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Thermal energy storage enhancement of lightweight cement mortars with the application of phase change materials

Sayanthan Ramakrishnan[a,*], Xiaoming Wang[b], Jay Sanjayan[a], John Wilson[a]

[a]*Centre for Sustainable Infrastructure, FSET, Swinburne University of technology, Hawthorn, Victoria, 3122*
[b]*Land and water flagship, CSIRO, Clayton, Victoria 3168, Australia*

Abstract

In this study, cement-based thermal energy storage composites (TESC) were developed by integrating a novel phase change material (PCM) composite into ordinary cement mortar (NC). The composite PCM is based on paraffin and hydrophobic expanded perlite and it is form-stable when integrating into cementitious composites. The composite PCM was integrated as partial replacement for fine aggregate and the replacement ratios are 20%, 40%, 60% and 80%. The mechanical and thermal performance of TESC was studied. The results revealed that the developed TESC shows superior thermal performance with acceptable mechanical properties. TESC prepared by replacing 80% of composite PCM (TESC-80) shows the apparent density of 1100 kg/m^3 and 28 days compressive strength of 18 MPa. Furthermore, TESC shows significant enhancement in thermal performance. In comparison to NC, TESC-80 shows an increase of 56% and 166% for thermal energy storage rate and thermal energy storage capacity respectively.

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Keywords: Phase change mateirlas (PCMs); cement mortar; lightweight concrete; thermal energy storage

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1. Introduction

The building sector consumes approximately 40% of primary energy consumption and contributes to 33% of global greenhouse gas emissions. Additionally, almost half of the building energy use is dedicated for space

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* Corresponding author. Tel.: +61426588234.
E-mail address: sramakrishnan@swin.edu.au

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conditioning in developed countries (1). Nevertheless, a large portion of space conditioning energy is ultimately lost through the building envelope due to the lack of thermal mass in modern buildings. Hence, energy savings through designing energy efficient buildings has become a major area of research. A common theme amongst the energy efficient building design strategies is the enhancement of thermal mass in the building envelope to store the solar thermal energy during daytime and re-radiate into the building during cooler nights. This can ultimately reduce the peak temperatures and temperature fluctuations in indoors (2, 3).

Thermal mass of the building can be increased by either increasing the material mass and/or increasing the heat capacity of the construction materials. The former application can be achieved by heavy/thick wall systems. However, this form of application require large building mass, and it has several drawbacks such as very long payback period due to high construction cost, heat accumulation in the building etc (4). On the other hand, increasing the heat capacity of building envelope without large increment in the material mass would be a good solution to overcome this issue. One possible manner of increasing the heat capacity of building envelope is to introduce a latent heat storage element which undergoes phase change within the comfortable temperature range. Phase change material (PCM) stores the thermal energy by converting solid to liquid when the temperature of the material increases above phase transition temperature. Similarly, the material releases the heat and becomes solidifies when the temperature reduces below the phase transition temperature. This process can be operated in a daily basis for a long time.

There are several ways to incorporate PCMs into the building envelope to increase thermal energy storage, utilizing walls, floor, ceiling, roof, etc. Successful utilization of PCMs and thermal energy storage capacity largely depends on the method of incorporation into the building envelope. PCM incorporation methods can be broadly categorized as direct impregnation or encapsulation of PCM before incorporation into building elements.

Direct impregnation methods are simple and easy to use; however, the amount of PCM absorption is low which result in lower thermal energy storage (5). Moreover, such methods are more vulnerable to leakage of liquid PCM (6) and the interaction between leaked PCM and binder materials can adversely affect the construction system . On the other hand, encapsulation techniques such as microencapsulated PCM and granular PCM composites can effectively hold large amount of PCM with superior heat transfer rate (7). Micronal® is a commercially available microencapsulated PCM that can be incorporated into concrete, mortar and plasterboard. Recent research has shown that microencapsulated PCMs can have a positive effect on thermal performance when fabricated with cement-based thermal energy storage composites (8, 9). However, some incompatibility problems with cement matrix have been experienced. Partially destroyed polymer shells with damaged PCM capsules were observed in cement matrix due to collision and abrasion with other aggregates and the high pH environment of the cement hydration system (9).

