

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.

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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

<i>Subscripts/superscripts</i>	
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 (CO₂) 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 CO₂ 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

Table 1
Composition of Portland cement concretes (PCCx^a).

Sample	MPCM (wt.%)	Cement (g)	Water (g)	Admixture (g)	Sand (g)	Aggregate (g)	MPCM (g)
PCC0	0	434	192	5.6	1057	705	0
PCC0.8	0.8	434	192	5.6	1004.2	705	18
PCC1.6	1.6	434	192	5.6	951.3	705	36
PCC3.2	3.2	434	192	5.6	845.6	705	72

^a x is the concentration (wt.%) of MPCM in the concrete.

Table 2
Composition of geopolymer concretes (GPCx^a).

Sample	MPCM (wt.%)	Alkaline solution (g)	Water (g)	FA ^b (g)	GGBFS ^c (g)	Sand (g)	Aggregate (g)	MPCM (g)
GPC0	0	161.6	56.4	242.6	161.4	893.1	868.6	0
GPC0.7	0.7	161.6	56.4	242.6	161.4	848.6	868.6	15
GPC1.3	1.3	161.6	56.4	242.6	161.4	803.8	868.6	30
GPC2.7	2.7	161.6	56.4	242.6	161.4	714.5	868.6	60

^a x is the concentration (wt.%) of MPCM in the concrete.

^b FA: Flyash.

^c GGBFS: Ground granulated blast-furnace slag.

MPCM-concrete samples were fully cured in water at room temperature for 28 days. For the thermal test, the fully cured samples were dried in an oven at 40 °C until the sample weight remained unchanged.

2.2. Scanning electron microscopy

The surface morphology and the structure of the microcapsules and MPCM-concrete were obtained by using scanning electron microscopy (SEM) (Quanta FEG-250 and Quanta FEI-200).

2.3. Size distribution of MPCM

The size distribution of MPCM were determined by 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.

2.4. Density and porosity

The density of MPCM-concrete samples were determined using EN 12390-7 [26]:

$$\rho = \frac{m_d}{V} \quad (1)$$

where ρ is the dry density of the MPCM-concrete, m_d is oven-dried weight and V is the volume of the sample.

The porosity test was done based on ASTM C1202-12, which has been used by other researchers [27,28]. The samples were oven-dried at 105 °C until a constant weight was achieved. It was previously confirmed by thermogravimetric analysis (TGA) that the microcapsules were completely stable at temperatures lower than 150 °C [29]. The samples were cooled down to room temperature before recording the oven dried mass m_d . Afterwards, the samples were immersed in water at room temperature until the weight of sample in water remains constant, and the buoyant mass of the saturated samples in water m_b were recorded. Finally, the saturated sample was moved out of water, the surplus water wiped from the surface, and the saturated sample in air m_s was recorded. The open porosity of MPCM-concrete samples can be calculated by:

$$\text{Open Porosity (\%)} = \frac{m_s - m_d}{m_s - m_b} \times 100 \quad (2)$$

2.5. Thermal properties

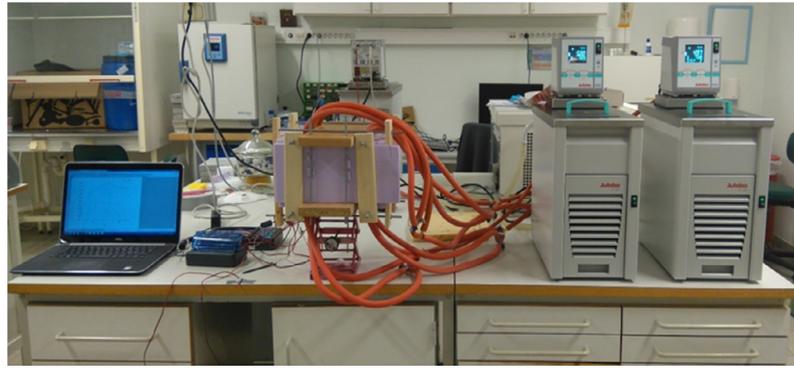
The guarded hot plates method, which is well suited for concrete samples, was utilized in order to characterize the thermal performance of the MPCM-concrete samples [16,30]. This method allows recording of temperature variations and heat fluxes exchanged through the sample during the testing process. The guarded hot plates system is presented in Fig. 1.

The thermal system includes two aluminum plate heat exchangers connected to thermal regulated baths that define the thermal conditions. The MPCM-concrete sample was sandwiched between two aluminum plate heat exchangers. A 40 mm thick polyethylene expanded foam (PEF) is used to form an insulated cover around the sample. This insulated cover will minimize the heat transfer from the lateral side face of the sample into the surrounding environment. Accordingly, the heat transfer through the MPCM-concrete sample can be calculated assuming one-dimensional thermal condition. Heat flux sensors (Captec, France) and K-type thermocouples (TC Ltd., UK) were inserted on both sides of the sample to measure the temperature variations and heat fluxes through sample during testing processes. All sensors were connected to a multichannel multimeter (LR8410-20 Hioki, Japan) to record the data.

