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Characterization of innovative mortars with direct incorporation of phase change materials

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ABSTRACT

The utilization of innovative cement mortars with direct incorporation of non-encapsulated phase change materials (PCM) is a solution for minimize the high energetic consumption of buildings, due their ability in regulate the temperature inside the buildings. The development of construction material with PCM, based in macro and microencapsulation techniques has been developed. However, the utilization of these techniques has a high cost. The direct incorporation of non-encapsulated PCM allows the cost reduction, due to the absence of PCM encapsulation and complex incorporation techniques, representing an innovative and promising way to contribute significantly for the energy efficiency of buildings. Four different compositions were developed and characterized according to their physical, mechanical and thermal properties. The physical behaviour was evaluated based in some properties in the fresh and hardened state such as workability, density and water absorption. The mechanical performance was evaluated based in the flexural and compressive strengths. Finally, the developed mortars were thermally tested based in temperature laws representative of the north part of Portugal, with a resource to a climatic chamber and a data acquisition system. The obtained results showed a decrease in the water absorption due to the partial PCM occupation of the mortar pores. On the other hand, it was observed a slight decrease in the mechanical properties do to the presence of higher liquid binder ratio. Finally, regarding to the thermal tests it was verified a decrease in the extreme temperatures and cooling and heating needs. The mortar with 20% of PCM presented the higher impact in the interior temperature regulation.

1. Introduction

Currently, there are huge environmental, social and economic concerns associated to high energy consumption in residential sector. The construction sector has a huge contribution to global energy consumption and greenhouse gas emissions, all over the world, mostly for heating and cooling the residential buildings. It is expected until 2050, an increase in the cooling needs of 150% in the world and of 300 to 600% in developing countries [1].

Currently about 10% of families lives in energy poverty without possibilities or spend more than 10% of their monthly budget to guarantee comfort conditions inside their houses. This problem is related to the poor quality of the buildings, high energy prices and very low family incomes. In Portugal around 29% of the families live in this situation of energy poverty [2]. Thus it becomes imperative to intervene quickly. The fight against energy poverty has to counteract and try to eliminate its causes. In this sense, and with the inability to reverse the energy prices or the low incomes of families, the focus must be placed mainly on the improvement of the buildings thermal efficiency and utilization of renewable energy sources [2].

The phase change materials (PCM) have the capacity to control the temperature inside the buildings, through their ability to store and release energy to the environment. Its principle of operation is activated by the exterior temperature variation, which is directly influenced by the solar energy. This ability allows obtaining sensibly constant temperatures inside the buildings and decreases the climatization needs, improving the buildings energetic efficiency [3]. It is possible to use several techniques to incorporate PCM into construction materials [4], such as: encapsulation (microencapsulation and macroencapsulation) [5], shape-establization [6], direct incorporation [7] and absorption by immersion [8] or capillarity [9]. The greatest part of the recent researchers used the encapsulation technique in gypsum plaster boards [10–12], concrete, mortars [13–16], PVC panels, blocks and bricks [17–19].

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Shilei et al. [10] carried out a study with PCM embedded in gypsum boards with 9.5 mm of thickness and 26% of PCM, with a transition temperature between 17.9 °C and 20.3 °C. The investigation allowed verifying a lower temperature oscillation in the test cells with PCM incorporation. Darkwa et al. [11] studied the behaviour of two different gypsum plaster boards incorporating PCM. In one solution, a gypsum plaster board with 12 mm of thickness was impregnated with PCM. In other solution, a simple gypsum board with 10 mm of thickness was coated with 2 mm of laminated PCM, both cases with the same PCM content. It was concluded that the PCM laminated utilization is more efficient contributing to an increase in the minimum temperature.

The incorporation of PCM microcapsules in mortars has been a subject with major developments. Cunha et al. [14] evaluated the influence of adding PCM microcapsules in the main properties of the mortars, observing a decrease in the mechanical behaviour. The incorporation of different types of PCM microcapsules in mortars leads to different behaviours in the different properties of the mortars [15]. The incorporation of PCM in mortars has raised several issues related to its behaviour at high temperatures. Cunha et al. [16] studied the exposure of different mortars to 20 °C, 200 °C and 600 °C, in order to simulate an accidental fire in a building. The results allowed observing a decrease in the mechanical properties of the PCM mortars when submitted to high temperatures.

