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Properties of cementitious mortar and concrete containing micro-encapsulated phase change materials

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HIGHLIGHTS

- Microencapsulated PCM in substitution of sand increase heat capacity of concrete.
- Fineness of PCM involves a filler effect and increase cement hydration.
- Low density of PCM compared with fine aggregates reduces compressive strength.
- Microencapsulated PCM remain intact in the cementitious matrices during mixing.
- Blend of 20% v/v is proposed as optimum PCM replacement in cement-based materials.

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ABSTRACT

More efficient energy usage in buildings with increased thermal mass and better thermal insulation has attracted considerable attention in recent years. As one the most widely used construction materials in the building industry, concrete has a great potential to be converted to a high performance thermal storage material by using phase change materials (PCMs). To demonstrate this, mortar and concrete mixes were blended with microencapsulated PCM as part replacement of fine aggregates and assessed for improved thermal performance. Specimens with varying amount of microencapsulated PCM were tested using calorimetry, differential scanning calorimetry (DSC), thermogravimetry (TGA), scanning electron microscopy (SEM), compressive strength and thermal conductivity. Results show that high specific surface of microencapsulated PCM particles has induced an acceleration of the cement hydration. However, the compressive strength at 28 days is still decreased when fine aggregates were substituted by PCM. Contrary to past observations, microencapsulated PCM is observed to remain intact in the cementitious matrices and contributed significantly to improve the heat capacity as well as to reduce the thermal conductivity of the mixes tested. A blend with 20%·v/v replacement was identified as the optimum PCM replacement.

1. Introduction

Phase change materials (PCMs) store latent heat during a phase transition from solid to liquid or liquid to gas or vice versa. This latent heat can be subsequently released as thermal energy. Although sensible storage has been used for centuries for passive thermal storage, latent storage materials provide more effective storage of heat with high energy density and store heat over a narrow temperature range [1]. Research on the use of PCMs in different building materials, with various methods of incorporation has found that PCMs store significant amount of thermal energy within a building envelope with less structural mass compared with sensible heat storage [2–6]. PCMs have been used to stabilise indoor temperature in a building by reducing temperature extremes and delaying the arrival of peak temperature, therefore conserving the energy that is normally used for space conditioning [3,7]. Experimental and numerical evaluation of building thermal performance and effective thermal properties of construction materials with PCM have been reported in related studies [2,3,7].

Some researchers have analysed the innovative use of PCM in cement-based materials as a solution for improving thermal comfort and reducing energy consumed for indoor space conditioning [7–11]. Encapsulation of PCM is preferred as it can hold the liquid

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phase of the PCM and recent development of microencapsulated PCM has shown improved thermal properties by creating finely dispersed PCMs, with high surface area, for more efficient heat transfer. Results from a study of two full scale concrete test cells using microencapsulated PCM were presented by Cabeza et al. [7]. A lower inner temperature of 3 °C was achieved with PCM which could make considerable impact on thermal comfort levels [12]. An increase in thermal mass due to the addition of PCM was observed by a series of experiments using different amounts of PCM in concrete mixes by Hunger et al. [9]. Results showed an energy saving of 12% was achieved with 5% PCM in the mix.

While cement-based materials containing PCM have beneficial outcomes on the thermal properties of concrete, adverse consequences on mechanical properties have been reported in some studies. Hunger et al. [9] found that the addition of PCM yields lower compressive strength in concrete. Based on the reported compressive strength experimental results by Hunger et al. [9] that ranged from 75 MPa to 21 MPa, 3% PCM content in the concrete resulted in accompanying compressive strength of 35 MPa and was stated as adequate for most constructional purposes. Meshgin and Xi [10] have also reported a loss in compressive strength of concrete with addition of PCM; the mix with 20% PCM resulted in compressive strength of 15 MPa compared with 21 MPa of the control mix. Only a few studies have focused on the reasons behind the changes in mechanical properties and the reported outcomes of these studies are different to each other. Dehdezi et al. [11] stated that bursting of PCM shells under loading at a post-curing stage were the underlying reason for strength decrease. Yet the hydration effects of concrete with PCM have not been considered here. However, Hunger et al. [9] and Fernandes et al. [13] identified that PCM microcapsules tends to damage during mixing stage and leaked paraffin wax interfere with the hydration products and cause the strength reduction. Therefore further studies are needed to identify the causes of these changes in mechanical properties and the optimum amount of PCM in cement-based materials.

