Construction and Building Materials xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Development of thermally adaptive Engineered Cementitious Composite for passive heat storage

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HIGHLIGHTS

- Thermal mass in building materials can help stabilize indoor temperatures.
- We consider increasing the thermal mass of a ductile concrete.
- The thermal mass is augmented by a paraffin component which melts at 23 °C.
- Inclusion of the phase change material increases thermal mass and resistance.
- Mechanical properties remain within structural range after paraffin addition.

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Phase-change material
Engineered Cementitious Composite
Building envelope
Passive heat storage

ABSTRACT

To provide passive heat storage in buildings, materials exhibiting a phase-change within building operating temperature can be incorporated into the envelope material. This study assesses the viability of incorporating a paraffin phase change material (PCM) into an Engineered Cementitious Composite (ECC) because the tensile ductility of ECC allows formation of thin panels—a favorable geometry for building façades. Inclusion of 3% PCM by mass provided a 40% increase in ECC specific heat capacity at phase change temperature while maintaining a 28 MPa compressive strength and 4% tensile strain capacity on average.

1. Introduction

Approximately 40% of home energy use is dedicated to space heating and cooling in the United States [1]. However, much of this energy is ultimately lost through the building envelope. Thus, in the field of building design, much effort has been dedicated to considering passive heat storage strategies such as roof ponds and thermal storage walls [2]. A common theme amongst the design strategies is utilization of high thermal mass in the building envelope to store heat during the warmest portion of the day and re-radiate heat into the building as temperature drops. This can flatten daily temperature fluctuations experienced indoors.

Thermal mass is the product of material mass and specific heat capacity, thus it can be increased by augmenting either. Since concrete is a ubiquitous envelope material, this study focuses on the feasibility of increasing its specific heat capacity such that the thermal mass of concrete envelopes can be increased without increasing the mass of concrete used. One manner of increasing the heat capacity of a composite material is introducing a component which undergoes a phase change within building operating temperature. As the phase change material (PCM) transitions from solid to liquid, heat is consumed to break chemical bonds. The opposite occurs as the material resolidifies and releases heat to its surroundings as bonds reform [3]. This provides a concentrated means of heat storage within the composite.

There are numerous phase change materials which have been considered for integration into building components such as hydrated salts, fatty acids and paraffins. An informative review of

Abberviations: PCM, phase-change material; ECC, Engineered Cementitious Composite; PCM-ECC, phase change material engineered cementitious composite; SEM, scanning electron microscope; DSC, differential scanning calorimetry; SHC, specific heat capacity; HVAC, heating ventilation and air conditioning.

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http://dx.doi.org/10.1016/j.conbuildmat.2013.12.104
0950-0618/

PCM types and applications in building materials is provided in Baetens et al. [3]. As discussed therein, each provides unique advantages and disadvantages in certain situations. Inorganic PCMs such as hydrated salts are affordable and thermally conductive, yet can supercool and lose storage capacity with thermal cycling. Non-paraffin organic PCMs do not experience supercooling, but do not provide phase-change at the desired indoor comfort temperature as ubiquitously as paraffins. Paraffins provide a phase-change temperature tailored to indoor comfort and retain thermal storage capacity with cycling, though their low thermal conductivity must be taken into account [3]. The latter results in an insulative effect in addition to the thermal storage of phase change. The indoor comfort temperature and life cycle considerations such as durability, cost and performance can guide the choice of PCM.

Paraffin PCM has thus far been successfully incorporated into self-compacting concrete in microencapsulated form [4]. The type of concrete chosen as the matrix for paraffin PCM in this study is an Engineered Cementitious Composite (ECC). Components of ECC include fly ash, fine aggregate, cement and fiber reinforcement, often a polymer fiber. The mix proportions are dictated by micromechanical principles in order to tailor the balance between parameters such as matrix toughness and fiber–matrix bond, allowing the concrete to provide tensile strength and ductility as well as compressive strength [6]. ECC was chosen due to its potential to be cast into thin panels for building envelopes potentially without need for reinforcing bars. ECC can also be made pigmentable [5]. This can allow for much creativity in geometry, color, and adjustment of surface reflectivity. Further, ECC can be used as a façade or structural material due to its compressive strength and tensile ductility [6]. The aim of this study is to experimentally test the hypothesis that a microencapsulated paraffin PCM can be incorporated into an ECC mix resulting in a new building material with significant improvement in heat capacity while retaining sufficient tensile ductility and compressive strength.

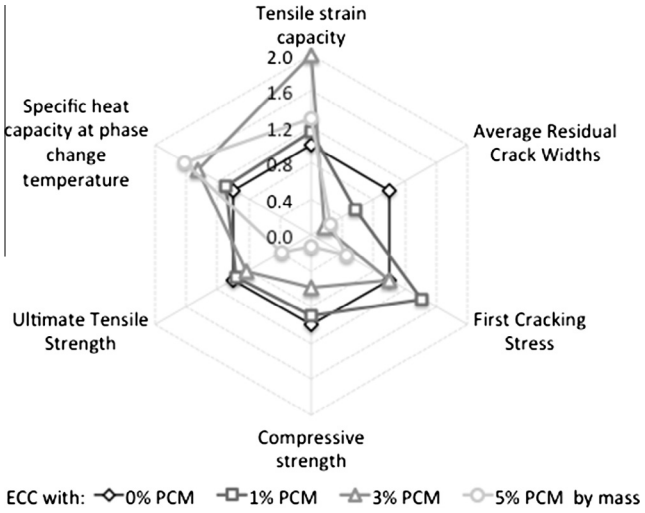

Fig. 1. Mechanical property averages of preliminary PCM-ECC mix designs normalized to that of the control ECC.