In some studies, the cost of the construction materials doped with PCM is very high, which makes impossible the practical application of the technology. The encapsulation technique present some disadvantages related with the cost of the PCM acquisition, materials production time, materials cost and adaptation of materials to the technique. Thus, it becomes urgent the study and development of functional construction materials based in simple techniques and economic raw materials, with high thermal performance, such as the non-encapsulated PCM. Although several studies have been performed with phase change materials, the utilization of direct incorporation technique still remains a subject undeveloped. The incorporation of non-encapsulated PCM added directly to the mortars, appears as an innovative and promising method to decrease the buildings energy dependence. This study is a continuation of the work previously developed by this research team [20]. It also should be noted that in this work cement mortars with incorporation of higher PCM contents (10% and 20%) were tested. Thus, the main aim of this study was to develop and characterize innovative cement mortars with direct incorporation of non-encapsulated PCM. Different tests were developed for different compositions (0%, 5%, 10% and 20% of PCM), evaluating their physical, mechanical and thermal properties.

2. Materials, compositions and methods

2.1. Materials

The choice of the materials used in this work took into account previous works developed by the authors about mortars with incorporation of phase change materials by different methods [13–16,20]. The formulation of developed mortars is based in different materials: Portland cement, fly ash (Table 1), aggregates (sand A and sand B), superplasticizer and non-encapsulated phase change materials. Table 2 presents the density of the different materials used.

The fly ash used was produced in the thermoelectric central of Pego in Portugal. The fly ash presents a loss on ignition category of A and a fineness category of N. The superplasticizer used was based in polyacrylate with 18% of solid residue.

Two different aggregates were used, sand A and B. The sand A has particles with a minimum dimension of 125 μm, maximum dimension of 500 μm and an average particle size of 439,9 μm. The sand B has particles with dimensions between 125 μm and 8000 μm and an average particle size of 762 μm.

Finally, the PCM used is non-encapsulated, composed by paraffin with a temperature transition between 20–23 °C and enthalpy of 200 kJ/kg. This material is commercialized by Rubitherm as RT 22 HC.

Table 1
Chemical composition of fly ash.

Chemical component	(%)
Silicon oxide (sio2)	49.12
Aluminum oxide (al2o3)	27.30
Iron Oxide (Fe2O3)	8.19
Calcium Oxide (CaO)	2.36
Magnesium Oxide (MgO)	1.42
Sulfates (SO3)	1.30
Potassium Oxide (K2O)	3.34
Sodium Oxide (Na2O)	0.99
Titanium Oxide (TiO2)	2.32
Ignition Loss	3.97

Table 2
Densities of the materials.

Material	Density [kg/m^3]
Cement CEM II B-L32.5N	3030
Fly Ash	2420
Superplasticizer	1050
Sand A	2600
Sand B	2569
PCM	760 (solid state)
	700 (liquid state)

2.2. Compositions

In this study four compositions were studied from the fresh state up to 28 days. A reference composition (0% PCM) and three compositions with incorporation of 5%, 10% and 20% of non-encapsulated PCM were developed (Table 3). The aggregate used in these mortars was constituted by 50% of sand A and 50% of sand B. The content of PCM is related to the aggregate mass. The binder was composed by 46% of cement and 54% of fly ash. The content of cement and fly ash is related to the binder mass. Some studies indicate that the incorporation of PCM and fly ash improves the thermal behaviour of the mortars doped with PCM [21].

2.3. Methods

In all the tests, the preparation and storage of the specimens were performed based in the European standard EN 1015–11 [22].

The developed mortars were characterized according to their physical, mechanical and thermal behaviour. The physical characterization was based in the workability [23], density, water absorption by capillarity [24] and immersion [25]. The mechanical behaviour was studied based in the flexural and compressive strengths [22]. The flexural tests were performed with load control, at a speed of 50 N/s and the compressive tests with a speed of 150 N/s.

Finally, the thermal behaviour was tested with resource to a climatic chamber with the aim to control the temperature laws representative of the seasons [20]. In this study, it was decided to simulate an extreme season with high temperatures (summer) and a

Table 3
Composition of the mortars (kg/m3).

