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USING PCM TO IMPROVE BUILDING'S THERMAL PERFORMANCE

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1. INTRODUCTION

Due to European Union (EU) and worldwide high energy consumption of the buildings stock, it is important to take measures to reduce these needs and, consequently, reduce the EU energy dependency as well as the greenhouse gas emissions. To improve the behaviour of the buildings, concerning thermal comfort of the occupants and energy performance, it is necessary to use thermal insulation and the buildings thermal inertia, to reduce the thermal amplitudes, the winter heat losses, the summer heat gains and to store the energy from solar gains [1, 2]. The use of phase change materials (PCM) in the buildings is a possibility to achieve this as it allows the use of latent heat storage to increase the thermal inertia without significantly increasing the building weight.

PCM-enhanced materials function as lightweight thermal-mass components of buildings, and contribute to reducing energy use in buildings and to the development of "net-zero-energy" buildings through their ability to reduce energy consumption for space conditioning and peak loads [3].

The use of PCM, to ensure the thermal inertia, in addition to the use of thermal insulation and shading systems, allows the reduction of the winter heat losses and summer heat gains. The use of solar gains, night cooling and off-peak electricity will reduce the evening temperature fluctuations and peak temperatures, increasing comfort conditions inside buildings. These measures will lower both annual energy consumption and the maximum power consumption, saving energy and running costs, for both heating and cooling seasons, both in residential or office buildings and have potential for application in retrofit projects [1, 2, 3].

The phase change in the PCM takes place over a small temperature span thus large amounts of energy can be stored by small temperature change in the PCM [1]. This means that PCM will not absorb any heat from the air until it has reached the desired temperature range, thus only excess heat will be stored.

PCM can be used to store or extract heat without substantial change in temperature. Hence it can be used for temperature stabilization in a building. The main advantage of PCM is that, depending on the PCM type, it can store about 3 to 4 times more heat per volume than sensible heat in solids and liquids at an approximate temperature of 20 °C [4]. Phase Change Material is also a useful option when there is a mismatch between the supply and demand of energy [5].

Some studies aiming the development of construction materials incorporating PCM were performed [6, 7, 8, 9, 10, 11, 12]. Several studies were also performed to evaluate the incorporation of micro-encapsulated PCM in renderings (cement mortars, gypsum mortars and aerial lime mortars) and in plasterboards [11, 13, 14, 15, 16, 17, 18]. These studies showed that the addition of PCM to cement and gypsum mortars results in some loss of mechanical strength [11, 13, 14, 15, 16, 17, 18]. The incorporation of PCM in aerial lime based mortars increased the mechanical strength (flexural and compression strength) due to the reduced pores' size in the hardened state, leading to better performance and durability [16].

Several studies [19, 20, 21, 22, 23, 24, 25] have demonstrated that the use of PCMs in well-insulated buildings can reduce heating and cooling energy in US residential buildings by as much as 25% in locations with useful diurnal temperature variations. Kuznik et al. [26, 27, 28, 29], Voelker et al. [30] and Schossig et al. [31] performed experimental investigation to test PCM incorporated in panels, plasterboard and gypsum plaster, and the results show that the PCM can reduce the peak temperatures 1º C to 2 ºC, and also smooth out the daily temperature fluctuations. Heim and Clarke [32] evaluated the performance of a 12 mm PCM-impregnated gypsum board in a test room from March to July and no significant difference in the indoor air temperature were detected, the wall surface temperature was 0.5ºC to 1.0ºC lower than in the case with traditional gypsum board. Castell et al. and Cabeza et al. [33, 34] evaluated the use of macro-encapsulated organic PCM in bricks and micro-encapsulated organic PCM in concrete walls and reported a reduction of 2ºC to 3ºC in the peak indoor air temperature over two weeks in summer.

The addition of PCM to cement mortars results in energy savings up to 12 % and reductions in temperature fluctuations can be achieved with only 5 wt% of incorporation [10, 14, 18].

In the Mediterranean Countries the thermal behaviour of buildings is declining, due to the current trend of using large windows and of reducing the buildings weight and, consequently, their thermal inertia. In this region the selection of the type and amount of PCM to be used is a challenge due to the different characteristics needed to achieve an adequate behaviour of the buildings during winter and summer periods.

In this study the use of micro and macro-encapsulated PCM in buildings was studied to evaluate the annual behaviour and to identify the amount of PCM needed to ensure a suitable thermal and energy performance of the buildings in Porto region.

2. METHODOLOGY

In order to evaluate the potentialities of the use of PCM for Porto climate a series of simulations with two phase change materials were carried out.