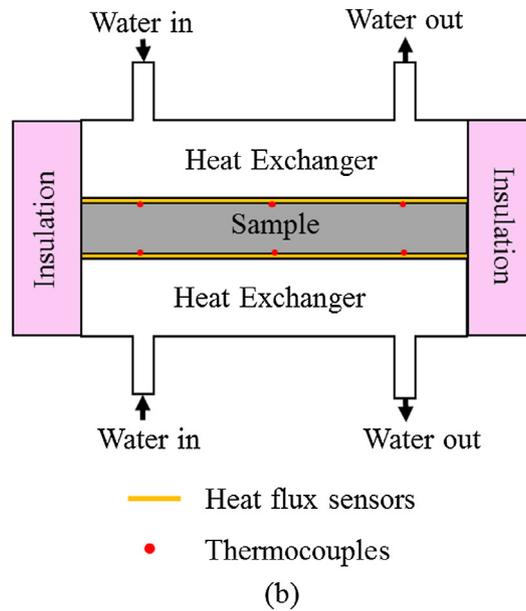
With the guarded hot plates system, the thermal properties of MPCM-concrete such as the thermal conductivity, its temperature in liquid and solid state for PCM, the specific heat capacity and the latent heat can be determined. Furthermore, it is possible to investigate the thermal performance of MPCM-concrete such as the thermal stability, and power consumption to stabilize the indoor temperature.

2.5.1. Thermal conductivity

The thermal conductivity of the MPCM-concrete samples was determined at temperatures below and above melting range of MPCM (20–32 °C) [29]. They are denoted solid thermal conductivity, λ_s (below melting point) and liquid thermal conductivity, λ_L (above melting point). Both aluminum plate heat exchangers were first kept at a constant temperature T_{init} until the heat fluxes were constant (thermal steady-state condition). Then, a temperature variation was imposed on the top aluminum plate heat exchanger from T_{init} to T_{end} and kept at T_{end} while the other aluminum plate heat exchanger was kept at T_{init} until a thermal steady state was reached. After reaching the thermal steady state condition, the average temperature on the top (T_{top}) and bottom (T_{bottom}) faces



(a)



(b)

Fig. 1. (a) The guarded hot plates system and (b) sketch of the cross-section of system.

of the block and the average heat fluxes (φ_{ave}) on both faces were recorded for thermal conductivity (λ) calculation via the following relationship:

$$\lambda = \frac{\varphi_{ave} d}{A(T_{top} - T_{bottom})} \quad (3)$$

where A and d are the area and the thickness of the MPCM-concrete block, respectively. In these experiments the dimension of the concrete samples were $A = 400 \text{ cm}^2$ and $d = 2.53 \pm 0.02 \text{ cm}$.

For solid thermal conductivity, T_{init} and T_{end} are set at 5 and 10 °C, respectively. While values of T_{init} and T_{end} of 45 and 50 °C are set to calculate the liquid thermal conductivity of MPCM-concrete.

2.5.2. Specific heat capacity/latent heat

The latent heat and the specific heat capacity (Eq. (4)) of the MPCMS-concrete sample were measured by the same testing system. The MPCM-concrete sample is initially isothermal at T_{init} . Afterwards, it was heated by raising the temperature of both aluminum plate heat exchangers from T_{init} to T_{end} by using oil thermostatic baths and at a heating rate of 10 °C/h. In this experiment, T_{init} and T_{end} were set equal to 5 °C and 45 °C, respectively. The average heat fluxes (φ_{ave}) and temperature on both faces of MPCM-concrete sample (T_{top} and T_{bottom}) during the test is determined via heat flux sensors and thermocouples, respectively. The solid

specific heat capacity, $C_{p-solid}$ (below melting range) and the liquid specific heat capacity, $C_{p-liquid}$ (above melting range) were estimated in the temperature range of 10–15 °C and 35–40 °C, respectively.

$$C_p = \frac{A\varphi_{ave}}{m \frac{dT}{dt}} \quad (4)$$

where C_p is specific heat capacity, m is the mass of sample.

Paraffin Rubitherm®RT27 has a melting point of about 27 °C. However, since it is of an industrial standard, it is melting over a temperature range. Therefore, the latent heat was calculated over the range 10–35 °C to ensure that the whole melting temperature range is covered. A long as the whole melting point area of the paraffin is included in the temperature range the calculated latent heat is not affected by the utilized temperature range. OriginPro 9.0 R1 was employed to calculate the latent heat.

2.6. Energy saving aspect

The thermal system was employed to investigate the effect of MPCM on potential energy saving aspects. The appropriate temperature profiles were imposed on the two sides of the sample to simulate the indoor and outdoor temperature. First, both aluminum plate heat exchangers were set to 23 °C until reaching a thermal steady-state condition. Then, the temperature of the bot-

tom aluminum plate heat exchanger (the simulated outdoor temperature, T_{outdoor}) was varied in the sequence: 23–20–32–20 °C at a rate of 1 °C/h. The simulated indoor temperature (top aluminum plate heat exchanger, T_{indoor}) was set stable at 23 °C throughout the experiment. The temperature and heat fluxes on both surfaces of the sample were recorded to measure heat losses towards the simulated indoor environment during the testing process (Fig. 2). The total heat losses or the energy supplied for heating/cooling of the system to maintain the simulated indoor temperature at 23 °C can be calculated by:

$$Q = \frac{\int_{t_{\text{ini}}}^{t_{\text{end}}} |\varphi_{\text{indoor}}| dt}{3600 \cdot 10^3} \quad (5)$$

where φ_{indoor} is the heat flux on the simulated indoor side of the sample, t_{ini} and t_{end} are the initial time and end time of the thermal cycle.

2.7. Thermal stability

The MPCM-concrete samples were subjected to 100 identical thermal cycles to investigate their thermal stability. In order to accelerate the thermal cycling effect, each thermal cycle was set by linearly increasing the temperature from 20 °C to 32 °C for 30 min, followed by a linear decrease from 32 °C to 20 °C for the same period of time. Subsequently, the MPCM-concrete samples were subjected to the energy saving aspect process described above to investigate the thermal stability of samples. For this test, only the samples with the highest concentration of MPCM (PCC3.2 and GPC2.7) were tested.

