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Performance of novel thermal energy storage engineered cementitious composites incorporating a paraffin/diatomite composite phase change material

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HIGHLIGHTS

- TES-ECCs have moderate 28-day compressive strength above 30 MPa.
- TES-ECCs reveal superior ductile performance in both flexure and tension.
- Composite PCM greatly improves thermal resistance and heat capacity of TES-ECCs.
- FA has beneficial effects on TES-ECCs' ductility and thermal insulation.

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ABSTRACT

In this study, a paraffin/diatomite composite phase change material (PCM) was used as fine aggregate in the production of novel thermal energy storage engineered cementitious composites (TES-ECCs) featuring high tensile ductility and heat storage capacity. The mechanical properties, volume stability and thermal properties of the developed TES-ECCs were investigated and compared with those of a normal fiber-reinforced cementitious composite (FRCC). It was shown that the TES-ECCs offer much better ductile performance and lower compressive strength, first-crack flexural strength and first-crack stress than the normal FRCC, which used silica sand instead as fine aggregate. The strain hardening capacity of the TES-ECCs is as high as 3.65%. Moreover, the TES-ECCs have noticeably lower thermal conductivity and higher specific heat capacity and afford better overall thermal insulation performance than the normal FRCC. In addition, fly ash was found to improve the TES-ECCs' ductility, decrease their thermal conductivity and drying shrinkage.

1. Introduction

Buildings consume enormous amounts of energy. In recent years, in particular, the energy consumption of buildings has been rising sharply due to population growth, the increasing demand for thermal comfort and the fact that more and more people spend their time indoor [1,2]. Hence, energy saving and conservation for buildings has become a hot topic worldwide [1–4]. Adoption of thermal energy storage systems in buildings is regarded as an effective way of improving building energy efficiency [2–7]. In general, there are three types of thermal energy storage—latent heat storage, sensible heat storage and chemical reaction heat storage. Researchers and engineers tend to prefer latent heat storage based on phase change materials (PCMs) over the other two [3–7]. This can be attributed to the obvious merits of PCMs, which are high heat storage density and small temperature and volume variations during the phase change process.

Cementitious composites are one of the most extensively used building materials around the world. Incorporation of PCMs into cementitious composites not only endows this popular building material with the novel capability of thermal energy storage, but also facilitates energy saving and conservation. An immersion technique that involved directly soaking porous cementitious composites in liquid PCMs was previously adopted for developing thermal energy storage cementitious composites [8]. But the PCMs would leak from the cementitious composites during the solid–liquid phase change process, and so the immersion technique is currently rarely used. To overcome this leakage problem, many form-stable composite PCMs have been successfully developed in the past decades [8–13]. Nowadays, a diverse range of thermal energy storage cementitious composites can be produced easily by

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directly incorporating form-stable composite PCMs into cementitious matrices. When form-stable composite PCMs were introduced, they were usually treated as either cement fillers or aggregate replacements, depending on their particle sizes [14–20]. Subsequent investigations [8,14–20] revealed that incorporation of composite PCMs could lead to such beneficial effects on the thermal performance of cementitious composites as reduced thermal conductivity and an enhanced heat capacity. Nevertheless, undesired adverse impacts of some composite PCMs on the mechanical properties of cementitious composites have also been documented [17–19]. Hunger et al. [18], for example, reported significant compressive strength loss in self-compacting concrete incorporating a micro-encapsulated PCM. They found that a large portion of the PCM capsules were damaged with paraffin wax filling surrounding the cementitious matrix, suggesting that compatibility between this type of PCM and the high pH cementitious hydration system was poor. Zhang et al. [19] also observed dramatic compressive strength loss, even when only a small amount of n-octadecane/expanded graphite composite PCM was incorporated into the cement mortar. Poor bonding between expanded graphite and the cement matrix could be one of the reasons. From these investigations [17–19], it can be concluded that compatibility between a composite PCM's supporting matrix and the cement matrix plays an important role in the mechanical performance of a fabricated thermal energy storage cementitious composite. Taking advantage of diatomite's pozzolanic property, Xu and Li [20] employed a paraffin/diatomite composite PCM to produce thermal energy storage cementitious composites. They reported that even 30% paraffin/diatomite composite PCM, by weight of cement, was incorporated, the fabricated thermal energy storage cementitious composite still had a 28-day compressive strength of 25.7 MPa, which was much higher than many other previously reported results [14–19].

