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Assessment of the thermal performance of plastering mortars within controlled test cells

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Abstract. Phase Change Materials (PCM) can be incorporated into plastering mortars in order to improve their thermal properties by exploiting latent heat storage of PCMs. As a consequence, plastering mortars that incorporate PCMs can be applied advantageously to building façades/partitions for improved thermal comfort levels while reducing the overall energy consumption for heating/cooling.

The assessment of plastering mortars with Phase Change Materials (PCMs) is experimentally investigated in this paper, aiming to assess the effectiveness of the PCM into the mortar, here termed as single PCM plastering mortar (SPCMM).

In order to demonstrate the effectiveness of the PCM mortar concept, two experiments have been performed. Two small-scale cubic test cells have been constructed, with outer edge of 26 cm and inner edge of 20 cm. In regard to the outer lining of these two cells, the following applies: one of them was externally lined with conventional mortar (here termed as REFM); and another lined with single PCM plastering mortar. The cells were closed, placed inside climatic chambers and subjected to realistic temperature scenarios in South European countries, whereas the inner temperature was continuously recorded. It was shown that a smoother indoor temperature profile is obtained when PCMs are implemented. An improvement in human comfort can thus be anticipated.

Introduction

The use of Phase Change Materials (PCMs) as thermal storage systems for buildings has been of interest since first application in the 1940s [1]. PCMs are suitable for assisting thermal control, because they store and release thermal energy during phase change process (melting and freezing processes). When the material is solidifying, it releases energy in the form of latent heat. Conversely, when the material melts, it absorbs thermal energy from its surroundings. This property of PCM is useful for temperature control in buildings. The storage of energy on behalf of a given PCM subject to a certain environmental condition strongly depends on its transition temperatures [2, 3].

The thermal energy storage property of PCMs is based on capability of the latent heat storage. For example, a given PCM can store eighteen times more energy than a regular masonry brick [4].. To reach the effective potential of the PCM for an extended period of the year it is important to adequately select its desirable enthalpy and transition temperatures.

Many numerical and experimental researches have been carried out in order to evaluate the incorporation of PCM into the building's material [5-7]. Several applications have been found for PCMs as energy storage systems and coming from a variety of sources. Microencapsulated PCM has been incorporated into plastering mortars [8, 9], masonry walls [10], tiles [11], and plaster boards [12, 13].

In this paper the incorporation of microencapsulated PCMs in cement based plastering is presented and experimentally tested. An experimental campaign is settled for the assessment of this material and the results are compared to those obtained for conventional reference mortars, which are frequently used as interior coatings.

For that propose two test cells were built with distinct interior coating: (i) one with conventional building materials, here termed as test cell REFM; (ii) another with incorporation of PCM in plastering mortar, here termed as test cell SPCMM. Both test cells were monitored when subjected to realistic temperature for heating and cooling test, with high temperature variation, in order to assess the effect of PCM incorporation.

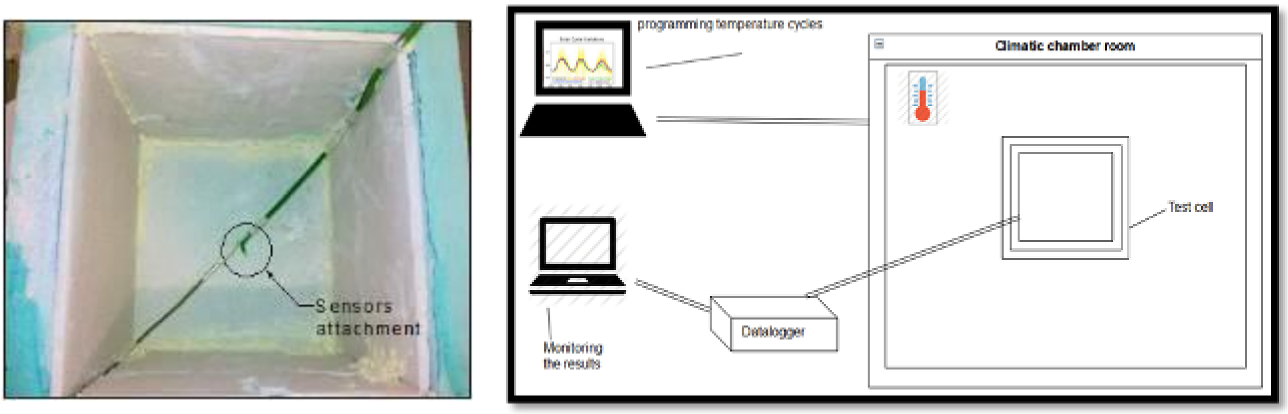
The results obtained from the experimental works provide grounds for better understanding the phase change phenomena of PCM mortar for the modeling approaches.

The work strategy is structured into two main steps: (i) material characterization; (ii) setting up the test cells and evaluating them under a realistic temperature scenario.