2.1 Simulation Program

To identify the most adequate PCM and the amount needed to ensure a suitable thermal and energy performance of the buildings, in Porto region, simulation, using EnergyPlus 7.2, was performed [35]. EnergyPlus was used as the simulation tool for this study as it has the capability to simulate phase change material in the building envelope [5, 36].

Kuznik and Virgone [29], Zhuang et al. [37] and Tardieu et al. [38] compared the EnergyPlus simulation results and experimental data and reported the existence of a good agreement with the simulation results and the experimental data and shown that the algorithm incorporated into EnergyPlus can simulate the PCM in building constructions.

Shrestha et al. [39] study shown that EnergyPlus predicted fairly well the heat flux through the walls and roof as well as the temperature distribution in the walls, but gave unreasonable results for both heat flux and temperature distribution in the attic floor which is an inter-zone surface. The study refers that the thermal bridges might be the problem [39].

The CondFD and PCM algorithms in EnergyPlus were validated by Tabares-Velasco et al. [40]. The Tabares-Velasco et al. [40] study identified a few key limitations and guidelines when using the EnergyPlus PCM model: time steps less than 3 min should be used; accuracy issues can arise when modelling PCMs with strong hysteresis; the default CondFD node spacing values can be used with acceptable monthly and annual results. However, if sub-hourly performance and analysis is required, users should use node spacing values about one third of the default size (equal to using a Space Discretization Constant in EnergyPlus of about 0.3 – 0.5) [40].

2.2 Building Characteristics

For this study a simplified model, based on AHSRAE 140:2011 [41] Base Case 600, was used to identify the type and amount of PCM to be applied in buildings. The model was a simple 8 m long, 6 m wide, and 2.7 m high room structure without interior partitions (Figure 1). The building has two south windows with 6 m^2 each, shaded by an overhang [41]. This design was chosen to avoid excessive simulation run time and to perform the analysis under controlled conditions.

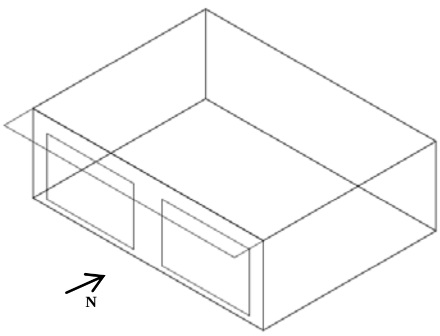

Figure 1 Simple model simulated.

To assess if the use of PCM is cost effective, a residential building was simulated. The building, with 91 m^2, has two bedrooms, two bathrooms and a living room with an open kitchen. The Window - Wall Ratio (WWR) of about 30% (15% of the floor area) was defined to optimize the daylight availability and the solar gains during winter and to minimize the unwanted solar gains during summer [42, 43]. The WWR is the percentage obtained by dividing the glazed area of the wall by the total wall area. The building has also a garage and a laundry. Figure 2 shows the building used for the study.

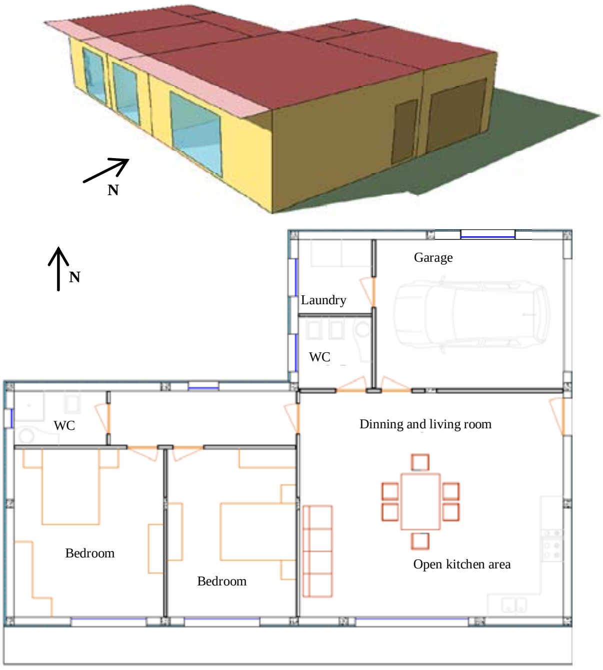

Figure 2 View and floor plan of the single family house simulated [44].

The building HVAC system is an ideal system with 100% convective air system and an efficiency of 100% with no duct losses and no capacity limitation. As, in Portugal the buildings are only acclimatized during occupied periods, the building mechanical system was set up to maintain the indoor temperatures at 20ºC in winter and at 25ºC, in summer, only during this period, that is between 6 pm and 8 am.

