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Microencapsulated phase change materials for enhancing the thermal performance of Portland cement concrete and geopolymer concrete for passive building applications

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ABSTRACT

Concretes with a high thermal energy storage capacity were fabricated by mixing microencapsulated phase change materials (MPCM) into Portland cement concrete (PCC) and geopolymer concrete (GPC). The effect of MPCM on thermal performance and compressive strength of PCC and GPC were investigated. It was found that the replacement of sand by MPCM resulted in lower thermal conductivity and higher thermal energy storage, while the specific heat capacity of concrete remained practically stable when the phase change material (PCM) was in the liquid or solid phase. Furthermore, the thermal conductivity of GPC as function of MPCM concentration was reduced at a higher rate than that of PCC. The power consumption needed to stabilize a simulated indoor temperature of 23 °C was reduced after the addition of MPCM. GPC exhibited better energy saving properties than PCC at the same conditions.

A significant loss in compressive strength was observed due to the addition of MPCM to concrete. However, the compressive strength still satisfies the mechanical European regulation (EN 206-1, compressive strength class C20/25) for concrete applications. Finally, MPCM-concrete provided a good thermal stability after subjecting the samples to 100 thermal cycles at high heating/cooling rates.

1. Introduction

The total energy consumption is dramatically increasing all over the world. Much of the energy demand can be attributed to building energy consumption, and a significant proportion of this energy is for heating and cooling purposes [1]. Improved construction techniques and enhanced material technology can greatly reduce the energy consumption needed to keep a comfortable indoor temperature. Thermal energy storage systems, including sensible heat storage and latent heat storage materials, can be used to conserve and save energy [2–6]. Sensible heat storage materials store energy by raising the temperature of the storage materials such as concrete, rock, or steel. For latent heat storage materials, also known as phase change materials (PCM), the thermal energy is stored during the phase change of the materials (e.g. melting, evaporating, or crystallization). Unlike sensible heat storage, latent heat storage systems are capable of storing energy with higher storage density at an almost constant temperature, which is referred to as the phase transition temperature of the materials. This makes latent heat storage materials more attractive than sensible heat storage materials for improving thermal comfort and reducing the energy consumption for heating/cooling purposes.

The capability to store or release thermal energy from PCM strongly depends on the heat storage capacity, thermal conductivity, the melting temperature of the PCM, and the outdoor environment that it is exposed to. Building materials, especially concrete based materials, with a high volume and surface area exposed to the indoor environment, as well as a high mechanical strength are potential candidates for integration with PCM. Furthermore, concrete provide the possibility to alter both thermal and mechanical properties of the PCM-materials. The incorporation of PCM into concrete can significantly improve the thermal energy storage capacity of building structures around the melting range of PCM

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Nomenclature

C_p	specific heat capacity, J/kg °C
Q	total energy consumption, kW h/m^2
T	temperature, °C
t	time, s
m	mass, kg
φ	heat flux, W/m^2
λ	thermal conductivity, W/m °C
ρ	density, kg/m^3
ε	concentration, wt.%
ΔH	latent heat, J/g

Subscripts/superscripts

s	saturated mass
d	dry mass
b	buoyant mass
S	solid state
L	liquid state
init	initial time of process
end	final time of process
top	top heat exchanger
bottom	bottom heat exchanger
ave	average
H	heating
C	cooling
MPCM	microencapsulated phase change materials

[7–9]. Therefore, the development of smart building materials with the direct addition of PCM could reduce the energy consumption for heating/cooling systems. However, interaction with surrounding materials and low heat transfer coefficients limit the direct application of PCM. In order to overcome these problems, microencapsulation may be utilized for incorporation of PCM into small polymeric capsules [10–13]. This provides not only an extremely high heat transfer area, but also prevents the leakage of PCM and interactions with the building structure. Microencapsulated phase change materials (MPCM) are therefore able to support PCM for utilization as thermal storage materials in building applications and energy storage systems [14–19]. Concrete-based materials with high thermal properties and high mechanical strength are potential candidates for MPCM integration. Concrete materials provide the possibility to alter both thermal and mechanical properties of the MPCM-concrete. The integration of MPCM in concrete is therefore a good strategy of passive building technology to reduce the energy consumption.