2.8. Compressive strength test

The mechanical properties of the MPCM-concrete were analyzed by using an Alpha 3–3000 system (Form + Test Seidner&Co. GmbH) based on EN 12390-3. The measurement was conducted for samples without MPCM (PCC0 and GPC0) and samples at the highest amount of MPCM (PCC3.2 and GPC2.7) before and after subjecting the samples to 100 thermal cycles, in order to investigate the effect of MPCM and thermal stability on the mechanical compressive strength of MPCM-concrete.

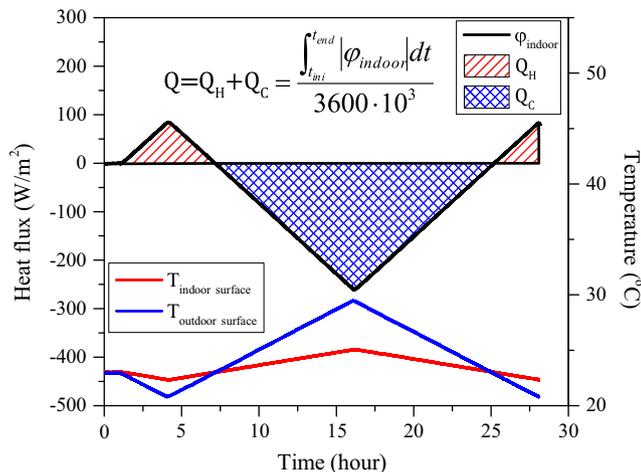


Fig. 2. Heat flux on the simulated indoor side (φ_{indoor}) and temperatures on the simulated indoor surface ($T_{\text{indoor surface}}$) and on the simulated outdoor surface ($T_{\text{outdoor surface}}$) of the sample versus time during a thermal cycle test. The total energy consumption for heating/cooling the system to maintain a stable simulated indoor temperature includes the energy used for heating (Q_H) when $T_{\text{indoor surface}} > T_{\text{outdoor surface}}$; and the energy used for cooling (Q_C) when $T_{\text{indoor surface}} < T_{\text{outdoor surface}}$.

3. Results and discussion

3.1. Size distribution

Fig. 3a shows a SEM image of the microcapsules. The diameters of the single microcapsules are in the range of 3–10 μm . However, it is clear that the microcapsules have a strong tendency to form agglomerated structures. This observation is in good agreement with the size distribution of the microcapsules (Fig. 3b). The volume average size distribution shows that the microcapsules have a diameter in the range between 10 and 1000 μm . The median value of the microcapsules diameter at 60% in the cumulative distribution (D_{60}) is 240 μm . The agglomerated microcapsule size is smaller than the size of sand ($D_{60} = 1000 \mu\text{m}$). The difference between the size distribution of agglomerated microcapsules and sand may alter the physical properties of the concrete samples.

3.2. MPCM-concrete density and porosity

SEM images (Fig. 4) present the microstructure of PCC0, PCC3.2, GPC0 and GPC2.7. For both types of concrete, the SEM images show no clear difference between the concrete matrix before and after addition of MPCM. This suggests that MPCM with components of low chemical reactivity (LDPE-EVA shell and paraffin core) does not have an obvious reaction with the concrete binder (cement hydration and geopolymerization process) at the current conditions. In addition, Fig. 4b and d illustrates that there are noticeable gaps between MPCM and both types of concrete matrix. These can cause a higher porosity in MPCM-concrete, which may influence the thermal properties and mechanical strength of MPCM-concrete.

Fig. 5 shows the MPCM-concrete density and open porosity. MPCM has the same effect on density and open porosity of both type of concrete. When the concentration of MPCM is raised, the density of MPCM-concrete decreases and the open porosity increases. This is consistent with previous studies of other MPCM-concretes [9,15]. The density decrease at higher concentrations can be explained by the replacement of sand by MPCM, which has a lower density. In addition, the increase of the porosity of the samples will also cause a density decrease.

The higher porosity of MPCM-concrete when the concentration of microcapsules is raised indicates that the addition of microcapsules plays an important role on the porosity of concrete. Three effects may affect the porosity of concrete when MPCM is included. The small size (3–10 μm) of single microcapsules can fill the cavity between aggregates, leading to improved particle packing density and decrease the porosity (first effect) [31–33]. On the other hand, the hydrophobic nature of LDPE-EVA/RT27 may cause an opposite effect. When microcapsules are added to concrete, they have a tendency to repel water, and air may adhere to the microcapsule leading to a higher porosity in concrete mixtures (second effect) [34,35]. The third possible effect is due to the smaller size of the microcapsule agglomerates compared to sand particles (Fig. 3). The surface area of microcapsules is much higher than that of sand for a unit replacement volume, resulting in an increase of the binder paste and water demand to cover the entire surface of the particles. Because the water content was kept constant for all samples in this study, more voids between particles (aggregates and microcapsules) might be formed [31]. This results in higher porosity of the concrete. A balance of these three effects governs the porosity of the concrete. Norvell et al. [33] demonstrated that the addition of BASF Mironal[®] microcapsules with an average diameter of 5 μm to cement mortar increased the packing density, resulting in the reduction of the porosity. However, he also revealed that the filling effect was significantly reduced for particle sizes larger than