2.3 Construction Solutions

The most common Portuguese construction solutions were defined for the exterior walls: single concrete wall with 15 cm; and single hollow brick wall with 22 cm, both with ETICS (External Thermal Insulation Composite Systems) insulation; and a double hollow brick wall (15 cm + 11 cm bricks) with insulation placed inside the air gap. The insulation thickness was defined in order the U-value of the three walls be the same (0.46 W/m^2 ºC), leading to the use of 4 cm of XPS (Extruded Polystyrene Insulation) in the single hollow brick wall, 6 cm of XPS in the single concrete wall and 3 cm of XPS in the double hollow brick wall. As one of the PCM selected is incorporated in gypsum plasterboards all the walls have plasterboard as inner layers, as shown in Figure 3.

The partition walls of the single family house are lightweight, have two plasterboards and mineral wool (MW) or PCM placed in the air gap. The building has a concrete slab with 5 cm of XPS. The ceiling has 10 cm of XPS and, 20 cm concrete and a suspended ceiling with 1.3 cm gypsum plasterboards. The windows are double glazed, 0.6 cm + 0.6 cm +0.6 cm (glass + air gap + glass), have a metallic frame with thermal cut, a light colour curtain and exterior venetian blind.

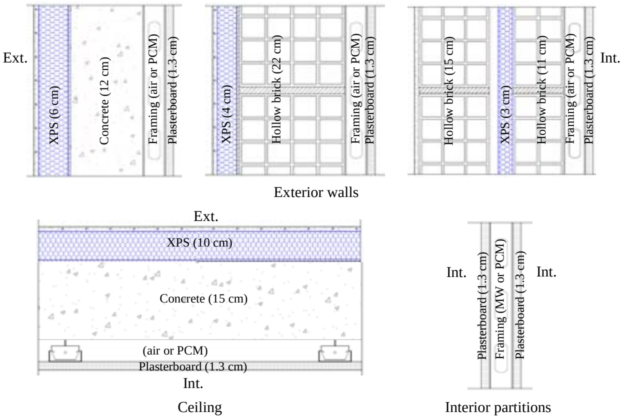

Figure 3 Composition of walls and roof.

2.4 Phase Change Materials

To perform the study gypsum plasterboards with micro-encapsulated PCM (paraffin, melting point: 23 - 26ºC; specific heat capacity: 1.2 kJ/kg K) and macro-encapsulated PCM (salt hydrate, melting point: 22°C - 28°C; specific heat capacity: 2.20 kJ/kg K) placed in the walls and ceiling were studied.

3. RESULTS AND DISCUSSION

The results showed that it is possible to improve the thermal conditions inside the buildings and reduce the temperature amplitude, both in the coolest and hottest day.

3.1 Simple Model

Figure 4 and Figure 5 present the data for the simple model with concrete walls without and with macro-encapsulated PCM. The use of PCM allows a 1.0ºC increase in the temperature in the coolest day and a 3.1ºC reduction in the temperature in the hottest day, when compared with a solution without PCM.

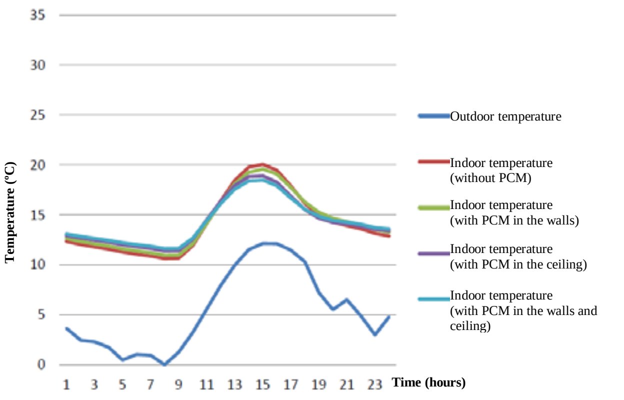

Figure 4 Temperatures for the coolest day – macro-encapsulated PCM and concrete walls.

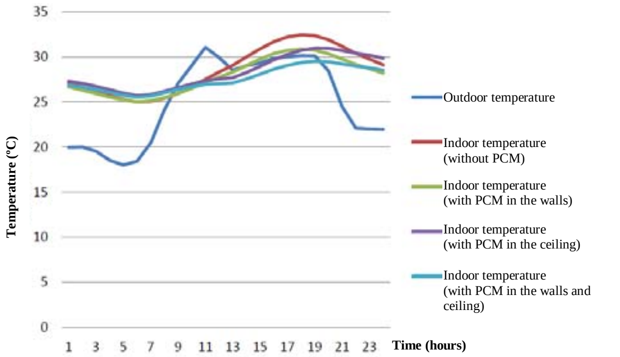

Figure 5 Temperatures for the hottest day – macro-encapsulated PCM and concrete walls.