On the other hand, granular PCM composites or form-stable PCMs are made by impregnating phase change materials into porous granular materials, which are then integrated into construction elements. In the last two decades, many form-stable PCMs have been fabricated by incorporating PCMs such as paraffin, fatty acids and eutectic mixtures of binary PCMs into porous materials such as diatomite, expanded perlite, expanded graphite etc. An extensive review of developed form-stable PCMs can be found in Memon (5). Some of those PCM composites have been investigated for the integration into cementitious composites. It is worth mentioning here that, however, most of the tested PCMs had phase transition temperatures much higher than ambient temperature so that the PCM was well maintained in the solid phase when mixed with cementitious materials. On the other hand, if the PCM melting temperature is lower than the ambient temperature, liquid PCM could leak from composites when it is mixed with water-hardening materials such as cement and gypsum, resulting in significant reduction of thermal energy storage (10, 11). The previous work reported by authors (12) demonstrated that a novel hydrophobic expanded perlite based form-stable PCM doesn’t show any liquid PCM leakage and it can be directly applied into cementitious materials. Also, authors reported that this composite PCM has good compatibility with cement matrix.

Cement mortar fabricated by mixing cement, sand and water has got many applications in building industry and incorporation of PCM into cement mortar not only provides the thermal energy storage capacity, but also facilitates energy conservation and energy savings in buildings. Moreover, paraffin/hydrophobic EP form-stable PCM is an excellent candidate to be used as composite PCM with large amount of PCM absorption and no sign of PCM leakage. In this study, we develop thermal energy storage cement mortar (TESC) with the incorporation of paraffin/hydrophobic EP composite PCM into ordinary cement mortar. First, paraffin/ hydrophobic EP composite PCM was integrated into ordinary cement mortar by absolute volume replacement method. Then the physical, mechanical and thermal properties of TESC samples were investigated. This is followed by evaluating thermal energy storage performance of TESC containing different mass levels of composite PCM.

Nomenclature

PCM	Phase change materials
TESC	Thermal energy storage cement mortar
NC	Ordinary cement mortar

2. Experimental investigation

2.1. Materials

The PCM used was commercial grade paraffin RT21 from Rubitherm®, consisting of saturated hydrocarbons with the molecular formula of C_nH_{2n+2}. Hydrophobic coated expanded perlite was supplied by Filchem Australia Pty Ltd. Ordinary Portland cement (OPC) complying with AS 3972 and silica sand with maximum particle size of 1.18 mm were used for the preparation of normal cement mortar (NC) and thermal energy storage cement mortar (TESC). A water reducing admixture (MasterPozzolith 370 from BASF) was used to improve the workability of TESC.

2.2. Fabrication of PCM composite and TESC

The paraffin/EP composite PCM was fabricated by absorbing the melted paraffin into the open pores of EP granules by capillary forces and surface tension. The mass percentage of the paraffin in the composite PCM was obtained as 50% in vacuum impregnation method based on the authors' previous study. The micro-morphology characterization, thermal properties and stability with cementitious materials are all documented in the authors' previous work [12]. Therefore, only information regarding morphological characterization and thermal properties are presented in Fig. 1. As can be seen from Fig. 1(a) and Fig. 1(b), the open pores of porous spherical EP granules are no longer visible in the composite PCM, ensuring that the paraffin is uniformly impregnated into EP and resulting composite PCM is form-stable. From Fig. 1(d), we can see that the composite PCM has a phase transition temperature and latent heat of 22.1ºC, 60.9 J/g and 20.2ºC, 61.8 J/g for melting and freezing processes respectively. The fabrication of ordinary cement mortar was carried out in accordance with ASTM C109, where the mixing ratio of sand to the cement is 2.75, and water to the cement is 0.485. TESC samples were fabricated by partially replacing composite PCM to sand by absolute volume replacement method, and the replacement levels are 20%, 40%, 60% and 80%. The detailed mix design is given in following table (table 1). The workability of all mixes was kept constant by adjusting the water reducing admixture content. The mixing procedure is as follows

Table 1. Mix design of materials.