This research demonstrates the effect of volume fraction and dispersion of microencapsulated PCM capsules on chemical, mechanical and thermal properties in cement-based materials. A detailed experimental analysis of the mechanisms of microencapsulated PCM on cement hydration rate, strength evolution and thermal properties will be undertaken as a novel approach in identifying the optimum amount of PCM in substitution of fine aggregates that should be used under current mix design, based on the tradeoff between mechanical and thermal properties. Special emphasis is placed on cement hydration and microscopical analysis in determining the reasons for strength reduction as a basis for future developments.

2. Materials and experimental methods

2.1. Materials

The concrete mix consists of General Purpose (GP) cement, 4 mm fine aggregates (sand) and 10 mm basalt coarse aggregates. The properties of cement used are presented in Table 1. The cement type used conforms to AS3972 [14] Type GP with an estimated phase composition (by mass) of 52.13% C_3S, 19.87% C_2S, 19.64% C_3A and 2.28% C_4AF based on AS 2350.2 [15]. Finer sand compared with 4 mm fine aggregates was used for some of the mortar specimens. Sieve analysis was conducted based on AS1141.11.1 [16] for both coarse and fine aggregates. The particle size distribution for the aggregates is shown in Fig. 1. Table 2, shows the general properties of the PCM which is a paraffin based microencapsulated PCM, (Micronal DS 5040X) commercially available from BASF for the building and construction industry with a transition temperature of 23 °C. The PCM is in powder form and the particle size ranges from 50 to 300 μm. Furthermore the particle size distribution of PCM and cement was measured using laser diffraction particle size analyser, Mastersizer 3000 series.

Table 1
Chemical composition and physical properties of cement used.

Component	Amount
Calcium oxide (CaO)	66.15%
Silica (SiO_2)	20.62%
Alumina (Al_2O_3)	7.89%
Sulphur trioxide (SO_3)	2.21%
Magnesium oxide (MgO)	0.98%
Alkalis ($Na_2O + K_2O$)	0.9%
Iron oxide (Fe_2O_3)	0.75%
Titania (TiO_2)	0.32%
Phosphorus (P_2O_5)	0.18%
Loss on ignition (LOI)	2.98%
Density (g/cm^3)	3.12
Specific Area (m^2/kg)	352

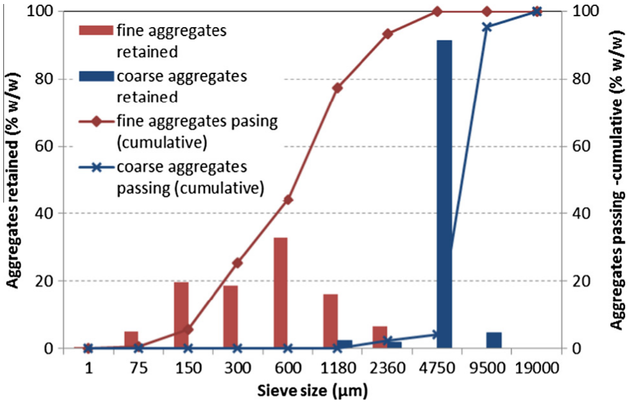

Fig. 1. Particle size distributions of fine and coarse aggregates.

Table 2
Properties of Micronal DS5040X.

Material	Transition temperature (°C)	Bulk density (kg m^{-3})	Latent heat capacity (kJ kg^{-1})
Paraffin core with Poly (methyl methacrylate) highly cross-linked shell	23	250–350	100

2.2. Experimental methods

2.2.1. Preparing concrete specimens

Concrete mixes were prepared with a fixed water-to-cement ratio of 0.5 as presented in Table 3. To provide an acceptable workability to the mixes, a third generation high water reducing superplasticiser was used. Different fractions of microencapsulated PCM ranged from 0% to 5% were used as a replacement of fine aggregates in the mix on mass basis. The mixing procedure for concrete comprised four steps. At first, all the dry ingredients except PCM were mixed for four minutes to obtain a homogenized mix. Then 90% of the total water quantity was added with the superplasticiser and mixing continued for another two minutes. Thereafter, microencapsulated PCM was added to the mixture to minimise the time of exposure to the mixing process. Finally the remaining water and superplasticiser was added to obtain a mixture with desired workability. The fresh mix was used for the subsequent