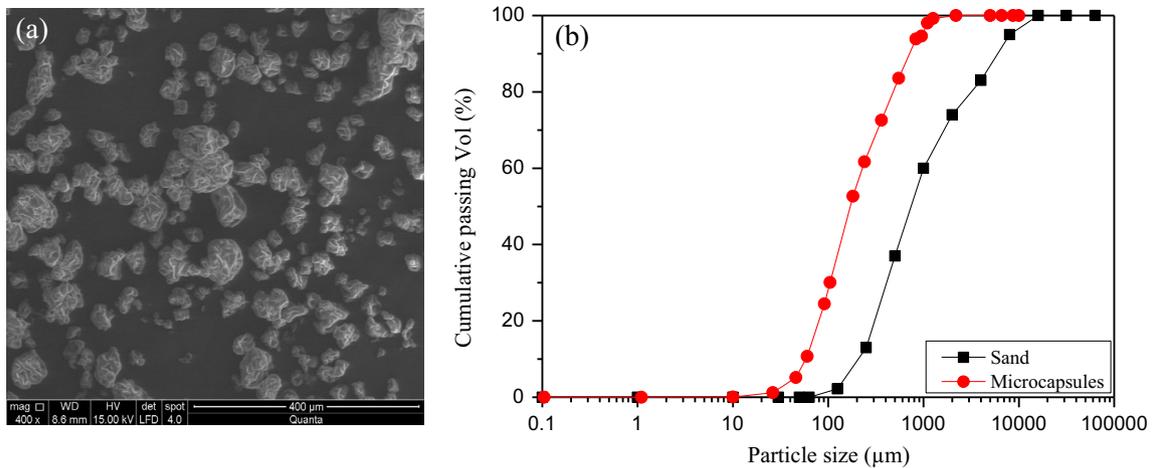


Fig. 3. (a) SEM image of the LDPE-EVA/RT27 microcapsules and (b) the size (diameter) distribution of the LDPE-EVA/RT27 microcapsules and sand.

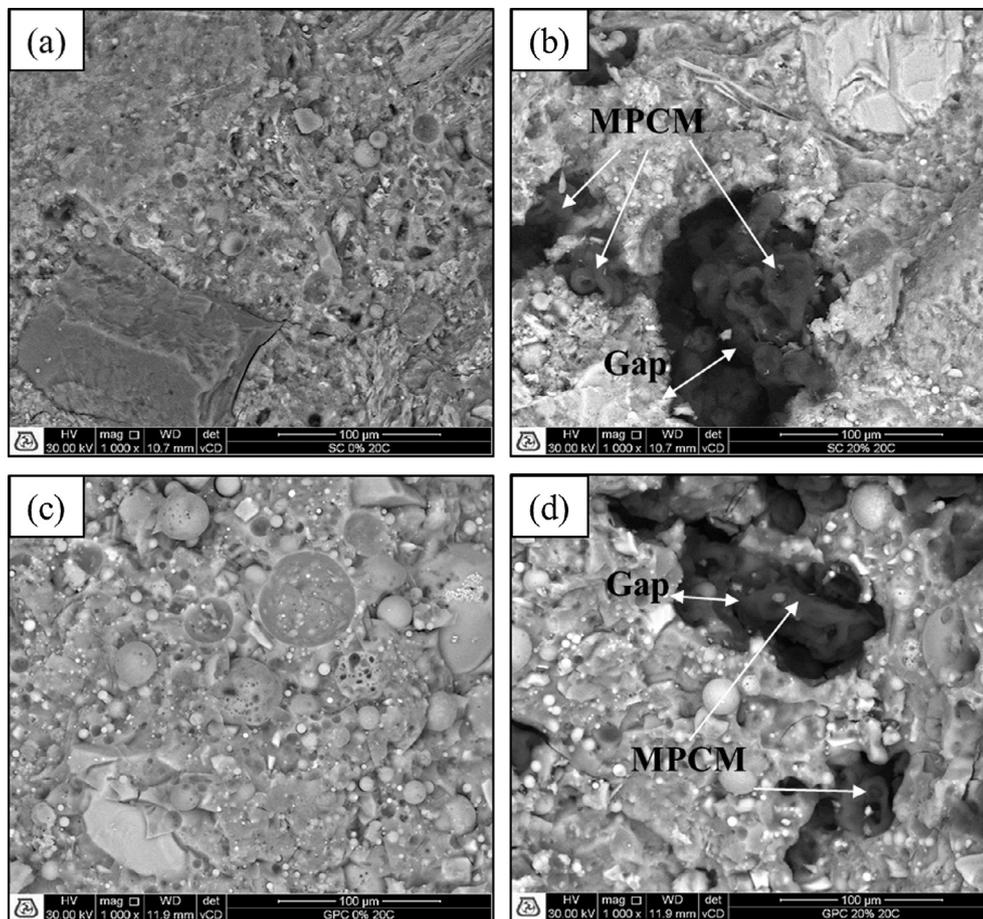


Fig. 4. SEM images of (a) PCC without MPCM (PCC0), (b) PCC containing 3.2 wt.% MPCM (PCC3.2), (c) GPC without MPCM (GPC0) and (d) GPC containing 2.7 wt.% MPCM (GPC2.7).

125 μm. This is in good agreement with Moosberg-Bustnes et al. [36] who studied the effect of average quartz size on the compressive strength of concrete. According to SEM images and MPCM size distribution (Fig. 3), MPCM has a tendency to form agglomerated structures with larger sizes ($D_{60} = 240 \mu\text{m}$). The agglomeration of the microcapsules is due to non-encapsulated PCM outside the microcapsules [29]. The large size of the agglomerates reduces the ability of the MPCM to fill up cavities and increase the tendency to entrap air on their surface and in their structure. Consequently,

the second and third effects are probably the dominant effects, resulting in an increase of the porosity of the concrete. The result of these effects is the obvious gap between concrete matrix and microcapsules in the SEM images (Fig. 4). Similar observations were also found previously [15,37,38].

