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Influence of microcapsule size and shell polarity on thermal and mechanical properties of thermoregulating geopolymer concrete for passive building applications

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ABSTRACT

Microencapsulated phase change materials (MPCM) were added to geopolymer concrete (GPC) for utilization as a thermal energy storage concrete for passive building applications. Three different MPCM were compared to examine the influence of the hygroscopic nature of the MPCM shell, the PCM core/polymer shell ratio, and the MPCM size on the microstructure, thermal properties and compressive strength of GPC. The combination of a hygroscopic nature of the polymer shell, a high core/shell ratio, and a small MPCM size were found to improve the interface bonds between microcapsules and the GPC matrix, increase the energy storage capacity of GPC, and results in a good dispersion of MPCM in the GPC matrix. After adding 5.2 wt% MPCM to GPC, the power consumption for stabilizing the indoor temperature at 23 °C may be reduced by up to 18.5 ± 0.3% for GPC containing PS-DVB/RT27 (paraffin Rubitherm®RT27 core and a shell of polystyrene cross-linked with divinylbenzene), 20.1 ± 0.7% for GPC containing PMMA/PCM26 (paraffin mixture core with a crosslinked polymethyl methacrylate shell) and 25.9 ± 0.3% for GPC containing MF/PCM24 (paraffin mixture core with a melamine–formaldehyde polymer shell). Adding MPCM to GPC induces a higher amount of air pockets, which weaken the compressive strength. Unfortunately, the same parameters that are advantageous for reducing the energy consumption also results in a greater decline of the compressive strength. The compressive strength is further reduced when the microcapsule core is in its liquid state. However, the compressive strength still satisfies the mechanical European regulation (EN 206-1, compressive strength class C20/25) for concrete applications, except for GPC containing 5.2 wt% of MF/PCM24.

1. Introduction

With approximately 40% of the total global energy consumption contributed by buildings, reducing the energy consumption for buildings plays a key role for reducing global warming [1,2]. In order to reduce the huge energy consumption of buildings, improved construction techniques and advanced material technology are required. Concrete-based materials are among the most used materials for building applications. With their high mechanical strength and the possibility of changing the properties by varying the concrete recipe, concrete can work not only as a structural material but also as a functional material for thermal energy storage. The energy storage capacity of concrete can be enhanced by integrating microencapsulated phase change materials (MPCM). MPCM can store and release large amounts of energy during the phase transition. This is a promising technology for improving the energy efficiency of buildings, with reduced power consumption for heating and cooling [3–9]. Due to the low thermal conductivity of MPCM and an enhanced porosity, the thermal conductivity of concrete is decreased after addition of MPCM [5]. The decline in the compressive strength of concrete is the main drawback of MPCM addition [3–6]. The destruction of microcapsules during the mixing process might be the reason for the reduction of the compressive strength [3]. The soft nature of MPCM may weaken the concrete [5], and a complete cement hydration may be prevented due to the hygroscopic nature of the

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MPCM [6]. In addition, the higher porosity after MPCM addition is probably contributing to the reduced strength [3,5,7].

Most studies of including MPCM in concrete structures are based on Portland cement concrete [3–9]. However, the high amount of CO_2 emission from production of Portland cement is a drawback of utilizing this type of concrete [10]. It is therefore a great advantage to replace Portland cement concrete by more environmentally friendly construction materials such as geopolymer concrete. Geopolymer is synthesized by alkali activation of materials rich in silica and alumina (from industrial waste materials such as fly ash (FA), coal ash, rice-husk ash, red mud and ground granulated blast furnace slag (GGBFS)) [11–14]. Using geopolymer as an alternative binder for concrete can greatly reduce the CO_2 emission from the cement industry. A few studies have examined integration of MPCM to geopolymer concrete [5,7], with promising results for improving the energy efficiency of buildings. It was found that the higher porosity after adding microcapsules contributes to the improvement of the thermal properties and the reduction of the compressive strength of geopolymer concrete. However, the effect of the MPCM properties (hygroscopic nature of the polymer shell, size of the microcapsules, storage heat capacity) on the thermal and mechanical properties of geopolymer concrete was not investigated in previous studies. In addition, it is important to evaluate the effect of the PCM state (solid or liquid) on the compressive strength of concrete.

In the current study, geopolymer concrete is employed as the concrete-based material for integration of microencapsulated phase change materials. Three kinds of microcapsules with variation of polymer shells, heat storage capacity and size were utilized to explore the influence on the microstructure, thermal, and mechanical properties of geopolymer concrete. The effects of the hygroscopic nature of MPCM and different PCM states were given special attention, as previous knowledge within this field is very limited. The effect of MPCM on the energy efficiency of buildings was estimated by determining the power consumption and power reduction of a heating and cooling system.

2. Experimental

2.1. Materials

Three different kinds of microcapsules were utilized. PS-DVB/RT27 was produced by a suspension polymerization process [15]. The MPCM are composed of a paraffin Rubitherm®RT27 core coated with a PS-DVB (polystyrene cross-linked with divinylbenzene) shell. PMMA/PCM26 (Micronal DS-5038X, BASF, Germany) has a core which is a paraffin mixture and highly crosslinked polymethyl methacrylate (PMMA) shell, with a core/shell ratio of 7:3 [16]. MF/PCM24 (Microtek MPCM24D) has a paraffin mixture core and melamine-formaldehyde polymer shell (MF). The ratio between the paraffin core and polymer shell is 9:1 [17]. Table 1 summarizes the characteristics of the three MPCMs.