For the simple model with single hollow brick walls the temperature in the coolest day increased 1.4ºC and in the hottest day the temperature was 4.1ºC lower when compared with the simple model without PCM. For the simple model with double brick walls the temperature is increased in 1.3ºC in the coolest day and decreased in 4.1ºC in the hottest day, when compared with a solution without PCM.

For the simple geometry with plasterboards with micro-encapsulated PCM, placed in the walls and ceiling, the temperatures differences are less than 0.5ºC for the three types of construction solutions for the walls, when compared with a solution without PCM (Figure 6 and Figure 7).

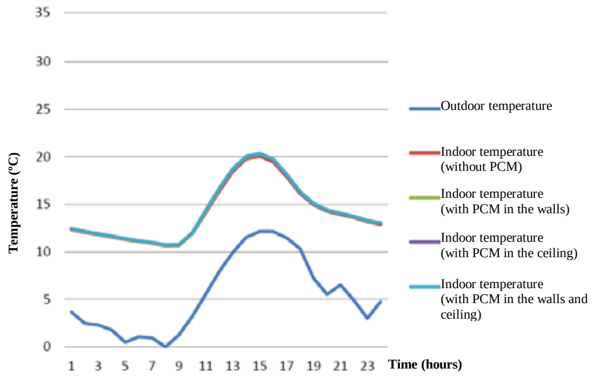

Figure 6 Temperatures for the coolest day – plasterboard with PCM and concrete walls.

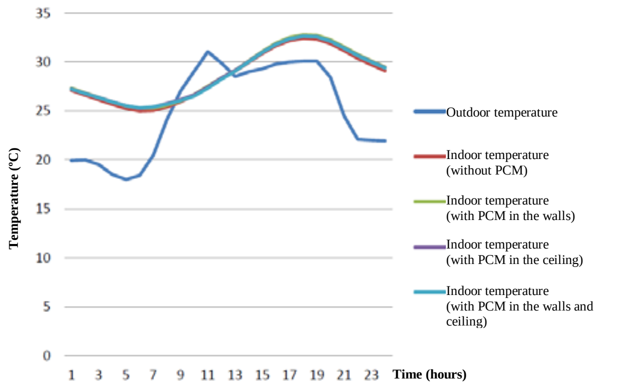

Figure 7 Temperatures for the hottest day – plasterboard with PCM and concrete walls.

The use of two layers of macro-encapsulated PCM allows a 5.2ºC reduction in the indoor temperature, in the hottest day, and

2.1ºC increase in the coolest day, when compared with a solution without PCM. The use of two plasterboards with micro-encapsulated PCM placed in the walls and ceiling leads to less than 1.0ºC differences in the temperatures, both for the coolest and hottest day. Thus, in these conditions the use of two layers of PCM is not advantageous.

The use of macro-encapsulated PCM is more beneficial than the use of micro-encapsulated PCM, due to the widest melting range, lower melting temperature and higher fusion enthalpy and also due to the greater amount of PCM used.

In the example studied the thermal comfort conditions (20ºC to 25ºC) are not reached in winter and summer. In winter it is necessary to use a heating system, but in summer, during the night, the occupation period, the thermal conditions are within the adaptive thermal comfort interval defined in ASHRAE 55:2010 standard [45] for naturally ventilated buildings. During summer the comfort conditions can be increased using night cooling and an adjustable shading system.

3.2 Single family house

As the use of macro-encapsulated PCM had better results it was selected to evaluate the performance of the single family house. As all the construction solutions had similar behaviour the single pane hollow brick walls were selected for the exterior walls construction solutions as they are less expensive.

Figure 8 and Figure 9 present the outdoor and indoor temperatures of the single family house with and without macro-encapsulated PCM placed in the façade walls and ceiling.