	Binder	Water	Aggregates				
Series	OPC cement	w/b	Aggregates/binder ratio	sand (vol %)	Composite PCM (vol %)	SP (%)	Flowability (mm)
NC	1	0.485	2.75	100	0	-	110±5
TESC-20				80	20	-	
TESC-40				60	40	0.5	
TESC-60				40	60	1.5	
TESC-80				20	80	2.5	

First, cement, sand and paraffin/EP composite PCM were dry mixed at low speed for 1 minute in a Hobart mixer. Water together with water reducing admixture (WRA) was then added to the dry mix and mixed for 2 minutes at low speed. Thereafter, one-minute-high speed mixing was performed to complete entire mixing process. Fresh mixes were poured into 50 x 50 x 50 mm3 steel moulds for mechanical and physical properties tests. The fresh samples were kept in moist environment for 24 hours and then samples were demoulded and cured in ambient water (23±0.5oC) till the day of testing.

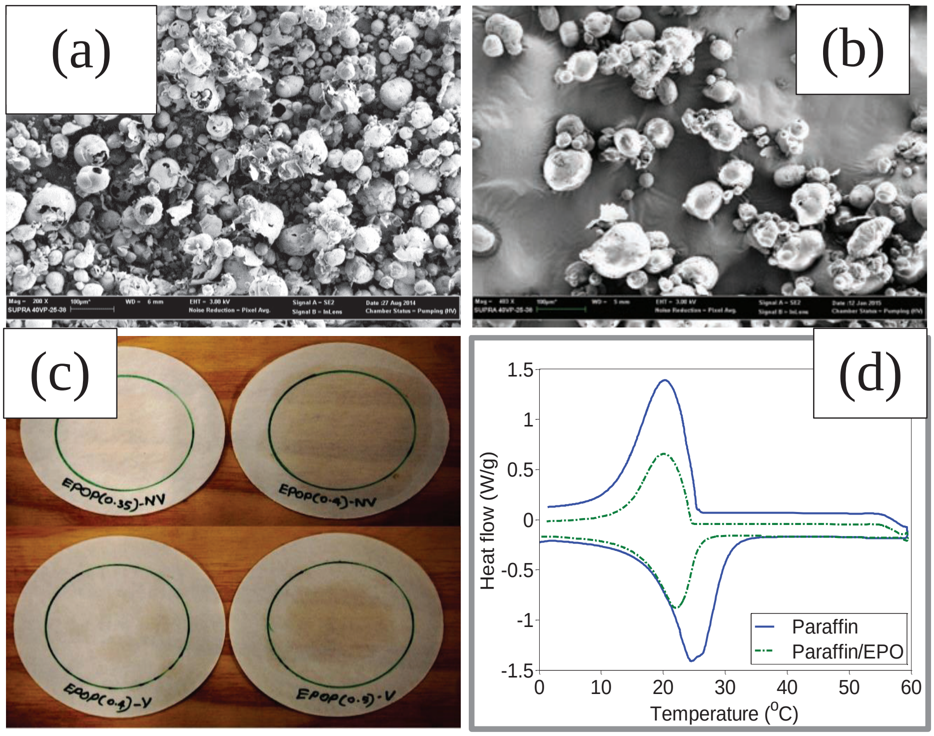

Fig. 1. Primary information of paraffin/EP composite PCM (a) and (b) SEM morphology of EP and paraffin/EP composite PCM (c) diffusion oozing circle test (d) thermal properties of composite PCM.