Geopolymer concrete containing microencapsulated phase change materials (MPCM-GPC) was fabricated by mixing class F fly ash (FA) (Norcem, Germany) (density = 2.26 ± 0.02 g/cm^3), ground granulated blast furnace slag (GGBFS) (Cemex, Germany) (density = 2.85 ± 0.02 g/cm^3), sand (Gunnar Holth and Skolt Pukkverk AS, Norway) (density of 2.7 g/cm^3), aggregates with an average size of approximately 10 mm (Gunnar Holth and Skolt Pukkverk AS, Norway) (density of 2.6 g/cm^3), retarder (FLUBE OS 39, Bozzetto Group, Italy) (density of 1.2 g/cm^3), an alkaline activator solution, and MPCM. The sand and aggregates were dried before use. The chemical composition of FA and GGBFS were obtained by X-ray Fluorescence (XRF) and is summarized in Table 2. Based on a previous study [19], the alkaline activator solution was mixed at a ratio of 1.5 of a sodium silicate solution (density = 1.93 g/cm^3, 35 wt% solid) and 14 M NaOH (560 g/L). Accordingly, $m_{Na2SiO3(aq)}$ = 120 g, and $m_{NaOH(aq)}$ = 80 g. Fresh GPC possesses a poor workability due to the high geopolymerization reaction rate, which has a negative effect on the integration of MPCM into GPC [5,7]. Therefore, a chemical admixture was utilized to improve the workability of the concrete and to facilitate a better distribution of MPCM in the GPC matrix. A naphthalene based retarder was selected due to its high effectiveness with geopolymer concrete containing fly ash class F [20–22].

Table 3 summarizes the composition of geopolymer concrete containing MPCM (MPCM-GPC). For the recipe, a 1 L mix design was obtained from previous studies [7,19]. To keep a constant volume, the sand was replaced by MPCM at the same volume percentage (see supporting document [18] for details). However, the MPCM content is calculated as a wt.% of the total concrete sample, for a clearer comparison of the energy reduction. The mixture was prepared by weighting the components. In order to minimize the effect of shear during the mixing process, MPCM was mixed into GPC during the final step. For more information about the mixing process and recipe, see Pilehvar et al. [7,19].

PCM was incorporated into GPC at 0, 1.3, 2.6 and 5.2 wt%. The concentration of MPCM was limited to 5.2 wt% since higher concentrations of MPCM resulted in too low workability of the geopolymer concrete. After mixing, MPCM-GPC were cast into molds at a size of 200 × 200 × 25 mm (for the thermal test) and 100 × 100 × 100 mm (for the compressive strength test). The samples were pre-cured at room temperature (20 °C) for 24 h. The samples were then demolded and kept in water at room temperature (20 °C) for 28 days to reach a fully cured state. Before conducting the thermal test, the fully cured samples were dried in an oven at 40 °C until the sample weight remained unchanged.

Table 1
The fundamental data of the microencapsulated phase change materials.

MPCM name	Density (g/cm^3)	Melting point* (°C)	Latent heat* (J/g)	Core/shell ratio	Refs.
PS-DVB/RT27	0.9	24.9	100	11:9	[15]
PMMA/PCM26	0.9	24.7	110	7:3	[16]
MF/PCM24	0.9	21.9	154	9:1	[17]

* The melting point and latent heat were determined by differential scanning calorimetry (DSC) (see Supporting document [18] for details).

2.2. Scanning electron microscopy

The surface morphology and the micro structure of the microcapsules (powder form) were obtained by Scanning electron microscopy (SEM) (Quanta FEG-250, Spain). For MPCM-GPC, the fractured surfaces of samples containing 2.6 wt% of MPCM were investigated using a Zeiss EVO50 EP Scanning electron microscope (Norway).

2.3. X-ray micro-tomography

The internal microstructure of GPC containing microcapsules were investigated using X-ray tomography. The X-ray micro-tomography cross-sectional slices of cylindrical samples were obtained using a Skyscan 1172 CT scanner (Bruker) with 80 kV incident radiation, 124 μA source current, 750 ms exposure time per frame and 0.3° rotation step. Tomographic reconstruction was performed using the Feldkamp algorithm [23] and the final pixel size was 6 μm. The samples were made in cylindrical form (1 cm diameter and 1 cm height) from completely curing GPC without MPCM and containing 2.6 wt% of microcapsules (PS-DVB/RT27, PMMA/PCM26 and MF/PCM24).

2.4. Size distribution of MPCM

Low Angel Laser Light Scattering (LALLS) laser diffraction using a Malvern Mastersizer 2000 (Malvern Instruments Ltd., Malvern, UK) equipped with a Scirocco 2000 unit for analyzing dispersions of the particles in air was employed to determine the size distribution of MPCM.