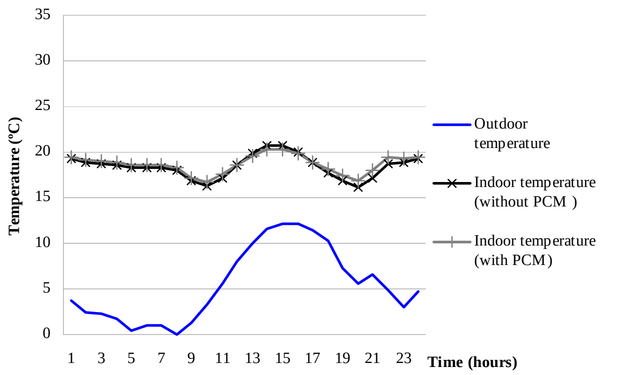

Figure 8 Temperatures for the coolest day – single family house.

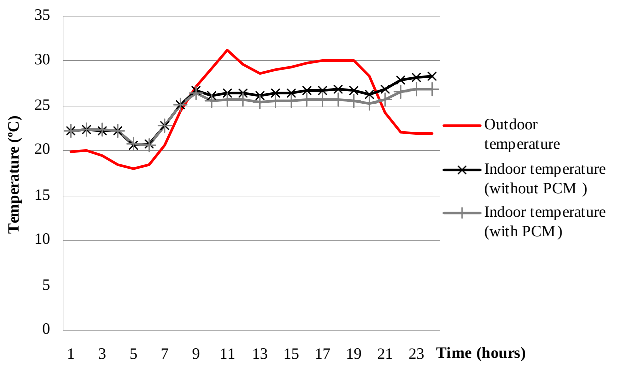

Figure 9 Temperatures for the hottest day – single family house.

The use of PCM allows a 0.7ºC increase in the temperature in the coolest day and a 1.4ºC reduction in the indoor temperature in the hottest day.

In the cooling period, the use of adjustable shading systems and night cooling allows that the thermal conditions fall within the adaptive thermal comfort interval defined in ASHRAE 55:2010 standard [45] for naturally ventilated buildings.

Since addition of PCM to the building envelope components can be expensive, a detailed study should be performed in order to determine whether it would be cost effective to use a PCM-enhanced construction solution on a specific wall, or ceiling.

The heating and cooling needs for the single family house are presented in Table 1, which depicts potential energy savings associated with addition of PCM on the exterior walls, interior walls and ceiling of the south facing rooms, for a single-story residential building located at Porto. It is noticeable that addition of PCM allows 16% reduction on the heating needs, 28% reduction on the cooling needs and 16% reduction in the annual energy needs.

Table 1 Heating and Cooling needs (kWh/m^2 year).

	Heating needs	Cooling needs	Annual needs
Without PCM	50.87	3.27	54.14
With PCM	42.95	2.34	45.29

The energy needs represent the thermal energy necessary, for heating and cooling, to maintain a given space at the comfort temperature. For this study, as previously referred, the building is only acclimatized during occupied periods (between 6 pm and 8 am) and the building mechanical system (with an efficiency of 100%) was set up to maintain the indoor temperatures at 20ºC in winter and at 25ºC, in summer.

The reduction in the energy needs allows annual savings of 113.13 € (considering a heating and cooling system with an efficiency of 100% and an energy cost of 0.1405€/kWh). As the installation cost of the PCM is of 18553.50€ (108.50€/m^2) it is not cost effective to use the PCM in the conditions defined.

4. CONCLUSIONS

An example of energy performance analysis based on results of whole-building energy simulations of a simplified geometry and of a 91 m^2 residential building located in Porto with and without PCM on exterior walls, internal walls and ceiling of the south facing rooms was presented.

Energy simulations were performed using EnergyPlus building energy simulation software. The results of the energy simulations of the simple geometry building showed that the plasterboard with micro-encapsulated paraffin was not effective as the amount of PCM was not enough to achieve an adequate behaviour leading to less than 0.5ºC differences for the indoor temperature, in the coolest and hottest day, for the three construction solutions analysed. The macro-encapsulated PCM solution presented a better behaviour both in the coldest (1.0ºC difference for the concrete wall, 1.4ºC and 1.3ºC difference for the single and double hollow brick walls, respectively) and hottest day (3.1ºC difference for the concrete wall and 4.1ºC difference for the hollow brick walls).

In the single family house the use of PCM allows a 0.7ºC increase in the temperature in the coolest day and a 1.4ºC reduction in the indoor temperature in the hottest day.

The results of the energy simulations of the single family house showed a 16% reduction in annual heating and cooling needs for the building with macro-encapsulated PCM-enhanced walls and ceiling relatively to a similar one without PCM, located in Porto. The use of the macro-encapsulated PCM, for the conditions defined, was not cost effective due to the high cost of the installation of PCM when compared with the annual energy savings. In these conditions, the payback time is greater than the PCM service life, thus the incorporation of PCMs in buildings is still an expensive technology.

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