrated cementitious composite was developed by incorporating a form-stable PCM based on paraffin and hydrophobic expanded perlite (EPO). Our previous research has revealed that this novel form-stable PCM composite prevents the PCM leakage in cementitious composites [16,39]. We also investigated the thermal reliability of PCM integrated cementitious composites by subjecting them up to 100 accelerated thermal cycles. The novel paraffin/EPO form-stable PCM integrated cementitious composite showed negligible variation in thermal performance after 100 thermal cycles, which indicates that it is thermally reliable.

Here, we first report the formulation and characterization of PCM-enhanced cementitious composites by integrating paraffin/EPO form-stable PCM into cement mortars. The physical, mechan-