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Energy Saving Potential of Cement-Based Mortar Containing Hybrid Phase Change Materials Applied in Building Envelopes

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ABSTRACT

This work reports an experimental study regarding the energy saving potential of an innovative concept of thermal energy storage, which consists in embedding more than one type of Phase Change Material (PCM) into cement-based mortars to apply as renderings in façade walls of buildings. The mortar simultaneously incorporates three distinct phase change materials and is termed HPCMM (Hybrid PCM mortar). The total mass percentage of PCMs in HPCMM can reach as high as 20%, while maintaining satisfactory performance in terms of mechanical properties/behavior of the mortar. The experimental program comprises two laboratory scale prototypes, materialized by two hollow boxes of outer dimensions 46×46×46cm^3, internally coated with HPCMM or REFM (reference mortar without PCM) and externally subjected to realistic daily temperature profiles. The prototypes were internally equipped with a heater that was programmed to keep the inside of the box within the acceptable range of comfort temperature, in correspondence to the simulation of a winter scenario (heating season). By monitoring the energy consumption of the heater, it was possible to infer that the prototype rendered with HPCMM led to a reduction of energy consumption of nearly 20% as compared to the prototype rendered with REFM.

INTRODUCTION

Thermal energy storage systems can assist the reduction of indoor temperature variations, and also shift the energy loads in buildings from peak hours towards off peak hours of energy demand. It has been evidenced that buildings are responsible for a significant portion of the word's energy demand, which is linked to the growth rate of population as well as the global tendency for improvement of societal demands/awareness for indoor thermal comfort [Halford *et al.*, 2007]. In particular, the indoor heating and cooling systems used in buildings amongst the most energy-demanding uses, corresponding to about 30% of energy use in this sector [Sayyar *et al.*, 2014]. Therefore, it is relevant to develop systems that can assist maintaining indoor temperature within comfort levels, while helping in the reduction of energy consumption for such purpose. Storage of energy improves the energy efficiency in buildings by allowing the energy to be used more rationally. The materials that take advantages of latent heat storage are normally called phase change materials (PCMs) [Duffie J. A *et al.*, 1980]. Latent heat storage can be explained in simple words: when the temperature increase of a given solid PCM reaches its melting threshold, the phase change occurs with relevant heat absorption. An opposite mechanism is felt in the passage from liquid to solid, with heat liberation occurring in such process. Due to these energy absorption/release processes, the PCM tends to enforce a stable temperature situation upon itself, which is a very favorable situation from the point of view of being able to keep a target temperature in a given room. A suitable PCM for a particular application should provide desirable phase change temperature, high latent heat capacity, durable under heating/cooling cycles, thermal conductivity, non-toxic, non-flammable, non-corrosive and economy [Zhou *et al.*, 2012].

One potential methodology for enhancing energy saving of buildings is the use of PCMs incorporated or even embedded into building materials. Typical PCMs that are desirable for building applications include salt hydrates, fatty acids, and paraffins. Paraffins have many desirable properties among other types of the PCMs such as: negligible super cooling, high latent heat, stability and resistance to phase segregation [Hasnain, 1998]. However, they have low thermal conductivity and also are rather costly due to the fact that, in the liquid state of phase change materials, PCMs requires costly containment (encapsulations) that causes increase in the cost of final product. Several researchers have investigated methods for incorporating PCM into construction materials such as: plastering mortars [Vaz Sá *et al.*, 2012], concrete slabs [Bentz *et al.*, 2007], bricks [Vicente *et al.*, 2014]. The incorporation of PCMs within the outside envelopes of buildings (e.g. plastering mortars) can render them particularly feasible to capture solar energy directly and store significant amounts of thermal energy in the building envelopes. In the other hands, incorporation of PCM into plastering mortars of building facades can improve thermal efficiency of buildings due to their ability to store energy and it allows reducing the energy consumption of heating/cooling systems used to control the indoor temperature of the room [Waqas A *et al.*, 2013].