2.3. Mechanical and physical properties test

The mechanical properties of NC and various TESC specimens were evaluated by measuring the compressive strength of cube specimen at 7 and 28 days. Compressive strength tests were performed by an automated compressive strength testing machine (Technotest C030/2T) at a loading rate of 0.5 Mpa. The maximum capacity and accuracy of the compression machine is 300 kN and 0.01 kN respectively.

The physical properties of cement mortars were evaluated by measuring the apparent density of cube specimens according to ASTM C830. After 28 days of casting, Cube specimens were removed from water and oven dried at 105 ºC until reaches a constant weight (D). Then the samples were moist saturated by using a vacuum pressure vessel. Following the vacuum saturation process, suspended weight (S) and saturated weight (W) of the specimen were determined by using a digital balance with a precision of 0.01 g. The apparent density (B) of TESC specimen were determined by Eqn (1)

$$B = \frac{D}{W - S} \tag{1}$$

2.4. Thermal properties and performance test

A thermal conductivity analyzer (TCi from C-Therm Technologies Ltd) was employed to measure thermal conductivity of TESC samples with size of 400 x 75 x 10 mm^3 at 28 days. The TCi analyzer measures the thermal conductivity of a small sample, by using the Modified Transient Plane Source (MTPS) method.

The thermal energy storage performance of NC and various TESCs were compared by using a self-designed testing setup as shown in Fig. 2. as can be seen from Fig, the testing setup mainly consists of a wooden-framed box (300 x 300 x 300 mm) covered by 50 mm thick expanded polystyrene (EPS) for five surfaces and the design panel as the top surface. It has to be noted that the application of EPS for five surfaces is to ensure that the test room is highly insulated on five surfaces and heat transfer would occur through the testing panel only, enabling the one-dimension heat transfer process through the testing panel.

The test room is placed in the climate controlled thermal chamber, which has been set for a temperature variation of 15 to 35 to 15ºC at a ramping rate of 0.04ºC/min. The temperature sensors and heat flux meter were also attached as shown in Fig. The temperature measurements were made using Type K thermocouples having an accuracy of ±0.1ºC. The heat flux sensors used were from Hukseflux, with the accuracy of 5%. Thermal performance of TESC panels were compared in terms of thermal energy storage rate and thermal energy storage capacity.

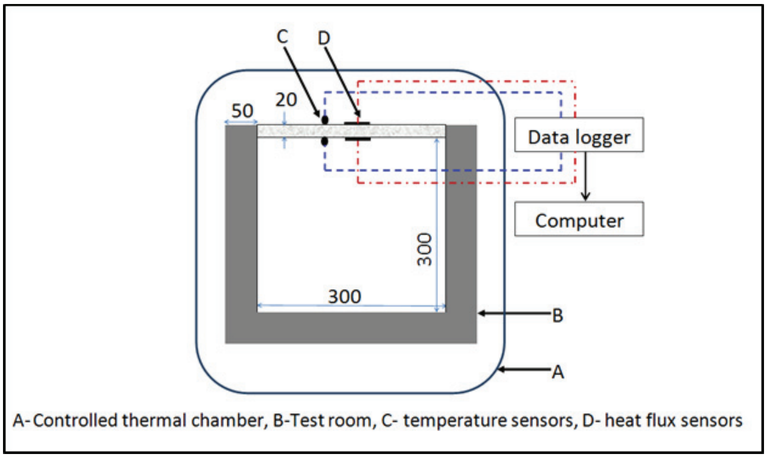

Fig. 2. Schematic diagram of thermal performance test setup.