Experimental program

Presentation and design of the test cells. An experiment has been designed to analyze the response of test cells without and with PCMs towards heating/cooling processes. The experiment analysed the evolution of thermal waves at the center of test cells when subjected to known external temperature evolutions.

Figure 1 shows the experimental set-up. The test cells were hollow cubes, with an internal hollow volume of 20×20×20 cm^3, and whose walls are composed of (from the inside to the outside of the cube): a 0.5cm thick layer of mortar (REFM or SPCMM); and a 3cm thick XPS layer (extruded polystyrene). One of the faces of the cube functioned as a removable lid to allow access to the inside of the cell (see Figure 1a). Each test cell was placed inside a controlled climatic chamber room with metallic interior walls. The sensors were connected to an automatic data logger. The scheme of the test setup is shown in Figure 1b.



(a) (b)

Figure 1- Simple experimental set-up designed to evaluate the heating/cooling behaviour in small scale test cells with and without PCMs: (a) Photo of sensor arrangement inside box, (b) test set-up.

Properties of the materials used. The materials used for the construction of the test cells were: SPCMM, REFM, and XPS.

The main thermo-physical properties of the materials used in both test cells, REFM and SPCMM, are synthetized on **Erro! A origem da referência não foi encontrada.**, where the corresponding test method for mortars are shown tests are EN 1015 [14] and EN 1745 [15].

Table 1 - Thermo-physical properties of the materials used in REFM and SPCMM test cells.

Thermo-physical properties	**Ab.**	Units	XPS	REFM	SPCMM	Test method	
						XPS	**Mortar**
Density	**ρ**	[kg/m^3]	33	2176.3	1360.3	Manuf. V	EN 1015 [14]
Specific heat	**c_p**	[kJ/(kg K)]	1.4	1.0	1.0	Manuf. V	EN 1745 [15]
Thermal conductivity	**λ**	[W/m K]	0.04	0.4	0.2	Manuf. V	Heat flow meter apparatus
Latent heat	**L**	[kJ/kg]	-	-	24.35	-	DSC test

Manuf. V corresponds to the provided values by the supplier [16].

Calorimetric analysis of mortars. Different experimental techniques (Figure 2) have been used for the characterization of plastering mortars with PCM incorporation. Thermal behavior of PCMs, phase change temperature and specific enthalpy for the phase change, have been evaluated with Differential Scanning Calorimetry (DSC, NETZSCH, 200F3), using standard aluminum 40 µl crucibles. The determinations of temperatures and latent heats of the solidification and melting processes have been established at scanning speeds of 0.1˚C/min both in cooling and heating. One test has been performed for each sample and the crucible has undergone three complete cycles of cooling/heating. The results of the cycles within the same sample were found to be reproducible with practical superposition of respective curves and results. The solidification and the melting processes have been registered for temperatures within 5˚C to 40˚C.

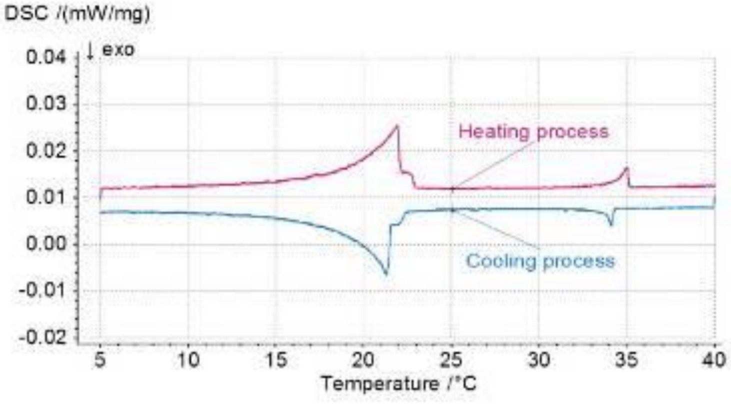


Figure 2- DSC thermograph for the mortar incorporated with PCM (SPCMM).

As can be seen in Figure 2(a) the melting process takes place within the range interval from 5˚C to 40˚C with a maximum temperature of 21.5˚C. The average value of the melting latent heat is 24.36 kJ/kg and 24.34 kJ/kg for cooling process obtained. The differences observed between the average values of both latent heats are considered normal, due to the nature of the process.

Characterization of the test cells. To characterize the test cells, the transversal heat transfer from one vertical wall of the test cell to the environment is calculated. The considered wall is located in the left of the box and it is assumed that the temperature of the surface of the wall is uniform and there is no heat loss through the transverse plane.