Compositions	Cement	Fly Ash	Sand A	Sand B	SP	PCM	Water
CEM-0PCM	162	198	429.8	429.8	23.4	0	104.4
CEM-5PCM	162	198	400.3	400.3	22.3	18	104.4
CEM-10PCM	162	198	379.7	379.7	14.4	36	104.4
CEM-20PCM	162	198	331	331	3.6	72	104.4

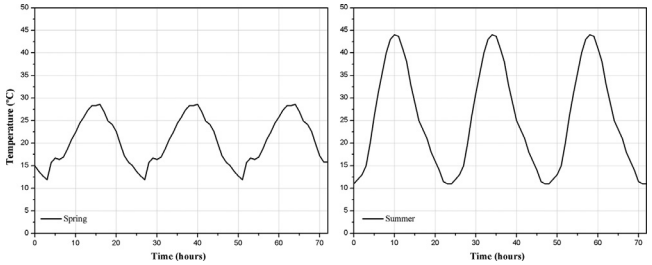


Fig. 1. Temperature law used to simulate the different seasons of the year.

season with intermediate temperatures (spring). The temperature laws used were obtained based in the climatic data collected at the weather station installed in the campus of the University of Minho in Portugal [20]. Thus, these tests were made for a specific type of clima, more specifically the summer and spring seasons of the north part of Guimarães, Portugal. The simulation of the summer season was performed with a temperature law between 11 °C and 44 °C. For the simulation of the spring season temperatures between 12 °C and 29 °C were used. For each season it was performed three cycles with duration of 24 h (Fig. 1).

A small-scale test cell with interior dimensions of 200 × 200 × 200 mm^3 was performed for each developed mortar. The small-scale test was made with an insulating material (extruded polystyrene) with 3 cm of thickness and coated on the inside with a mortar layer of 1 cm. One thermocouple was placed inside each cell. The small-scale test cells were placed inside a controlled climatic chamber provided with thermocouples for test temperature. The thermocouples used during the tests were type K and were connected to a data acquisition system (AGILENT 34970A), recording the temperature inside the climatic chamber and small-scale test cells at every minute. Fig. 2 shows the setup of the thermal tests.

3. Physical characterization

3.1. Workability

The workability tests were performed keeping the water-binder ratio constant at 0.29 and varying the superplasticizer content. The tests were developed in order to obtain the same workability, by flow table tests. The results were only considered valid when between 140 and 150 mm.

The mortar manufacturing process was carried out according to a previously established plan, keeping its constituents at a constant temperature between 22 °C and 25 °C. Initially, the liquid constituents of the mortar (water, superplasticizer and PCM) were mixed. Subsequently, the homogenized aggregates and binders were added. The mixing process was only completed with the mortar in a homogeneous state, usually after 2:30 min of mixture.

Fig. 3 shows the superplasticizer content and the liquid-binder ratio of the developed mortars. It was verified a reduction in the

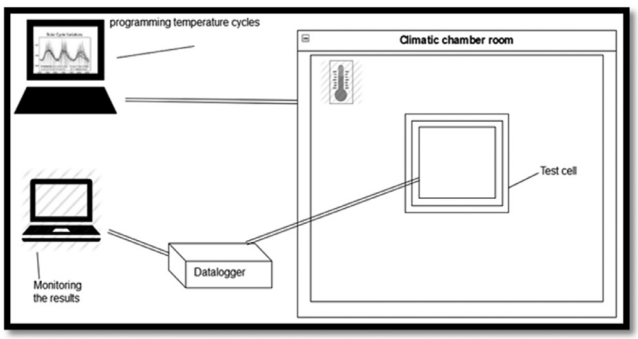


Fig. 2. Setup of the thermal tests, adapted from Kheradmand et al. [26].

superplasticizer content higher to 5% with the PCM incorporation. However, the incorporation of a higher PCM content leads to a higher liquid-binder ratio, the incorporation of 5% PCM led to an increase of about 17% in the liquid-binder ratio. This behaviour can be explained by the fact that the PCM is added in its liquid state. Thus, the PCM in the liquid form can work as an agent to improve the mortars workability, providing a higher flow table diameter.

3.2. Density

According to Fig. 4, it was observed that the incorporation of non-encapsulated PCM cause a slight increase in the density of the developed mortars. The incorporation of 5% of PCM leads to an increase of about 5% in the density. This behaviour is related with the fact of the PCM occupy part of the microstructure of the mortar and the low density of the material, compared to the other constituents (Table 2).

3.3. Water absorption by capillarity

According to Fig. 5 it was observed that the incorporation of non-encapsulated PCM leads to a reduction in the coefficient of water absorption by capillarity. The incorporation of 5% of PCM causes a diminution higher than 34%. This behaviour can be explained by the total or partial PCM occupation of the mortar pores [7,27]. On the other hand, the PCM presence also causes a barrier to the water evaporation. Thus, the mortars with higher PCM content exhibit lower water absorption coefficient by capillarity.