In this study, hybrid paraffin based phase change materials were used in the same mortar, here termed as HPCMM (using more than one type of PCM with distinct melting ranges and specific enthalpies). The hybrid PCM was incorporated into a cement based plastering mortar, and the thermal performance of such mortar was evaluated using a small scale prototype (hollow enclosure rendered with HPCMM), equipped with a internal heater and subjected to an environmental daily temperature profile compatible to a typical winter day in the north of Portugal. An additional prototype comprising a coating mortar without any kind of PCM was also prepared and testing for comparative purposes. It is noted that the internal heater was connected to a thermostat dully set to keep the inside of the tested box within a predefined thermal comfort temperature range. The energy consumption of the heater during the process of testing was assessed with an energy meter for both HPCMM and REFM prototypes. The positive outcome in terms of energy saving points to a positive prospect in regard to further developments of the application of HPCMM in the context of residential buildings.

EXPERIMNETAL PROGRAM

Materials and formulations. The initial selection of materials for this research was limited to those exhibiting phase change in the temperature range of 5–30°C, which covers the sol-air temperature variations in the typical winter climatic conditions of the location of the building, in Southern European countries (such as Portugal) as well as thermal comfort range. In this way, three types of paraffin-wax-based (organic) PCMs were considered for the experimental program reported herein: RT10 with melting temperature of 10°C (from RUBITHERM paraffin RT series), MC28 with melting temperature of 28°C (from DEVAN MICROPOLISH MC series), and BSF26 with melting temperature of 26°C (from BASF microencapsulated Micronal series DS 5001). The properties of the PCMs selected for this study, as provided by their suppliers [BASF Micronal, 2008; Microthermic, 2012; Rubitherm GmbH, 2012], are presented in Table 1. According to previous developments of this research team [Kheradmand M *et al.*, 2016], the formulation of mortars with incorporation of hybrid PCMs allowed the mass fraction of PCM to reach nearly 20% of the global mass of the mortar. It should be mentioned that, the performance in terms of main properties of the mortar was maintained at satisfactory levels, such as: workability, compressive strength, flexural strength and adhesion [Cunha *et al.*, 2015].

Table 1. Properties of PCMs, provided by suppliers [BASF Micronal, 2008; Microthermic, 2012; Rubitherm GmbH, 2012].

PCM type	Operating temperature ranges (°C)	Latent heat of fusion (J/kg)	Melting point(°C)	Apparent density at solid state (kg/m^3)	Particle size distribution range (μm)
RT10	2–12	150000	10	880	–
BSF26	10–30	110000	26	350	5–90
MC28	22–32	170100	28	*	14–24

** No information available on behalf of the suppliers.*

The mix designs of the two mortars studied herein, together with their adopted designations (REFM for the reference mortar and HPCMM for the hybrid PCM mortar) are presented in Table 2. It is noted that the formulation of mortars HPCMM adopted herein comprises the three distinct PCMs mentioned above, in line with previous works of this team [Kheradmand M *et al.*, 2016]. The three PCMs are placed in equal mass quantity, thus globally reaching 18.34% of weight within the mortar. It is interesting to note that, an adequate behavior (i.e., absence of drying cracks) was obtained with both formulations of REFM and HPCMM.

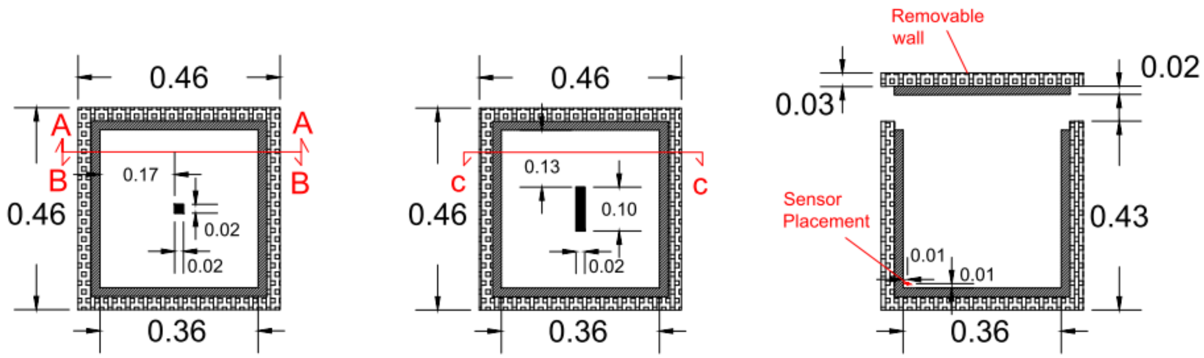
Table 2. Mix proportions of formulations REFM and HPCMM (including photos at hardened stage)

