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Experimental and Numerical study on Energy Performance of Buildings Integrated with Phase change materials

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Abstract

An experimental and numerical study has been carried out to evaluate the energy saving potential of thermal energy storage cementitious composite (TESC) in commercial buildings. Here, TESC was fabricated by integrating a composite phase change material based on paraffin and expanded perlite into ordinary cementitious composite. The TESC developed was used to study the thermal performance of an experimental room in the laboratory. Thermal performance test revealed that TESC reduced the peak indoor temperature by approximately 5.6°C during summer design days with the peak shift of 1.5 hours. The potential application of TESC in commercial buildings evaluated by building simulation in EnergyPlus showed that TESC can provide an annual energy savings of 16-25% in major Australian cities.

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1. Introduction

The building sector is known to be contributing large portion of energy consumption and greenhouse gas emissions, representing 40% of primary energy consumption and 33% of greenhouse gas (GHG) emissions globally. Additionally, energy consumed for space conditioning is being as a major part of the building energy, representing almost half the energy consumption in developed countries [1]. Therefore, much effort has been dedicated to consider passive heat storage strategies in the building design field such as thermal energy storage. A common practice in the passive design strategies is the enhancement of thermal mass of the building envelope with the application of phase change materials (PCMs) to store the excess solar thermal energy during daytime and re-radiate into the building during cooler nights. PCM stores the thermal

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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 [2]. This can ultimately reduce the peak temperatures and temperature fluctuations in indoors [3, 4].

Many experimental and numerical studies have tried to incorporate PCM into building materials to enhance the thermal mass of the building. For example, PCMs have been incorporated into concrete, plasterboard, masonry bricks tiles etc. Cementitious composites are most widely used building materials and incorporation of PCM into cementitious composites not only enhance the thermal energy storage capacity of building materials, but also facilitates energy conservation and savings in buildings. However, operation of PCM involves frequent solid and liquid transformation, which would result in leakage of liquid PCM [5]. Therefore, it must be ensured that the PCM doesn't cause leakage from the supporting materials during the operational stage.

It is demonstrated in the authors' previous work [5] that a novel composite PCM fabricated on hydrophobic expanded perlite (EP) supporting material does not show any liquid PCM leakage and it is highly compatible with most construction materials. Furthermore, this previous investigation provided the foundation for the current study on investigating the energy performance of buildings when this novel composite PCM is integrated into building fabrics. Therefore, here we carry out an experimental and numerical study of paraffin/hydrophobic expanded perlite composite PCM integrated cementitious composite to evaluate the energy performance of commercial buildings in major Australian cities.

2. Experimental and Numerical methods

2.1. Fabrication of paraffin/EP composite PCM and TESC

The paraffin/EP composite PCM was fabricated by using vacuum impregnation method, where paraffin and EP were mixed at 60°C ambient temperature and vacuum pressure conditions until a uniform mixture is achieved. Finally, the composite PCM was derived after cooling at room temperature. It was found that the optimum paraffin amount in the composite is 50 wt% as reported in authors' previous study [5]. The composite PCM was then integrated into ordinary cementitious composites to develop thermal energy storage cementitious composite (TESC) and mix proportion of materials are given in Table 1. An ordinary cementitious composite (NC) was also prepared to compare the thermal performance enhancement of PCM.

Table 1. Mix proportion of materials

Series	Binder		Aggregates		
	OPC cement	Water w/b	Aggregates/binder ratio	Sand (vol%)	PCM composite (vol%)
NC	1	0.5	3	100	0
TESC	1	0.5	3	25	75

2.2. Thermal performance test

The thermal performance of the TESC panels was studied by using a laboratory made test room set up as depicted in Fig. 1(a). The test cells were consisting hollow cubes, with an internal hollow volume of 300 x 300 x 300 mm³, whose walls are composed of (from the outside to the inside of the cube): a 13 mm thick timber layer and a 16 mm thick test panel. One of the faces of the cube functioned as a removable lid to permit access to the inside of the room. The test rooms are placed inside a controlled climate chamber with metallic interior walls and having a volume of 300 l, thus providing enough clearance for the air circulation

inside the chamber. The temperature variation inside the chamber was programmed to match the representative weather data of Melbourne, Australia for the period of 22-26, January. In regard to temperature monitoring, k-type thermocouples (an accuracy of 0.1°C) were positioned at inner and outer surface of the test room and in the centre of the room. The physical arrangement of the test setup is shown in Fig. 1 (b). All temperature sensors were connected to an automatic data acquisition system (data-logger), with the data recording frequency of one minute.