The developed mortars were categorized according to their water absorption by capillarity coefficient based in the Portuguese specification NP EN 998-1. It was observed a minimum classification of W2 (Table 4), which is very important especially for the PCM mortars, since it indicates that the mortar pores are saturated with non-encapsulated PCM.

Fig. 6 shows the mortars behaviour during 7 days of testing. It was verified that the mortars without PCM incorporation have a higher water absorption capacity, due to a larger amount of free pores in their matrix. As expected, it was also observed a smaller water absorption capacity related to the higher incorporation of PCM. This behaviour shows that the phase change material is contained within the mortar pores, limiting its absorption capacity. This also indicates that the PCM did not move from the matrix mortar after the application, making this technology very promising. Thus, the great advantage of this technology is associated to the exemption of any type of PCM encapsulation, reducing the mortars production costs.

3.4. Water absorption by immersion

Regarding to Fig. 7 it was observed a decrease in the water absorption by immersion with the incorporation of PCM. It is important note that the incorporation of 5% of non-encapsulated PCM leads to a decrease in the water absorption of 15%. The mortars with incorporation of 10% and 20% of PCM show the lower content of water absorption by immersion. Once again, this behaviour can be justified by the total or partial filling of the mortar pores by the PCM.

4. Mechanical characterization

The mechanical behaviour of the mortars was evaluated based in the flexural and compressive strengths. In Fig. 8 is possible to observe the flexural and compression results of the mortars. It was verified that the incorporation of a PCM content until 10% did not cause significant variations in the mechanical behaviour. However, it is important to note that the incorporation of 20% of PCM leads to a more expressive decrease in the mechanical behaviour, about 8% and 19% in the flexural and compressive strength, respectively. This behaviour is related to the presence of higher liquid binder ratio in the mortars doped with

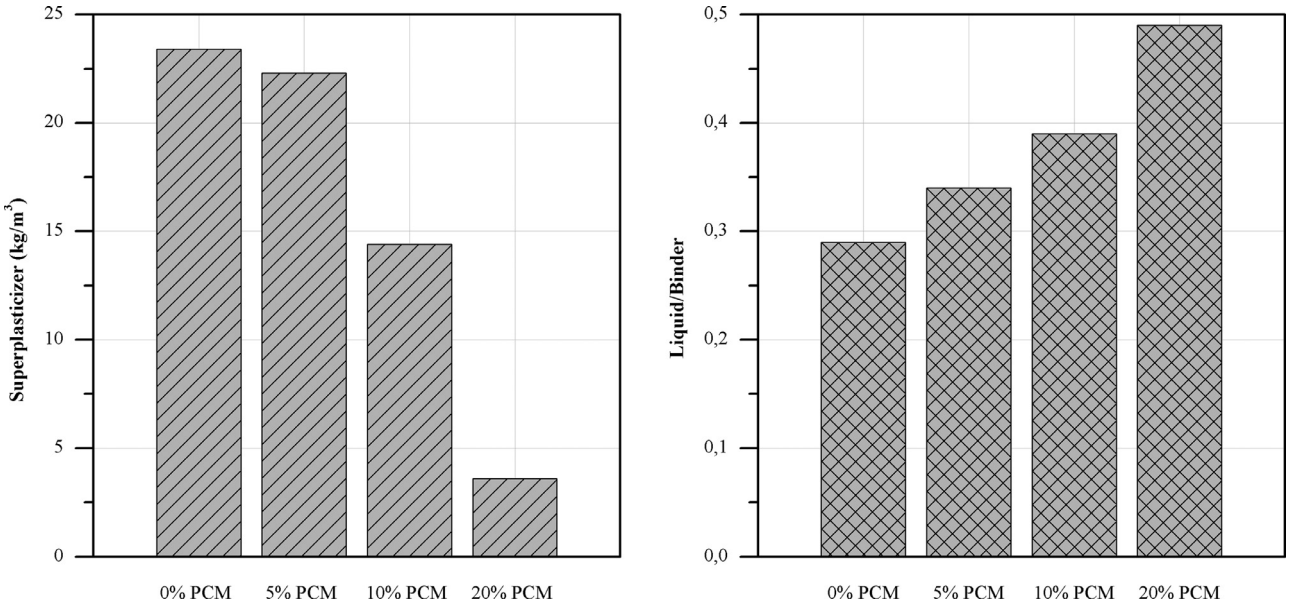


Fig. 3. Superplasticizer and liquid-binder ratio of the developed mortars.