3. RESULTS AND DISCUSSIONS

Figure 3 demonstrates the compressive strength development of NC and TESCs at 7 and 28 days. As shown in Fig. 3, compressive strength of TESC decreases with the increasing amount of paraffin/EP composite PCM replacement level. When replacement levels are 20%, 40%, 60% and 80%, strength reduction percentages at 7 days are 22%, 27%, 52%, 70% respectively. Corresponding strength reduction at 28 days are 12%, 33%, 53%, 70% respectively. The reduction in compressive strength with increasing replacement level of composite PCM are due to the low mechanical stiffness of porous EP and hence weaken the load transfer path in cement matrix. Although compressive strength of TESCs is greatly reduced in comparison with that of NC (i.e., NC has 53.8 MPa at 28 days), TESC-60 still has a compressive strength of 25 MPa at 28 days. This compressive strength will still be well acceptable for many applications according to literatures (13).

Fig. 4 shows the apparent density of TESC specimens with the increasing replacement level of composite PCM. As shown in Fig. 4, the apparent density of TESCs reduce with the increasing replacement level of composite PCM, and the corresponding reduction levels in apparent density with the replacement level of 20%, 40%, 60% and 80% are 4%, 13%, 27% and 44% respectively. The reduced apparent density can be advantageous to increase the thermal energy storage of lightweight concrete which are generally found to be lack of thermal capacity.

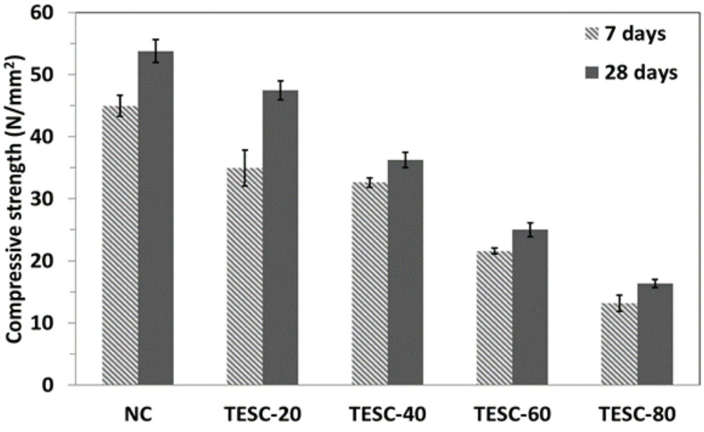

Fig. 3. Compressive strength of NC and various TESCs at 7 and 28 days.

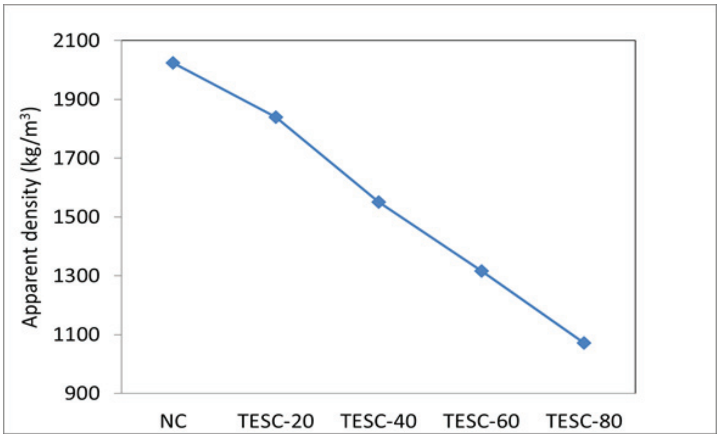

Fig. 4. Apparent density of NC and TESCs.

3.1. Thermal properties and performance test

Effect of paraffin/EP composite PCM on thermal conductivity of TESCs is shown in Fig.5. It can be seen that the thermal conductivities are decreased with the increasing replacement levels of composite PCM. In comparison with NC, the reduction in TESC-20, TESC-40, TESC-60 and TESC-80 are 15.8%, 31.6%, 52.6% and 65.8% respectively. Moreover, the lower thermal conductivity of TESC will be advantageous to improve the building thermal insulation performance in addition to the thermal energy storage capacity.