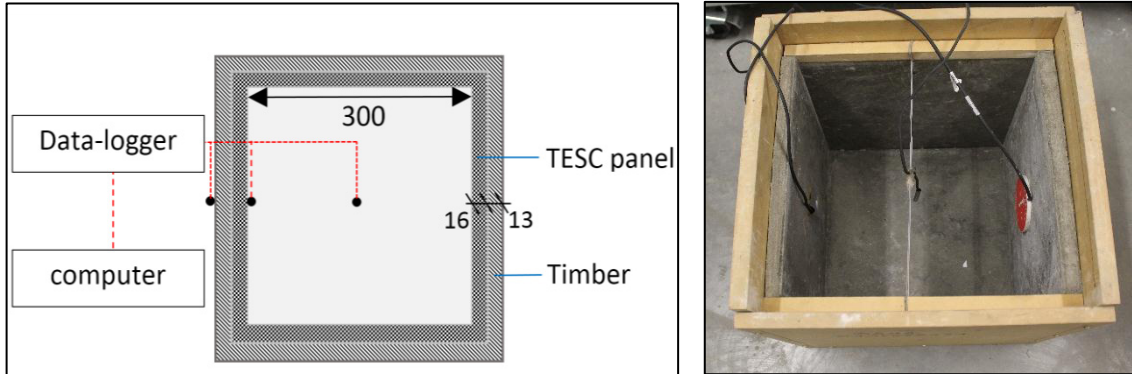


Fig. 1. (a) schematic diagram of test cell [units: mm] (b) physical set up of experiment

2.3. Numerical simulation of TESC in buildings

In order to evaluate the energy saving potential of TESC in buildings, a multi-zone commercial building is considered (see Fig. 2(a)), consisting in the installation of TESC panels on the concrete floors and brick walls, with the aim of improving energy efficiency in lightweight buildings. It is considered as a module of a typical office building of the 1980's, with large glazed facades, a concrete frame with well-insulated envelope and very light partition walls to separate the offices. The building was refurbished by installing TESC as the inner linings of walls and floor renders. The detailed construction elements and relevant properties are given in Table 2. The PCM used in this study has a melting temperature and latent heat capacity of 27°C and 166kJ/kg respectively. The enthalpy-temperature variation of paraffin is shown in Fig. 2 (b). The building was modelled in building energy and thermal load simulation software EnergyPlus to evaluate the energy efficiency with the TESC refurbishment. The dynamic thermal simulations were carried out for the major climate zones in Australia such as Melbourne and Sydney.

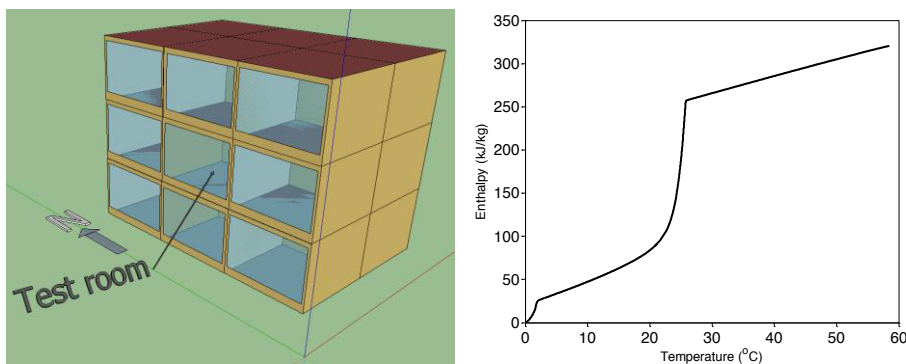


Fig. 2. (a) Thermal zones of the house (b) Enthalpy-temperature relationship for paraffin