According to Fig. 5, PCC has higher density and lower porosity than GPC for all samples. Furthermore, the porosity of GPC increases at a higher rate than that of PCC when raising the concentration of MPCM. As can be seen from Fig. 5b, the porosity

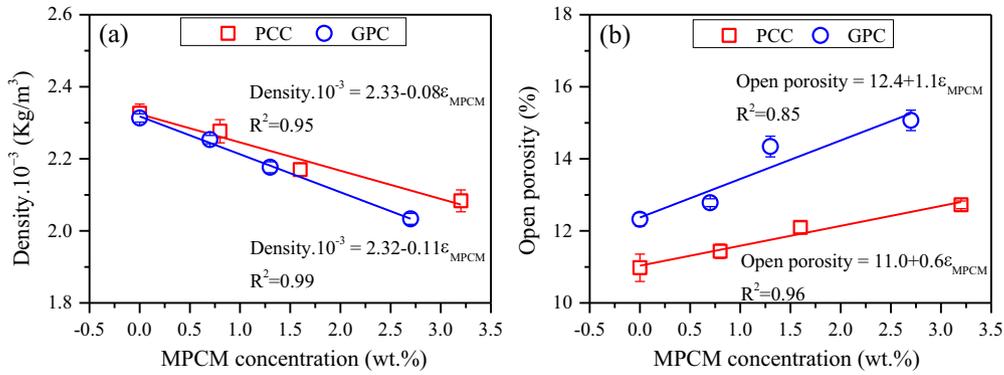


Fig. 5. (a) Density and (b) open porosity of GPC and PCC as a function of MPCM concentration (ϵ_{MPCM}).

increases with concentration at a rate of 1.1 for GPC and 0.6 for PCC. The reason for this is unclear, as several effects may come into play. The effect of MPCM on the particle packing density might be different between GPC and PCC due to the different binders. The compatibility between the microcapsule shell and the binder is not necessarily the same for the two systems. In addition, GPC has a much lower workability and shorter setting time than PCC. The lower workability of GPC could increase the probability of forming entrapped air voids during the mixing and pouring process.

3.3. Thermal properties

The thermal conductivity of MPCM-concrete is an important parameter for thermal energy storage applications. The heat fluxes and the measured temperatures on both sides of the MPCM-concrete when the paraffin Rubitherm®RT27 is in solid and in liquid state are shown in Fig. 6. The value of the temperature difference and the average value of the heat fluxes during a steady state were used to determine the apparent thermal conductivity of the MPCM-concrete via Eq. (3). The apparent thermal conductivity of MPCM-concrete in liquid and solid PCM state is summarized in Fig. 7.

According to Fig. 7, the thermal conductivity of MPCM-concrete decreases with the concentration of microcapsules. The addition of MPCM causes the reduction of thermal conductivity of the concrete due to the lower thermal conductivity of the microcapsules compared to that of replaced sand and also the porosity increase. The thermal conductivity of the paraffin Rubitherm®RT27 and polymer LDPE/EVA shell are approximately 0.2 W/m °C and 0.13–0.34 W/m °C [39], respectively, while the average thermal conductivity of

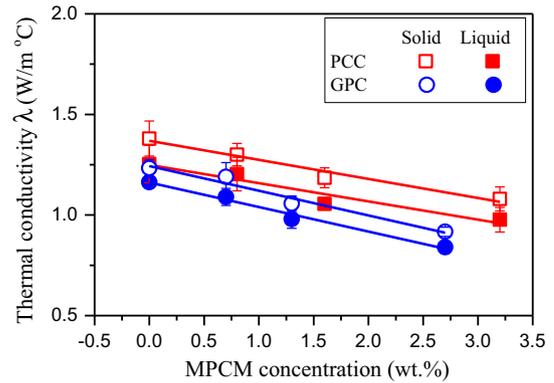


Fig. 7. The solid thermal conductivity and the liquid thermal conductivity of GPC and PCC as a function of MPCM concentration.

sand is in the range of 1.80–2.50 W/m °C depending on the degree of water saturation (information provided by the supplier). Moreover, for a constant MPCM concentration, the thermal conductivity of concrete in solid PCM state is higher than that in the liquid PCM state. This is because the thermal conductivity of PCM in a solid state is higher than that in a liquid state [16,40]. This observation is supported by Cui et al. [16] studying the effect of microcapsules on thermal properties of cement mortar.

Comparing PCC and GPC, the thermal conductivity of PCC is higher than for GPC. The reduction rates of thermal conductivity of GPC and PCC are similar for the liquid and solid states of PCM. They are 0.12 for GPC and 0.09 for PCC. The slightly different MPCM concentration dependencies of GPC and PCC might be related to

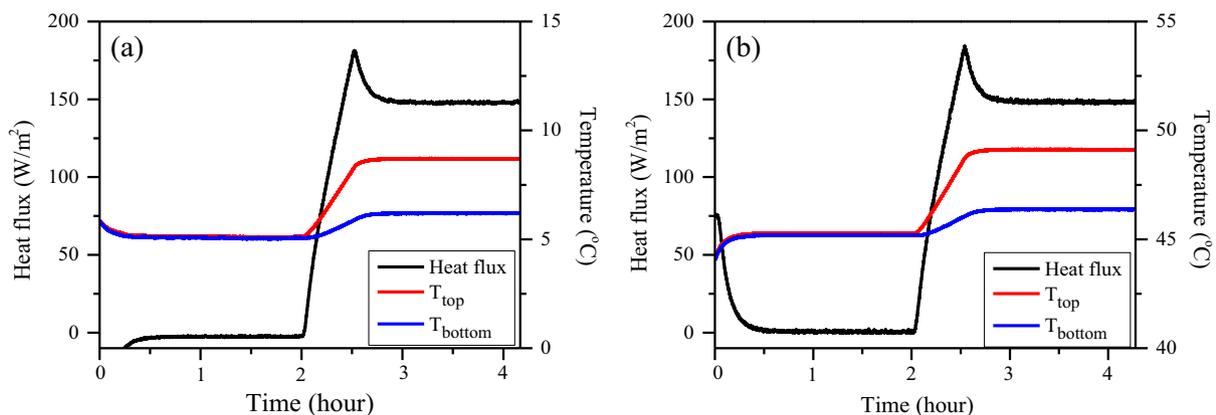


Fig. 6. Heat flux and temperatures versus time during (a) the solid thermal conductivity and (b) the liquid thermal conductivity test of PCCO.

the corresponding change in porosity (Fig. 5b), as air pockets will decrease the thermal conductivity.