Materials	Formulations (percentage of the total weight of mortar)			
	REFM		HPCMM	
Cement type I-42.5R (SECIL)	22.64		31.32	
Sand	64.23		30.59	
Water	12.45		18.79	
Super plasticizer	0.63		0.94	
RT10	-		6.12	
BSF26	-		6.12	
MC28	22.64		31.32	

The determination of the specific enthalpy of the mortar specimens was performed through DSC testing with recourse to a NETZSCH 200 F3 Maia, following the methodology recommended by EN ISO 11357-1 [1997]. One specimen was prepared for the study of HPCMM, with a weight of 37.88 mg. A heating rate of 2°C/min was considered for the experiment. The applied program steps for the test procedure of specimens were the following: (i) initial isothermal period at 0°C for 5 minutes; (ii) dynamic heating up to 40°C according to the proposed rate (2°C/min).

Design and fabrication of two layered active system prototype. In order to assess the effect of the hybrid PCM concept into plastering mortars used as internal coatings for energy saving in buildings, two closed prototypes equipped with a heater element were built with laboratory scale dimensions. The outside of the prototype was cubic with an edge length of 46cm. The prototypes were hollow, and the materials used for the construction of the prototype walls were (from inside to outside): a 0.02m thick layer of REFM or HPCMM, and a 0.03m thick layer of extruded polystyrene (XPS). The schematic diagram of the physical models and cross section of the model are shown in

Figure **1**.



(a) Plan view C–C. **(b)** Cross section B–B. **(c)** Sensor placements cross section A–A.

Figure 1. Schematic representation of the prototype equipped with a heater element placed inside the climatic chamber. Units: [m].

The composition of the walls of the prototype is not a typical one in building envelopes. In fact, the target in this study was to have a small-sized prototype, with relatively thin walls, which would however have a thermal transmittance (U ≈ 0.89 W/m^2K) lower than the maximum limit according to Portuguese regulations for vertical elements, which is of U = 1.45 W/m^2K [RCCTE, 2006], thus having a reasonably similar thermal behavior to actual building envelopes.

The heating system was placed inside the prototype (center of the heater coinciding with the geometrical center of the cube) as shown in figure 1. The heater (ROTFIL-air heater series) had dimensions of 0.02m×0.02m×0.1m, with a power rating of 300 W. The heater was connected to a multifunctional electricity source with a temperature controller (OMRON-E5CSV). The control of the heating system was made in order to maintain the temperature within the prototype within a predefined comfort level. The standard ASHRAE55 [2004] recommends that air temperature inside residential buildings should be at least ≈ 20°C during winter season.

Physical test configuration. The test setup for a total number of 2 experiments (one for REFM and one for HPCMM) was performed under a typical Portuguese winter scenario. The sensor for controlling the heater element was attached to the corner-bottom sensor inside the prototype as this would be the coldest region within the prototype. The main comparative evaluation parameter of the performance of the two studied plastering mortars was the energy demand of the heater in order to maintain adequate internal comfort levels. The scheme illustrated in figure 2a shows the temperature controller and the energy meter units programmed to measure/control the interior temperature of the prototype which is attached to the placement of corner bottom sensor (here termed IT), monitor the exterior temperature (placed at climatic chamber ambient), and assess the power consumption of the heating element unit. The operating principle of the devised system is presented in figure 2b. The heater becomes ON when the measured temperature inside the box in under 20˚C. Conversely, the heater is OFF when the temperature reaches (or surpasses) 20ºC. The IT sensor was connected to data acquisition system (AGILENT 34970A). Electrical consumption of the heating units was measured using a dedicated energy meter (OWL_USB). Each one of the two experiments was carried out for three full day cycles (72 h). The climatic chamber in which the test was conducted also allowed the control of internal relative humidity, which was set to the constant value of RH = 50% throughout all the performed experiments. The physical arrangement of this setup can be observed at the pictures of the prototype/monitoring shown in figure 2c.