Fig. 6 shows the thermal performance curves in terms of thermal energy storage rate and thermal energy storage capacity for two consecutive thermal cycles. From Fig. 6(a), one can observe that a maximum heat storage rate of 154 W/m^2 in TESC-80, in comparison to 99 W/m^2 in NC panel. Moreover, thermal energy storage capacity from Fig. 6(b) clearly indicates that the TESC panels have significant energy storage capacity compared to NC panel. For instance, TESC-80 has a maximum energy storage capacity of 125 kJ/kg, compared to 47 kJ/kg in NC. According to this study, thermal energy storage performance of the TESC was improved by the incorporation of paraffin/EP composite PCM.

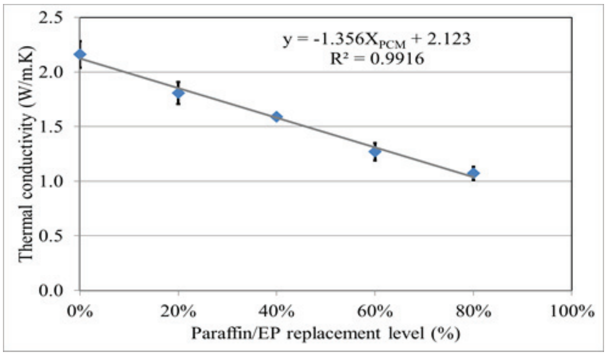

Fig. 5. Thermal conductivity of NC and various TESCs.

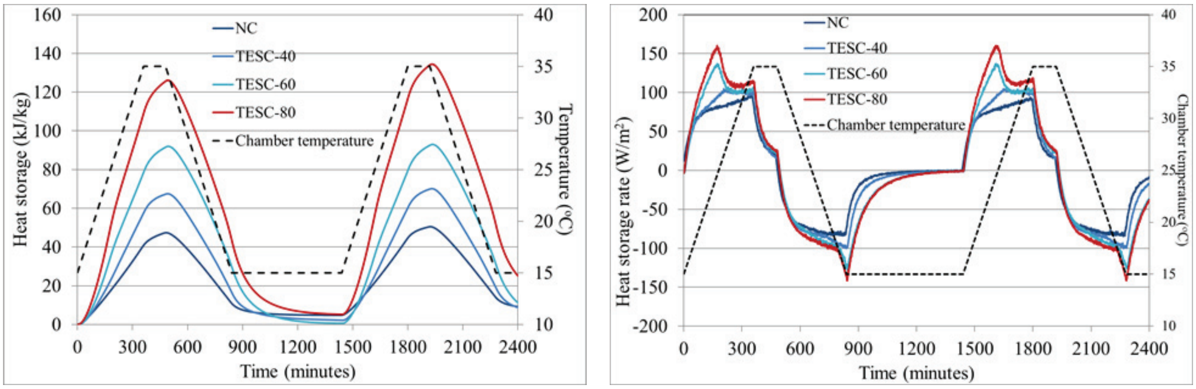

Fig. 6. Thermal energy storage performance of NC and various TESCs (a) thermal energy storage rate (b) thermal energy storage capacity.

4. Conclusions

In this study, thermal energy storage cement mortar (TESC) was developed by incorporating paraffin/EP composite PCM into ordinary cement mortar. Based on the presented experimental study, following conclusions can be extracted:

- Incorporation of paraffin/EP composite PCM into ordinary cement mortar results in obvious reductions on mechanical properties. In comparison with NC, the corresponding maximum reductions in 7 days and 28 days compressive strength are 60.7%, and 65.8% respectively.
- The replacement of composite PCM to fine aggregate results in producing lightweight TESC, and with the replacement level of 80%, a density of 1100 kg/m^3 can be achieved.
- The incorporation of composite PCM into cement mortar exhibits lower thermal conductivity and resultant TESC has high insulation capacity compared to NC.
- Thermal energy storage performance of TESC was significantly improved with the addition of composite PCM. In comparison with NC, a 56% and 166% increment was observed in TESC-80 for thermal energy storage rate and thermal energy storage capacity respectively.

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