The specific heat capacity of the PCC samples in the region 5–45 °C is shown in Fig. 8. In order to determine the specific heat capacity of samples containing PCM in solid and liquid state, the average value of specific heat capacity from 10 to 15 °C (below the melting range of PCM) and from 35 to 40 °C (above melting range of PCM) were employed. The specific heat capacity in both states is summarized in Fig. 9a.

The results show that the specific heat capacity of MPCM-concrete is nearly the same when the PCM is in solid or liquid state, although the specific heat capacity of microcapsules (determined by differential scanning calorimetry) is higher in solid state ($C_{p\text{-solid}} = 3050 \text{ J/kg } ^\circ\text{C}$) than in liquid state ($C_{p\text{-liquid}} = 2740 \text{ J/kg } ^\circ\text{C}$). This is possibly due to low microcapsule concentrations, which are too small to significantly affect the values of the specific heat capacity of the concrete samples. This observation is in good agreement with Joulin et al. [17]. Interestingly, the specific heat capacity is not changed when the concentration of MPCM is increased from 0 to 3.2 and 2.7 wt.% for PCC and GPC, respectively. This observation is different from Joulin et al. [17], who found that the specific heat capacity of MPCM-mortar increased with microcapsule concentration due to the higher specific heat capacity of microcapsule compared to mortar. The smaller microcapsule concentrations applied compared to that of Joulin's (14 wt.%) is probably reason for this difference. The low concentrations of microcapsules utilized in the current study may be too small to significantly increase the specific heat capacity of the concrete.

The latent heat of the samples was determined within the temperature range of 10–35 °C and is presented in Fig. 9b. The latent heat exhibits a linear increase with respect to the microcapsule concentration. However, the latent heat of PCC increases at slightly higher rate than that of GPC (0.72 for PCC and 0.60 for GPC), as can be seen in Fig. 9b. This can be attributed to the different porosity of GPC and PCC.

3.4. Energy saving aspect

In order to investigate the influence of microcapsules on reducing energy consumption for heating and cooling systems, the indoor and outdoor temperatures were simulated utilizing the thermal analysis system. The samples were subjected to a simulated outdoor thermal cycle where the temperature was changed from 23–20–32–20 °C at a rate of 1 °C/h. The total duration of this heating-cooling cycle was 27 h. The simulated indoor temperature was set at 23 °C throughout the experiment.

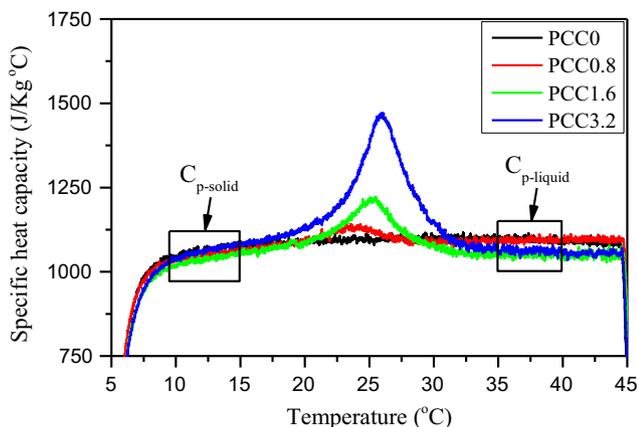


Fig. 8. The specific heat capacity of PCC at different concentrations of MPCM.

The total heat losses towards the indoor environment can be calculated by integration of the heat flux on the simulated indoor side of the sample (Fig. 10). This calculated energy corresponds to the energy consumed by the heating/cooling system to stabilize the simulated indoor temperature at 23 °C. According to Fig. 10a, the heat flux as function of time is a straight line without any obvious transition point from MPCM addition. This deviates from previous studies [15,16,38] where a transition point was found around the melting point of paraffin. When the paraffin is completely melted, the effect of the latent heat process ends, causing a steeper increase of the indoor surface temperature and the indoor heat flux. This should cause a transition point on the heat flux curve [16]. The lower microcapsule concentrations (3.2 wt.% for PCC and 2.7 wt.% for GPC) applied here compared to that of Borreguero (10–15 wt.%) [38] or Cui (5–20 wt.%) [16] is probably reason for this difference. This observation is in good agreement with Hunger et al. [15] who reported that there was no clear transition point until adding 5 wt.% of MPCM to concrete. The calculated energy consumption using Eq. (5) for a thermal cycle is shown in Fig. 10b.