The cross-sectional composition of the walls of the test cell is not a typical one in building envelopes. In fact, the target in this case is to have a small-sized test cell, with relatively thin walls, which would however have a thermal transmittance ($U \approx 1 W/m^2K$) lower than the maximum limit according to Portuguese regulations for vertical elements (of U = 1.45 W/m^{2}K) [17], thus having a reasonably similar thermal behavior to actual building envelopes. The inner plastering mortar under test should have a feasible and realistic size and thus a 0.5 cm thickness was selected. In order to assure the desired transmittance, and the material characteristics (conductivity of λ = 0.04 W/m K [18]), the necessary thickness of polystyrene insulation was of 3 cm. Calculation of U-value for vertical element:

$$R_T = R_{si} + \frac{\lambda 1}{d1} + \cdots + \frac{\lambda n}{dn} + R_{se} \qquad (1)$$

$$U = \frac{1}{R_T} \qquad (2)$$

Where:
d= is the thickness of the material layer in the component (m);

λ= is the design thermal conductivity of the material (W/m K);

R_T=thermal resistance of homogeneous layer (m^2.K/W);

U=thermal transmittance (W/m^2.K);

R_{si}= air film resistance of internal surface (m^{2}K/W);

R_{si}= air film resistance of external surface (m^{2}K/W).

The air film resistance of internal surface should be considered as 0.13 (m^{2}K/W) in regard to the horizontal direction of heat flow according to ref. [19]. Also, the value of 0.04 (m^{2}k/W) should be considered for the air film resistance of external surface.
The schematic section view of a vertical wall of the test cell depicted in Figure 3. Such section comprises (from the inside to the outside of the box): a plaster mortar (REFM or SPCMM); and a XPS layer. The total thermal resistance and U values were calculated by using the resistance in series model as:
For the REFM test cell:

$$R_{T(REFM)} = 0.13 + \frac{0.04}{0.03} + \frac{0.4}{0.005} + 0.04 = 0.933(\,m^2K/W)\,,\, U_{REFM} = \frac{1}{R_T} = 1.072\ (\,W/m^2K)$$

For the SPCMM test cell:

$$R_{T(SPCMM)} = 0.13 + \frac{0.04}{0.03} + \frac{0.2}{0.005} + 0.04 = 0.945(\,m^2K/W)\,,\, U_{SPCMM} = \frac{1}{R_T} = 1.058(\,W/m^2K)$$

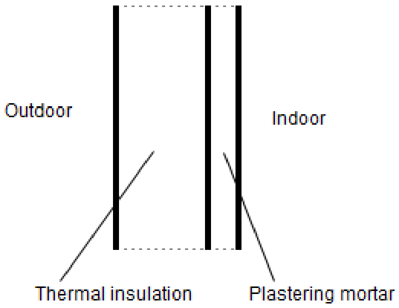


Figure 3- Schema of the wall of the test cell.

Test methodology. Each prototype test cell was be placed inside a controlled climatic chamber with metallic interior walls and volume of 100 × 100 × 100 cm^3, thus enabling enough clearance space between the outer limits of the test cell and the inner limits of the climatic chamber. The temperature cycles inside the climatic chamber were programmed to match the sol–air temperature corresponding to the surface temperature of a vertical wall facing south, which is considered to be the most unfavorable situation for summer time in Portugal (as well as other South-Western European regions). Sol–air temperature ($T_{sol-air}$) was predicted according to the following equation [8]:

$$T_{sol-air} = T_{air} + \alpha I_g R_{se} \tag{3}$$

T_{air} is the exterior temperature (°C); α the absorption coefficient of the surface; I_g the global solar radiation (W/m^2); and R_{se} 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 a normal day of summer in northern Portugal (Guimarães), as shown in Figure 4. An absorption coefficient α=0.6 was considered [8]. The value of external surface resistance was adopted as R_{se}=0.04((m^{2}K)/W) in accordance to the recommendations of ISO 6946 [19]. As a result of the application of the sol–air temperature model, a 24h cycle, with maximum sol–air temperatures of 44°C and minimum of 10°C for the summer was obtained as shown in Figure 4.

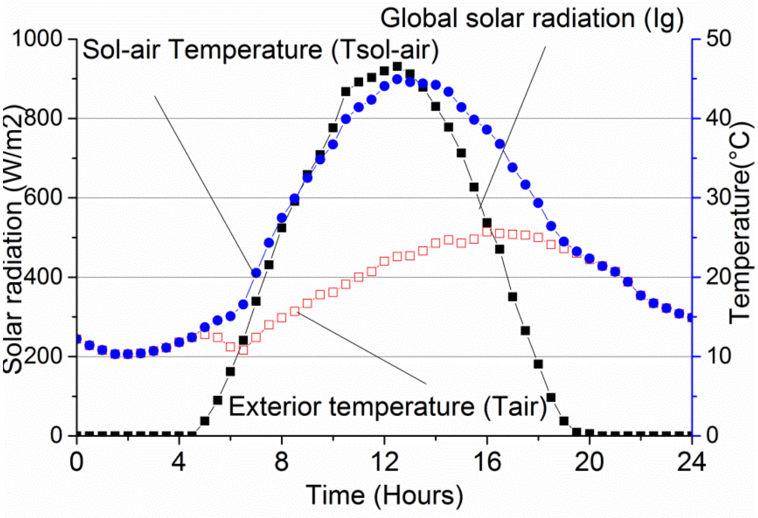


Figure 4- Exterior temperature, solar radiation and sol–air temperature of a summer day in Guimaraes, Portugal.