Table 2. Specification of house design

Surface	Description
Exterior walls	110-mm thick brickvener construction having internally finished with NC/TESC
Floors and ceilings	200 mm thick non-insulated concrete, rendered by NC/TESC and then surface finished with floor carpets
Roof	Flat roof with concrete roof tiles
Windows and shadings	4 mm thick single glazing with an aluminum frame. Internal venetian blinds are operated when the incident solar radiation exceeds 200 W/m ²
Doors	Timber doors (50mm thickness)

3. Results and discussions

3.1. Thermal performance test

Thermal performance comparison of NC and various TESCs were evaluated by monitoring the inner surface temperature and indoor temperature of the test room for the simulated time period. Fig. 3(a) shows the outdoor air temperature variation and indoor temperature variations during the test period. It can be observed that, throughout the test period, the maximum indoor air temperature in TESC integrated test cell is lesser than NC integrated test cell. For instance, a reduction in peak indoor temperature of 1.3°C can be observed for the first day. However, such temperature reduction does not show a full exploitation of latent heat capacity in PCM as the maximum outdoor temperature only reached about 25°C. Nevertheless, large temperature reductions can be observed when the outdoor air temperature increases above 30°C. During the 5th day of the experiment, a maximum temperature reduction of 2.7°C can be seen in the TESC integrated testing room. It can also be seen that the minimum indoor temperature in PCM integrated test room found to be higher than NC integrated test room on the same day. However, such increase cannot be observed in the other periods of the experiment. It is believed that the outdoor air temperature in the 5th day is sufficient to melt all the PCM and hence result in the large reduction of indoor temperature fluctuations. However, during the first four days, maximum outdoor temperatures are just about the melting temperature of PCM and would not be able to exploit the latent heat capacity of PCM. In this instance, high thermal resistance of TESC partially helps to reduce the peak indoor temperature. Furthermore, a time delay in the peak indoor temperature of approximately 1.5 hours can be observed throughout the testing period. This will help to facilitate the peak load shifting in PCM integrated buildings compared to ordinary buildings.

In order to study the complete exploitation of PCM with the allowance of adequate time to solidify at night, two consecutive design days were considered, having the maximum outdoor air temperature of 35°C with the minimum night temperature of 15°C. The comparative study on the behaviour of test rooms during this period with the outdoor air temperature profile is shown in Fig. 3(b). From Fig. 3(b), it can be clearly seen that the PCM has a significant contribution to reduce the peak indoor temperatures during the summer periods. A maximum peak indoor temperature reduction of 5.6°C can be observed on the first day. This maximum reduction was reduced to 4.3°C on the second day as still the PCM has not been solidified completely. Future studies are required to enhance the heat storage/release performance of PCM applications by considering high conductive additives in TESC.