2. Material and methods

2.1. Mix proportions

The materials used in the design of PCM-ECC are class F fly ash, fine silica sand, type 1 cement, water, poly-vinyl alcohol (PVA) fiber, superplasticizer, and a PCM of microencapsulated paraffin wax with a melting point of 23 °C. The PCM used in this study was in dispersion form.

A preliminary study of mix designs was conducted to determine an appropriate level of PCM content for detailed exploration. PCM contents of 0%, 1%, 3% and 5% by mass were considered as demonstrated by Hunger et al. [4], and compared based upon mechanical property requirements and specific heat capacity (SHC) improvement. The mechanical and thermal properties were determined in accordance with the procedures described in Sections 2.3 and 2.4. Fig. 1 provides average values of these properties for each mix normalized to that of the control 0% PCM-ECC mix design detailed in Table 1. Based upon the tolerable decrease in compressive and tensile strength of 3% PCM-ECC in tandem with a significant increase in tensile strain capacity and SHC, this design was chosen for further study.

Thus, the two mix designs explored in further detail in this study are the control 0% PCM-ECC mix and 3% PCM-ECC mix, proportions of which are provided in Table 1. The control mix was created to serve as a matrix conducive to inclusion of PCM, rather than as an optimal, standalone ECC design. It was hypothesized that the addition of PCM would lower the matrix toughness of ECC, in turn lowering the composite compressive and tensile strength. Thus, a high-activity class F fly ash was utilized to raise the matrix toughness beyond the desired level in the control mix, and counter-act the hypothesized effect of PCM inclusion in the 3% PCM-ECC mix. Further, to allow the water content in each mix to remain comparable, the 3% PCM-ECC mix uses an adjusted water content to account for the portion of water added via the PCM dispersion assumed available for cement hydration, determined by preliminary mechanical evaluation of test batches.

The overall water and superplasticizer content were dictated by the necessary rheology for optimal fiber dispersion and air bubble minimization in addition to workability requirements. It is noteworthy that use of superplasticizer is limited by its tendency to cause segregation of matrix components at high concentrations. Mini-cone flow rate tests were conducted on the fiberless matrix of all batches tested, and the water and superplasticizer content determined by that needed to provide a flow rate of 24–33 s as recommended by Li and Li to serve the aforementioned goals [7]. These preliminary tests allowed determination of water content in the mix designs discussed in this article.

2.2. Scanning electron microscopy

In order to determine whether the PCM microcapsules were ruptured in the mixing and curing processes, images were taken of a cured 3% PCM-ECC specimen with a scanning electron microscope (SEM). A Quanta 200 3D apparatus was utilized for this process.

Fig. 2 provides one such SEM image. The PCM capsules are 5 μm in diameter on average and resemble crumpled spheres prior to addition to the matrix. From Fig. 2, we can see that the visible PCM capsules appear to have remained unruptured. We can also observe the PCM particles amidst other components of the ECC matrix. Smooth, spherical fly ash particles, 0.2–100 μm in diameter are dispersed throughout. The relief of a buried PVA fiber near the left side of the frame is also noticeable, as well as an interconnected system of dark capillary pores. The SEM imaging process also allows us to observe the distribution of PCM capsules within the matrix. In this SEM image, we can see that the visible capsules have dispersed rather than clumped. The differential scanning calorimetry results discussed in Section 3.3.1 corroborate this observation.

2.3. Mechanical testing methods

Mechanical testing focused upon compressive and tensile properties. As ECC is designed to provide ductility, tensile strength is an important parameter to monitor in addition to compressive strength. The 28-day compressive strength of control (0% PCM) ECC and 3% PCM-ECC were tested using cubes with 50.8 mm sides, testing

Table 1
PCM-ECC batch proportions. All proportions provided as mass with respect to cement content.

Batch name	Type 1 cement	Fly ash (class F)	Sand (F-100)	Water	Superplasticizer[a]	PVA fiber[b]	PCM dispersion
0% PCM-ECC	1	2	1.11	0.79	0.02	0.06	0.00
3% PCM-ECC	1	2	1.11	0.67	0.02	0.06	0.36

[a] ADVA 05 from W.R. Grace.
[b] 12 mm in length with a 40 μm diameter and a 1.2% oil coating.

Please cite this article in press as: Desai D et al. Development of thermally adaptive Engineered Cementitious Composite for passive heat storage. Constr Build Mater (2014), http://dx.doi.org/10.1016/j.conbuildmat.2013.12.104