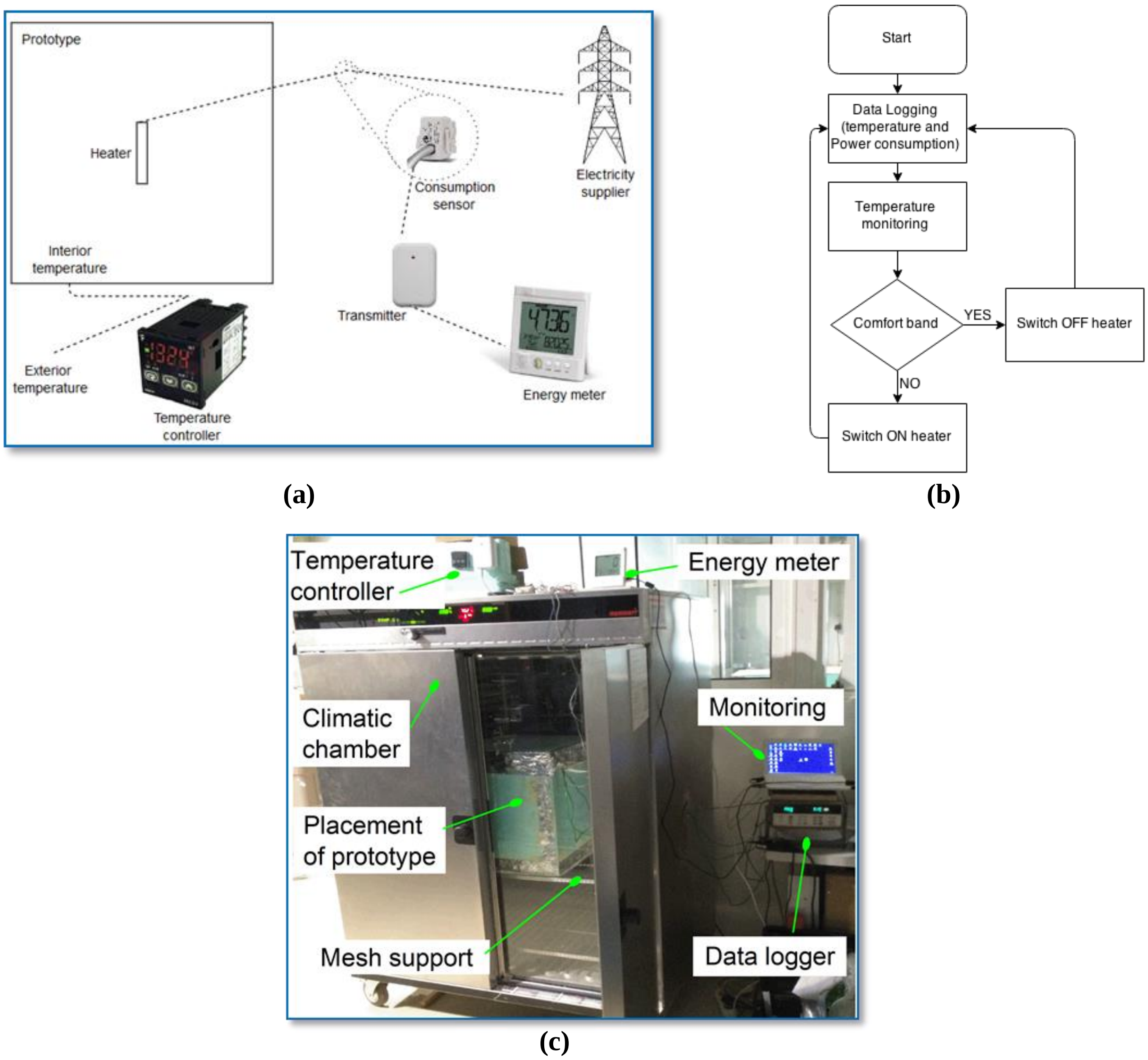


Figure 2: (a) Monitoring and control arrangement system scheme; (b) experimental procedure for the heater element; (c) photo of the prototype ready for testing, highlighting the location of the prototype within the climatic chamber.