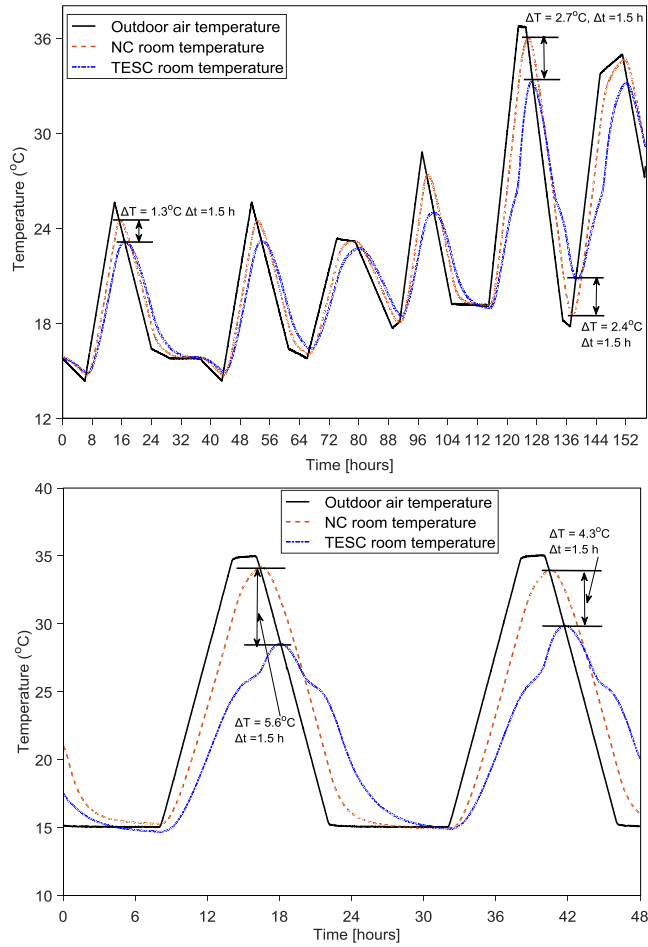


Fig. 3. indoor temperature variation during (a) January 7-11, Melbourne (b) two summer design days

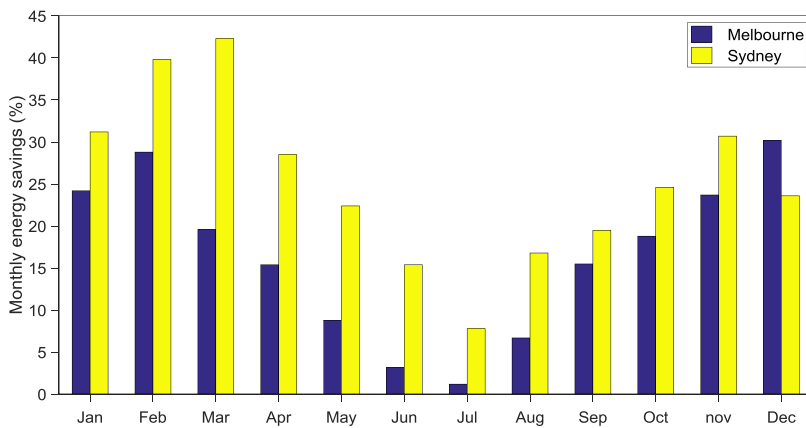


Fig. 4. Energy saving potential of TESCs in major Australian cities (a) Melbourne (b) Sydney

3.2. Energy saving potential of TESC in commercial buildings

Fig. 4 shows the energy saving potential of building refurbishment with TESC in the major climate zones of Melbourne and Sydney. From figure, it can be seen that there is a significant energy savings when building refurbished with TESC, compared to NC. Particularly, the climate zone of Sydney has high energy savings compared to Melbourne, due to the favorable melting temperature of PCM. Whereas, Melbourne require lower melting temperature to achieve optimum energy savings as reported by previous researchers [6, 7]. Furthermore, monthly energy savings of 20-40% were observed for the summer period of December to March in both climate zones. On this basis, the total annual energy savings were estimated as 16% and 25% for the climate zones of Melbourne and Sydney respectively when building refurbished with TESC.

4. Conclusions

In this study, energy performance of buildings integrated with phase change materials (PCMs) was investigated with the experimental and numerical simulation studies. Here, thermal energy storage cementitious composite (TESC) was developed by integrating a novel paraffin/EP composite PCM into ordinary cementitious composites to the application of building interior envelopes. Thermal performance tests conducted on a laboratory scale test room reveals that the TESC can reduce the peak indoor temperature by up to 5.6°C with the peak delay of approximately 1.5 hours. Furthermore, the building application of such TESC was evaluated by dynamic thermal simulation for typical commercial buildings with the aid of EnergyPlus. It has been demonstrated that the PCM incorporation into building envelopes can provide an annual energy savings of 16-25% for the climate zones of Melbourne and Sydney respectively.

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