A total of two experiments were conducted by submitting the two test cells (REFM and SPCMM) to the summer environmental conditions, with each experiment lasting 72 h (3 cycles of 24h), because of the necessity of having a full undisturbed cycle (the middle one). The third cycle was intended to confirm that the second is already equal to the third. The climatic chamber in which the test was be conducted also allowed the control of internal relative humidity, which was set to the constant value of RH=50% throughout all the performed experiments. In regard to temperature monitoring, the use of PT100 probes allowed the temperature measurement with a very good precision for this application (±0.01°C). The PT100 were positioned at several locations within the controlled test cells (center and mortar layer), with the final intention of monitoring internal temperature variations and temperature profile variations along the linings. All sensors were connected to an automatic data logger system, with a minimum acquisition rate of 1 measurement per each 30 seconds of testing during the whole period of experiment.

Results and discussion

The registered temperatures at the center of both test cells are plotted in Figure 5. Several differences between the temperatures in the REFM test cell and the SPCMM test cell are observed.
The maximum recorded temperature in the SPCMM test cell is 2.9˚C lower than for the REFM test cell, demonstrating at laboratory scale the energy storage potentials of PCMs. The cooling process is

smoother for the test cell with PCMs. Peak temperatures are reached with 1.23 hours delay in the SPCMM test cell, when compared to the REFM test cell, indicating that the stored energy is released. The minimum temperature in the PCM treated test cell is 4.5˚C higher than in the REFM test cell.

When ambient temperature decreases (cooling process), the PCMs release energy at a controlled rate maintaining higher temperatures in the test cell with PCM (SPCMM) in comparison to the test cell without PCMs. Overall, the incorporation of PCM in to the plastering mortars leads to the enhancement of the test cell thermal inertia. The overall observations for this warm day scenario are similar to those reported by Romero-Sánchez for test cells with light wallboards containing PCM [20] under similar environmental conditions: the incorporation of PCM leads to a reduction of peak temperatures and an increase in minimum temperatures. In a full scale building this process could lead to an increase of indoor comfort and a consequent reduction of energy demands for heating/cooling.

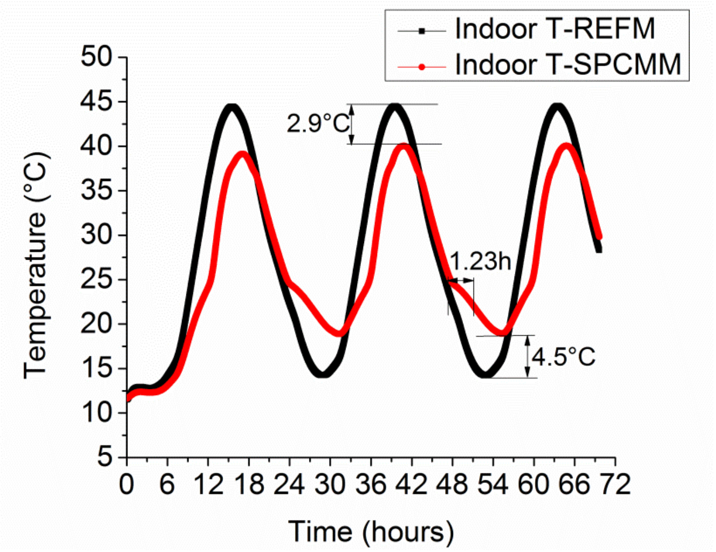


Figure 5- Temperature measurement during a typical summer day.

Conclusions

The research reported in this paper aimed main objectives: (i) to characterize a plastering mortar with incorporating PCM as a construction materials, to be used in inner wall surfaces in order to increase thermal comfort inside buildings; (ii) to use laboratory scale experimental test setups based test cells with and without PCM, for assessing thermal behavior of the plastering mortars when submitted to daily temperature cycles.

The results of the test cell experiments allowed the observation of the effectiveness of the test setup to highlight the added value of PCM’s in the inner temperature of the cell. In fact, the typical PCM benefits were observed: lagging the temperature evolution inside the test cell and reducing the temperature amplitude. The data obtained from these experiments can be used for validation of numerical simulation models, which can in turn be used for virtual testing of real-scale applications. Further experiments are planned with distinct PCM materials and combination of more than one type of PCM in the plastering mortar in order to assess potential added benefits.

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