Each prototype was placed inside a controlled climatic chamber. The climatic chamber was programed to follow temperature cycles that matched the sol-air temperature for a vertical wall facing south, located in the North of Portugal considering the winter scenario. The sol-air temperature ($T_{Sol-Air}$) was computed according to Eq. (1) [Vaz Sá *et al.*, 2012]:

$$T_{Sol-Air} = T_{Air} + \alpha I_g R_{se} \tag{1}$$

T_{Air} is the exterior temperature (°C); α is the absorption coefficient of the surface; I_g is the global solar radiation (W/m^2); and R_{se} is the external surface resistance ((m^{2}K)/W). The values of exterior temperature (T_{Air}) and global solar radiation (I_g) were considered regarding average hourly values recorded for representative day of winter in Guimarães, obtained from a weather station located within the campus of the University of Minho. An absorption coefficient $\alpha = 0.6$ was considered in correspondence to colour of the surface material (XPS) [ISO6946, 2007]. The value of external surface resistance was adopted as R_{se} = 0.04 (m^2K)/W in accordance to the recommendations of [ISO6946, 2007]. As a result of the application of the sol–air temperature model, the 24h cycle shown in figure 3 was obtained for winter scenario.

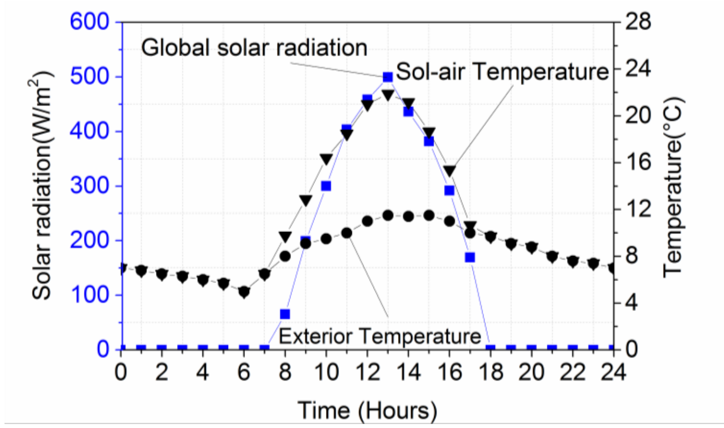


Figure 3. Exterior temperature, solar radiation and sol–air temperature of a winter day in Guimarães, Portugal.

RESULTS AND DISCUSSIOIN

Characterization of the mortars. Phase change temperature and specific enthalpy are two key properties of PCMs. Figure 4 shows the specific heat capacity of the HPCMM under a heating process as well as the corresponding calculated specific enthalpy.

The first, second and third peak temperature in the specific heat capacity curve belongs to the RT10, BSF26 and MC28 with melting temperatures around 15ºC, 24ºC and 26ºC respectively (see figure 4). It should be stated that for the sake of brevity, the DSC testing of the reference mortar (REFM) that did not contain any PCM was just a straight line confirming that such material did not endure any internal phase change transition. Therefore, no further discussion will be made on REFM mortar.