Portland cement concrete (PCC) is the most utilized concrete for applications utilizing microencapsulated phase change materials [15–17]. PCC has several advantageous properties, such as high thermal conductivity, high specific heat capacity, high density, and high mechanical strength. However, PCC exhibits a negative effect on the environment due to the emission of carbon dioxide (CO_2) during the production of cement [20]. In comparison to PCC, geopolymer concrete (GPC) not only exhibits corresponding advantageous properties as PCC, but also higher initial strength, small drying shrinkage, high fire resistance, superior acid resistance and shorter setting time [21]. The geopolymer binder is synthesized by alkali activation of aluminosilicate materials in amorphous form, which are produced from industrial waste materials. Geopolymer is therefore more environmentally friendly and cheaper than Portland cement [22,23]. The use of geopolymer concrete can significantly reduce the amount of CO_2 emission from the cement industry, the primary driver of global warming. Accordingly, geopolymer is a very interesting alternative to Portland cement as a binder for concrete. However, the thermal properties of geopolymer concrete containing MPCM have not been reported previously. Researchers utilizing MPCM have mostly utilized standard concrete recipes, which are more readily available for Portland cement. In addition, problems with short setting times of GPC [21,24], can be worsened when MPCM is added to the mixture. The comparison between Portland cement concrete and geopolymer concrete with the addition of MPCM is therefore very interesting.

While the integration of MPCM in concrete can improve the thermal energy storage capacity of the building structure, it also reduces the mechanical strength of concrete [9,15]. A good knowledge of the effect of microcapsules on the thermal and mechanical properties of concrete therefore plays an important role to optimize the efficiency of passive house construction.

In this article, the integration of MPCM into Portland and geopolymer concretes was investigated, respectively. The microcapsules have a shell of low density polyethylene (LDPE) and ethylvinylacetate (EVA) copolymer, and a core of paraffin Rubitherm®RT27, abbreviated LDPE-EVA/RT27. RT27 is selected as the PCM material due to the high latent heat (100 J/g), a melting point around 27 °C (which is suitable for achieving good temperature control in warm climates), and the lack of chemical interactions with the alkaline solution and the surrounding environment [25]. In addition, it will not corrode metal reinforcements within concrete structures. The effect of MPCM content on the thermal performance and mechanical properties (compressive strength) of PCC and GPC were investigated. MPCM were added by replacing the same volume percentage of sand, utilizing concentrations up to 3.2 and 2.7 wt.% for PCC and GPC, respectively. The comparative analysis between PCC and GPC was given special attention, since previous knowledge within this field is limited.

2. Experimental

2.1. Materials

The microencapsulated phase change materials (MPCM) were made by a spray drying process [25]. The MPCM are composed of a paraffin Rubitherm®RT27 core coated with the LDPE-EVA (low density polyethylene (LDPE) and ethylvinylacetate (EVA) copolymer) shell [25].

MPCM were integrated into two different types of concrete; Portland cement concrete (PCC) and geopolymer concrete (GPC) at various concentrations. Tables 1 and 2 present the composition of PCC and GPC mixtures. The MPCM replaced the same volume percentage of sand, and the MPCM concentration in total solid weight of concrete was calculated. PCC samples were fabricated with 0 wt.%, 0.8 wt.%, 1.6 wt.%, and 3.2 wt.% of incorporated MPCM (Table 1). For GPC (Table 2), the concentration of MPCM was 0 wt.%, 0.7 wt.%, 1.3 wt.%, and 2.7 wt.%. Higher amounts of MPCM resulted in too low workability of the concretes to produce usable samples. The dimensions of the samples were 20 × 20 × 2.53 cm for the thermal test and 10 × 10 × 10 cm for the compressive strength test. According to the mechanical regulations, the