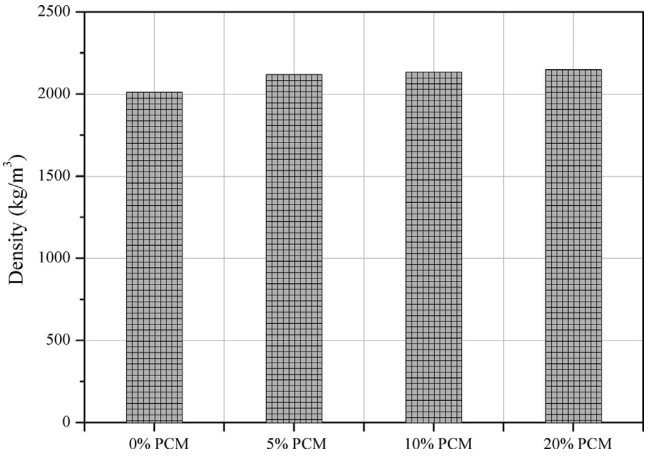


Fig. 4. Density of the developed mortars.

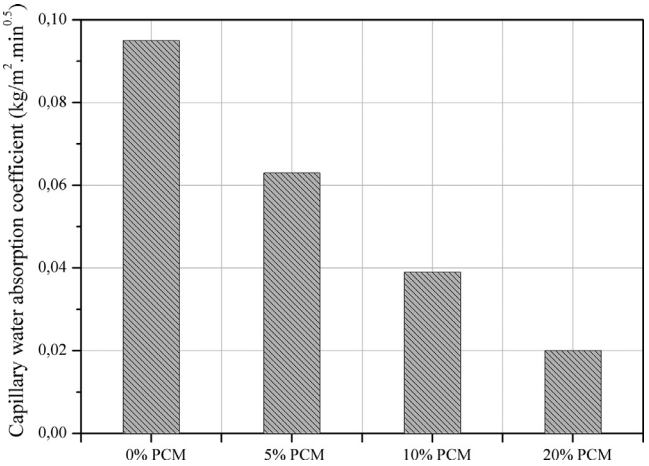


Fig. 5. Capillary water absorption coefficient of the developed mortars.

PCM (Fig. 3). On the other hand, the incorporation of a non-encapsulated PCM in the mortars production also affects the curing process, since a delay can exist in the cement hardening process [7,27]. Thus, it was also expected a more significant loss in mechanical

Table 4
Classification of mortars according to the water absorption by capillarity coefficient.

Composition	Water absorption by capillarity coefficient (kg/m2.min0.5)	Classification NP EN 998-1:2010
CEM-0PCM	0.095	W2
CEM-5PCM	0.063	W2
CEM-10PCM	0.039	W2
CEM-20PCM	0.02	W2

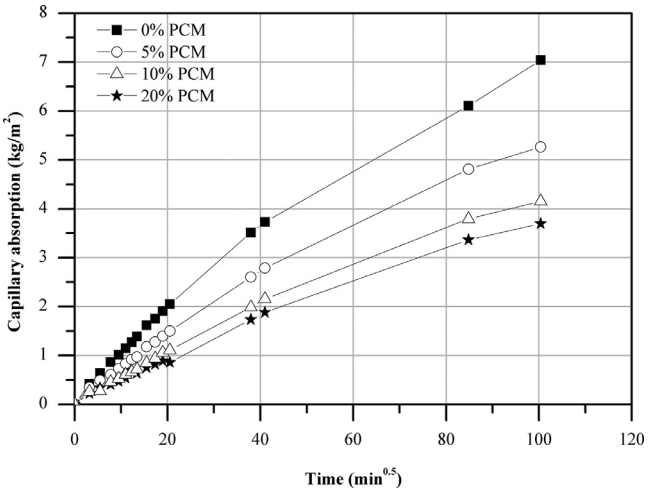


Fig. 6. Water absorption by capillarity of the developed mortars.

behaviour for mortars with higher PCM incorporation content, as verified in this study.