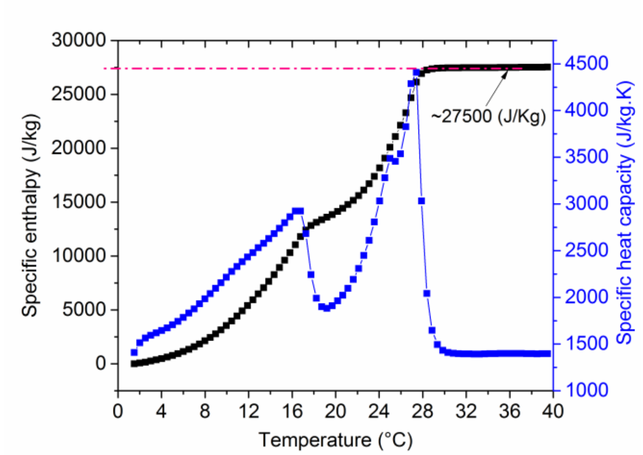


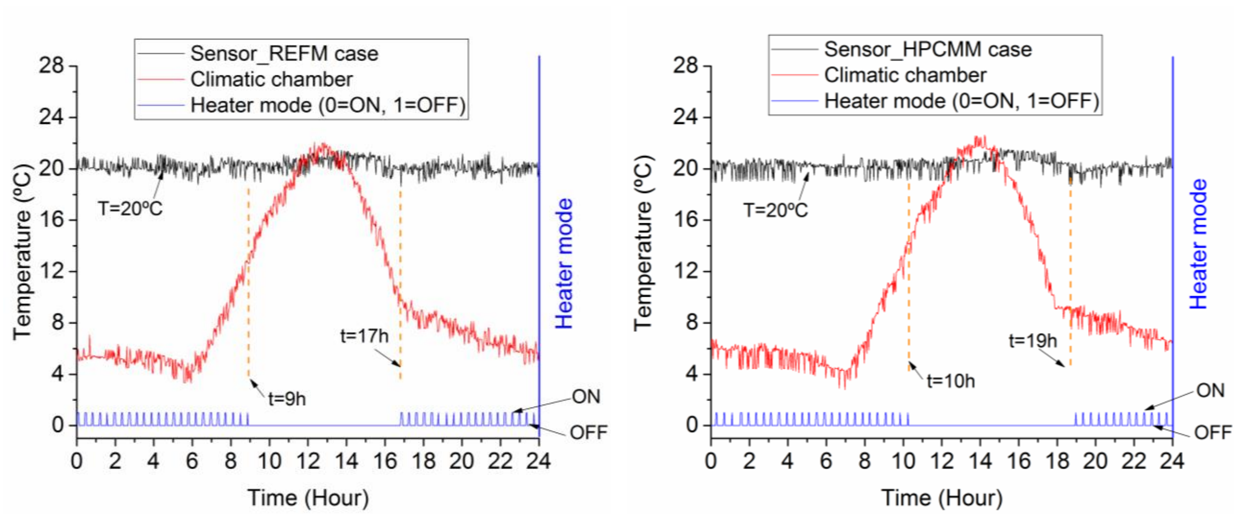
Figure 4. Specific heat capacity and specific enthalpy for HPCMM mortar with heating rates of 2°C/min.

In order to calculate the specific enthalpy $H(T)$ of the mortar with PCM, based on the DSC output, the calculation procedure for each phase change followed Eq.(2):

$$H(T) = \frac{1}{\varphi}\int_{T_{onset}}^{T}\left[DSC(T)_{sample} - DSC(T)_{baseline}\right]dT \tag{2}$$

where $DSC(T)_{sample}$ is the value of DSC signal at temperature T from the thermogram (mW/mg), $DSC(T)_{baseline}$ is the value of DSC signal at temperature T from the baseline of the thermogram for the phase change (mW/mg), φ is the heating rate (°C/s), T_{onset} is the onset temperature (°C), and T is the temperature (°C). The results of the calculation of specific enthalpy evolution along temperature for HPCMM are shown in figure 4. It can be observed that the accumulated specific enthalpy is about 27500 J/Kg.

Thermal performance and energy saving potential of mortars. Figure 5a shows the air temperature variations recorded inside the REFM prototype over a 24h period (2nd cycle), represented together with the externally imposed temperature, as well as the information about the periods in which the heater was activated by the control system. As shown in this figure, during a cycle of 24h, interior air temperature was adequately kept at the minimum comfort temperature of about 20ºC according to the predefined set point temperature for the heater. During first 9h period, when the ambient temperature was under about 14ºC, the heater experienced both modes of OFF and ON with small intervals as to maintain the interior temperature of the prototype at the limit temperature of 20ºC. Between the instant t≈9h and t≈17h, the effect of the thermal inertia of the walls seems to have been enough to ensure the 20ºC inside the prototype without the need for activation of the heater system.