Engineered cementitious composite (ECC) is a class of ultra-ductile fiber-reinforced cement-based structural materials. ECC is tailor-made based on micromechanical analysis that quantitatively considers the interaction among fiber, matrix and their interface under loading [21]. With a moderate fiber volume fraction of 2%, ECC can demonstrate superior tensile ductility that is at least 100 times that of concrete [21–28]. Because of its high tensile ductility and limited crack width of around 60 μm, ECC has emerged as a promising alternative to normal concrete and fiber-reinforced concrete for structural performance improvement [24–28]. A wide range of thermal energy storage cementitious composites have already been explored [14–20]; nevertheless, they can only be considered as normal cementitious composites or normal fiber-reinforced cementitious composites because of their poor tensile ductility. Thermal energy storage engineered cementitious composites (TES-ECCs) featuring high tensile ductility and heat storage capacity have seldom been reported.

In the authors' previous work [20], normal thermal energy storage cementitious composites were developed by incorporating a laboratory-made paraffin/diatomite composite PCM. This previous investigation demonstrated the high compatibility between the employed paraffin/diatomite composite PCM and the cement system, thanks to diatomite's pozzolanic property. Moreover, this previous work forms the foundation for the current study on TES-ECCs. The same paraffin/diatomite composite PCM is adopted in the current study. PCMs may be applied in building exteriors, e.g. exterior walls and roofs, to keep them cool in the hot summer days. These materials help reduce heat conduction between the building's indoor and outdoor environments, thus enhancing building energy efficiency. The phase change temperatures of PCMs for building interiors range from 22 °C to 28 °C, which makes these types of PCMs unsuitable for building exteriors, due to the much higher outdoor temperatures in the summertime [29]. As a research attempt, a paraffin/diatomite composite PCM with a higher onset melting temperature of 41.1 °C was tested in the current study. However, the actual effectiveness of the developed TES-ECCs in improving building energy efficiency will have to await further investigation—preferably through field trials—in the near future. In the meantime, the mechanical properties, volume stability and thermal properties of the two developed TES-ECCs, namely TES-ECC1 and TES-ECC2, were investigated and compared with those of a normal fiber-reinforced cementitious composite (FRCC).

2. Experimental program

2.1. Materials and mix proportions

Raw materials used for fabricating the normal FRCC and TES-ECCs included ordinary Portland cement (OPC), fly ash (FA), a laboratory-made paraffin/diatomite composite PCM, silica sand, polyvinyl alcohol (PVA) fibers, a polycarboxylate-based high-range water-reducing admixture (HRWRA), methyl-cellulose (MC) and tap water. The chemical compositions of OPC and FA are given in Table 1. The paraffin/diatomite composite PCM used in this study was made in the laboratory. Its thermal property, thermal stability and chemical compatibility are all documented in the authors' previous work [20]. Therefore, only information regarding morphologies and thermal property of the composite PCM is shown in Fig. 1. As can be seen from Fig. 1(a), the paraffin/diatomite composite PCM has a yellow-tinted color and a maximum particle size of 300 μm. Scanning electron microscopy (SEM) observations of the composite PCM are shown in Fig. 1(b) and (c). It can be seen from the figures that the paraffin had found its way into the diatomite pores, ensuring form-stable performance. The thermal property of the composite PCM determined by differential scanning calorimetry (DSC) is presented in Fig. 1(d). The onset melting temperature and enthalpy of the composite PCM during the melting phase change process are 41.11 °C and 70.51 J/g, respectively; they are 47.54 °C and 71.96 J/g, respectively, during the freezing phase change process. The silica sand used also has a maximum particle size of 300 μm. The PVA fibers used are 39 μm in diameter and 12 mm in length. The density, nominal tensile strength, Young's modulus and elongation at rupture of the PVA fibers are 1.3 g/cm^3, 1530 MPa, 33 GPa and 6.5%, respectively. For the purpose of reducing chemical bonding between the PVA fibers and the cement matrix, the fibers were oil-coated at 1.2 wt.% at the manufacturing stage.

Table 2 presents mix proportions of the fabricated normal FRCC and TES-ECCs. The mixtures were all prepared at the same water/binder ratio of 0.27, aggregate/binder ratio of 0.25, and fiber volume fraction of 2%. The major mix design difference between the normal FRCC and TES-ECCs was the type of aggregate used. Whereas silica sand was employed in the normal FRCC, the paraffin/diatomite composite PCM was used as the TES-ECCs' matrix aggregate. Furthermore, FA was introduced to partially replace cement as an additional binder component in TES-ECC2, and the OPC/FA ratio in TES-ECC2 was around 2. In addition, HRWRA and MC were both employed for improving the workability of all the freshly prepared mixtures.

2.2. Testing methods

Fresh mixtures of the normal FRCC and TES-ECCs were prepared using a Hobart mixer. The solid ingredients—binder materials, aggregate and MC powder—were firstly dry mixed for 1 min at low speed. Then, water and HRWRA were added. The resulting mixture was mixed at low speed for 2 min and at high speed for another 2 min. After that, the PVA fibers were added, followed by