According to Fig. 10, the addition of MPCM significantly improves the thermal performance of concrete in terms of saving energy. There is no significant difference in energy consumption between PCC and GPC in the absence of MPCM. However, the energy consumption decreases from $2.82 \pm 0.10 \text{ kW h/m}^2$ (without MPCM) to $2.51 \pm 0.03 \text{ kW h/m}^2$ (3.2 wt.% MPCM) for PCC and from $2.74 \pm 0.13 \text{ kW h/m}^2$ (without MPCM) to $2.32 \pm 0.03 \text{ kW h/m}^2$ (2.7 wt.% MPCM) for GPC after adding microcapsules. Accordingly, energy consumption for heating and cooling to maintain the indoor temperature can be reduced up to 11% for PCC (3.2 wt.% MPCM) and 15% for GPC (2.7 wt.% MPCM), compared to the samples without MPCM. The results reveal that in addition to the energy storage capacity of MPCM, the increase of thermal insulation (thermal conductivity reduction) plays an important role in the energy saving mechanism at the studied conditions. The improved properties of GPC containing MPCM compared to PCC is probably due to the formation of a structure with more insulating pores when MPCM is added to GPC.

Comparing the open porosity (Fig. 5b) with the thermal conductivity (Fig. 7), the latent heat (Fig. 9b), and the power consumption (Fig. 10b), it is evident that the enhanced porosity plays a vital role for the thermal properties of these samples. Addition of MPCM causes a higher porosity increase for GPC than for PCC. The air pores provides an enhanced thermal insulation effect. Accordingly, GPC experience a stronger decrease in thermal conductivity, a lower increase in latent heat, and a higher energy saving efficiency. Adding MPCM to GPC causes a higher energy saving efficiency than for PCC (Fig. 10b) even though the latent heat increases more for PCC (Fig. 9b). It is therefore clear that for reducing the power consumption of these samples, the thermal insulation effect of the air voids is more important than the increased latent heat from the MPCM.

3.5. Thermal stability

The heat fluxes on the indoor side of MPCM-concrete before and after subjecting the samples to 100 thermal cycles are shown in Fig. 11. The results show that there is no detectable change in the energy consumption after subjecting the samples to 100 thermal cycles. Accordingly, MPCM-concrete possesses a good thermal stability over 100 accelerated melting/solidification cycles.

3.6. Compressive strength

Results of the compressive strength measurement are presented in Fig. 12. The results show that increasing the amount of MPCM causes significantly lower compressive strengths. This is

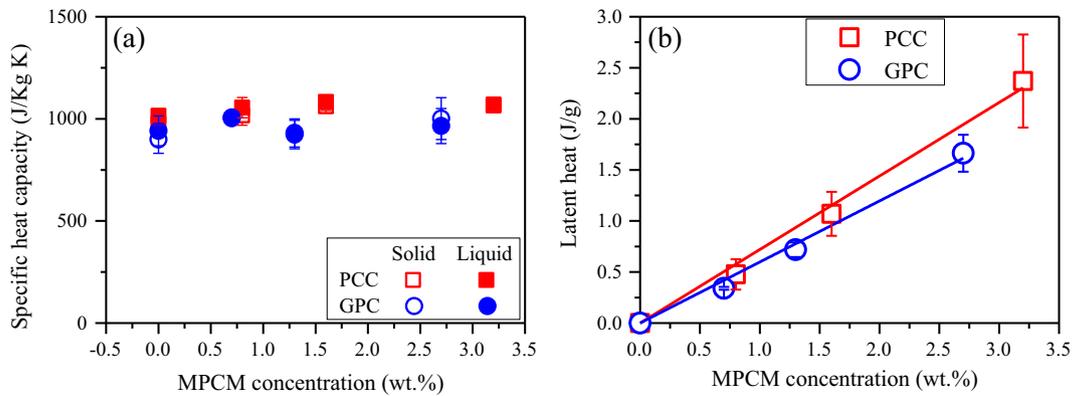


Fig. 9. (a) The specific heat capacity of GPC and PCC at solid and liquid state of PCM and (b) the latent heat of PCC and GPC at different concentrations of MPCM.

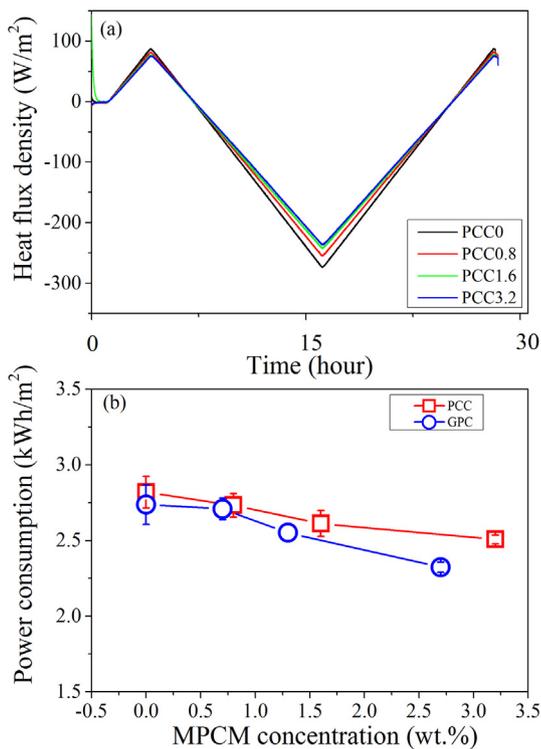


Fig. 10. (a) Heat flux density on the simulated indoor side of PCC at different MPCM concentrations and (b) the energy consumption needed for heating/cooling the system to maintain a simulated indoor temperature of 23 °C for PCC and GPC.