(a) **(b)**

Figure 5. Monitoring temperature variations at different positions inside the prototypes under tested controlled environment accounting heater modes: (a) REFM and (b) HPCMM.

The results of thermal behavior in the hybrid PCM prototype (HPCMM) are shown in figure 5b. In fact, Figure 5b is homologous to Figure 5a, except for the fact that it deals with HPCMM. The observations are also analogous to those already made for REFM. In brief, in the case of HPCMM there is a possibility of taking advantages of PCMs due to the fact that they can absorb or release the heat during their phase change temperatures, and therefore the necessity of activation of the heater is felt for smaller durations. For further evaluation of the impact of the PCM on thermal efficiency of the system, the cumulative energy consumption by the heater equivalent to the both cases of REFM and HPCMM were calculated for a period of 24h and are demonstrated in figure 6. The configuration with PCM allowed approximately 20% reduction in energy demands for maintaining the temperature inside the prototypes within the comfort temperature. This shows that the electricity saving achieved in each day comes from PCMs and is affected by outdoor temperature.

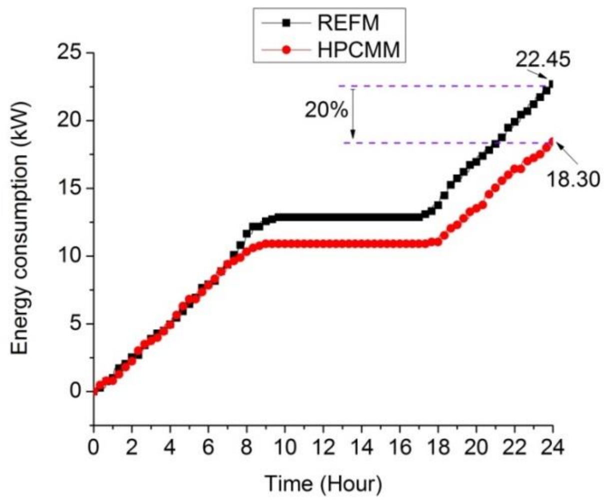


Figure 6. Accumulative energy consumption versus time.

CONCLUSION

This paper presents the thermal characterization (DSC) of mortars containing incorporated phase change materials targeted for thermal comfort in buildings. The study encompasses a reference mortar termed REFM, as well as a mortar containing hybrid PCMs (called HPCMM) with mass fraction of 18.34% of PCM with melting temperatures of 10°C, 26°C and 28°C. The hybrid blend of three distinct types of PCM has proved advantageous for improved efficiency thermal comfort assurance in buildings (reducing energy consumption for heating/cooling seasons), and their feasibility at material/thermal level as well as energy saving potential were evaluated in this work.

From the material level investigation, the thermal behavior of the PCM mortar has been analyzed, namely in regard to the peak temperatures on the specific heat capacity, as well as on the calculated specific enthalpy. It was found that tests with three peaks intensify the overall shape of the curve for hybrid PCM mortar. Furthermore, the calculated specific enthalpy for phase transition was obtained based on the considered heating rate.

A two layered wall prototype enclosure was designed to complement high latent heat storage capacity and energy saving potential of hybrid PCM through laboratory scale testing. The prototype incorporated hybrid PCM mortar. A second prototype with a reference mortar that did not contain any PCM was also made and tested for comparative purposes. The energy saving results indicated a reduction of 20% in energy demand to maintain the interior within the thermal comfort range by application of the hybrid PCM mortar. These results confirmed the important benefits of hybrid PCM mortar in terms of energy efficiency, thermal comfort and energy cost saving.

This method of latent heat storage can further benefit from variable electricity prices during the day by shifting the peak load of consumption. It is however remarked that the melting point of the PCM needs to be selected according to the thermal comfort requirements.

ACKNOWLEDGEMENTS

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