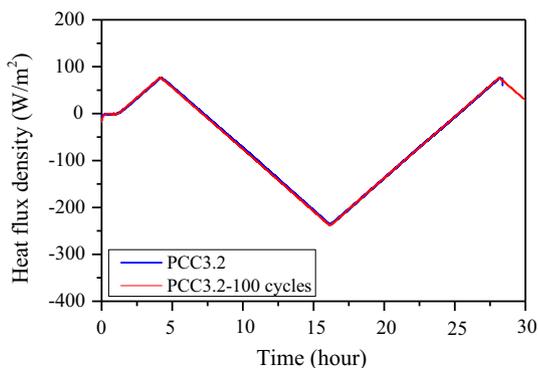


Fig. 11. Heat flux density on the indoor side of PCC containing 3.2 wt.% of MPCM before and after exposing the samples to 100 thermal cycles.

probably because MPCM is a material with low mechanical strength and stiffness and can be easily broken under compressive force [9,15,39]. Furthermore, the higher porosity after adding MPCM can contribute to the reduction the compressive strength of MPCM-concrete. In addition, the compressive strength of PCC and GPC decreases by 42% and 51% after adding 3.2 wt.% of MPCM to PCC and 2.7 wt.% of MPCM to GPC, respectively. This indicates that the compressive strength of GPC decreases at higher rate than that of PCC, although a smaller amount of MPCM is added to GPC than PCC. This might be caused by the higher porosity increase of the GPC samples.

Additionally, the gaps between concrete matrix and microcapsules (Fig. 4) reveal a poor interface between microcapsules and the concrete matrix. This leads to an increase of the thermal contact resistance and weakens the mechanical strength of concrete. In order to solve this negative effect, Zhang et al. [41] modified the surface of the microcapsules to improve the compatibility between the microcapsules and mortar matrix, thus improving the compressive strength of the MPCM-mortar. Future work could focus on improving microcapsules with low tendency of agglomeration, high compatibility to the concrete matrix and strong mechanical properties.

It is also important to point out that although the loss of compressive strength of concrete is significant after adding microcapsules, the compressive strength of GPC2.7 (45.3 ± 0.8 MPa) and PCC3.2 (34.1 ± 0.4 MPa) confirms to the mechanical European regulation (EN 206-1, compressive strength class C20/25) for concrete for building construction. An optimal system should contain as many microcapsules as possible (to improve the thermal

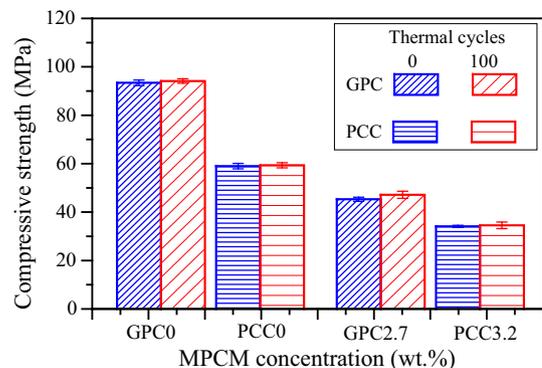


Fig. 12. The compressive strength of concrete including PCC without MPCM (PCC0), PCC containing 3.2 wt.% MPCM (PCC3.2), GPC without MPCM (GPC0) and GPC containing 2.7 wt.% MPCM (GPC2.7) before and after subjecting the samples to 100 accelerated thermal cycles.

performance), while still satisfying the European regulation for compressive strength. Unfortunately, further increasing the MPCM concentrations causes a too low workability of the concretes to produce usable samples.

Fig. 12 also shows that the compressive strength of MPCM-concrete is the same (within the experimental errors) before and after exposing the samples to 100 thermal cycles. This illustrates that the MPCM-concrete can experience temperature changes around the melting point of paraffin many times without changing the properties. A higher number of thermal cycles will be tested in the future to obtain more information about thermal cycling resistance of MPCM-concrete.

4. Conclusion

Materials with high thermal energy storage capacity were fabricated by direct mixing of microencapsulated phase change materials (MPCM) to Portland cement concrete (PCC) and geopolymer concrete (GPC). The addition of MPCM strongly affects the thermal performance and compressive strength of PCC and GPC. Raising the amount of microcapsules reduces the thermal conductivity and increases the latent heat of concrete. Interestingly, the replacement of sand by microcapsules did not change the specific heat capacity of concrete. Furthermore, the addition of microcapsules caused an increase of the porosity of the concrete. Microcapsules were found to have a stronger effect on GPC than on PCC, causing a higher porosity increase of GPC compared to PCC (slopes of 1.1 for GPC and 0.6 for PCC). The enhanced porosity is probably the reason for the higher thermal conductivity reduction rate of GPC (0.12) compared to PCC (0.09).

The increase in latent heat and the decrease in thermal conductivity could significantly improve the thermal performance of concrete building materials in terms of saving energy. The power consumption for stabilizing the indoor temperature at 23 °C may save up to 11% (PCC) and 15% (GPC) after adding 3.2 wt.% MPCM to PCC and 2.7 wt.% MPCM to GPC. This indicates that the thermal insulation effect play an important role on the energy saving in building applications.

Unfortunately, the addition of microcapsules resulted in a significant loss of concrete compressive strength. After adding 3.2 wt.% of microcapsules, the compressive strength of PCC decreased around 42%. For GPC, the reduction of compressive strength is higher than that of PCC. It is approximately 51% after integrating 2.7 wt.% of microcapsules. The loss of compressive strength may be ascribed to low mechanical strength of microcapsules and the enhanced porosity. Although the loss of compressive strength is significant, the compressive strength of MPCM-concrete satisfies the demand of mechanical properties for structural applications. It is therefore, possible to increase the amount of microcapsules to improve the thermal performance and still satisfy the demand of mechanical properties for structural applications. In addition, the agglomeration of microcapsules may reduce the ability of the microcapsules to fill in cavities in the concrete matrix, leading to higher porosity of the concrete. Improved microcapsules with reduced tendency for agglomerations and good mechanical properties would be interesting for further studies.

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