The mortars were classified according to specification NP EN 998-1, in order to evaluate their applicability [28]. The developed mortars did not present any structural function, however it was decided the development of cement mortars with a minimum classification of CSII. Thus, it will be possible to apply and use the interior lining mortar with a classification higher than the minimum classification allowed. According to Table 5, it was verified that all the studied mortars possess the standard maximum classification, CSIV. Thus, it was possible to

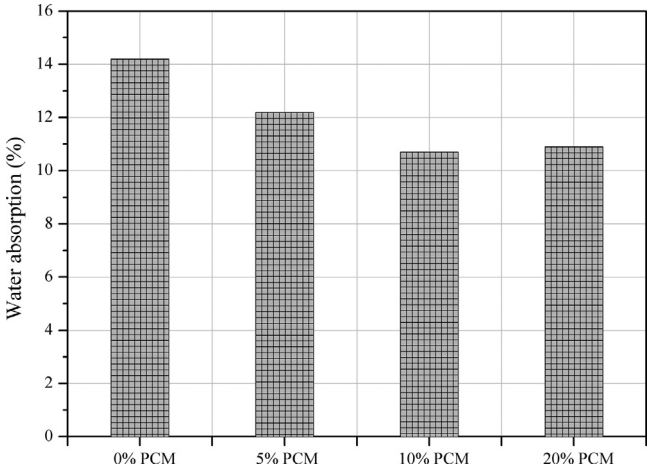


Fig. 7. Water absorption by immersion of the developed mortars.

develop several mortars with integration of non-encapsulated PCM with a good and appropriate mechanical behaviour.

5. Thermal characterization

In this study, it was defined a heating situation, when the temperatures are below 20 °C and cooling situation when the temperatures are higher than 25 °C. Thus, it was possible to determine when the mortars did not reach the comfort temperature range.

5.1. Summer

Fig. 9 shows the thermal behaviour of mortars with direct incorporation of PCM in a summer situation. It was perceived that the PCM mortars showed a lower maximum temperature and higher minimum temperature, reducing the cooling and heating needs. On the other hand, it was also possible to observe that all the mortars exhibit a similar behaviour when the temperature inside the test cells is near to the comfort temperature range. Thus, the storage and release energy effect is more expressive when the temperature inside the test cell diverges significantly to the comfort temperature range. The mortars with PCM incorporation have an improved thermal behaviour, evidenced by the lower extreme temperatures. It was also observed that the incorporation of a larger amount of PCM resulted in a better thermal behaviour, with a more significant decrease in the maximum temperature and an increase in the minimum temperatures, which translates into lower heating and cooling needs. As expected, the mortar with 20% of PCM incorporation presents a more interesting thermal behaviour, evidencing by the highest decrease in the extreme temperatures.

Table 5
Classification of the developed mortars according to the compressive strength.

Composition	Compressive strength (MPa)	Classification NP EN 998-1:2010
CEM-0PCM	18.5	CSIV
CEM-5PCM	17.8	CSIV
CEM-10PCM	17.6	CSIV
CEM-20PCM	14.9	CSIV

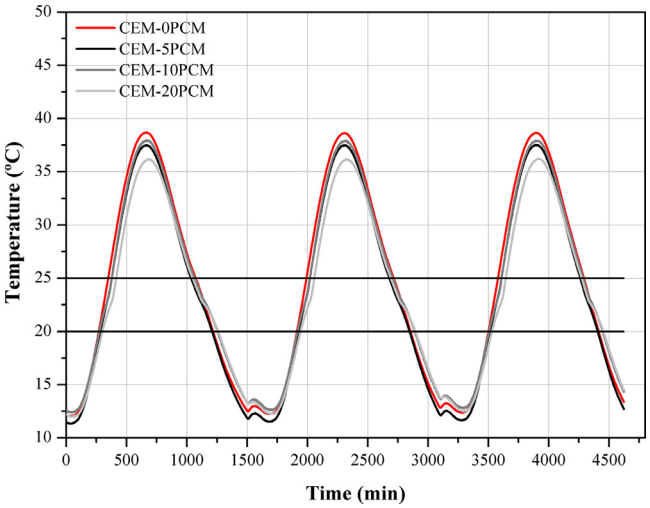


Fig. 9. Thermal behaviour of the developed mortars in summer situation.

Fig. 10 shows the extreme temperatures obtained during the thermal tests in the test cells for the different developed mortars. It was verified a decrease in the maximum temperature of 4% and an increase in the minimum temperature of 8%.

It was also detected a lag time delay between the extreme temperatures (maximum and minimum temperatures) of the reference mortars and PCM mortars (Table 6). The incorporation of 5% of non-

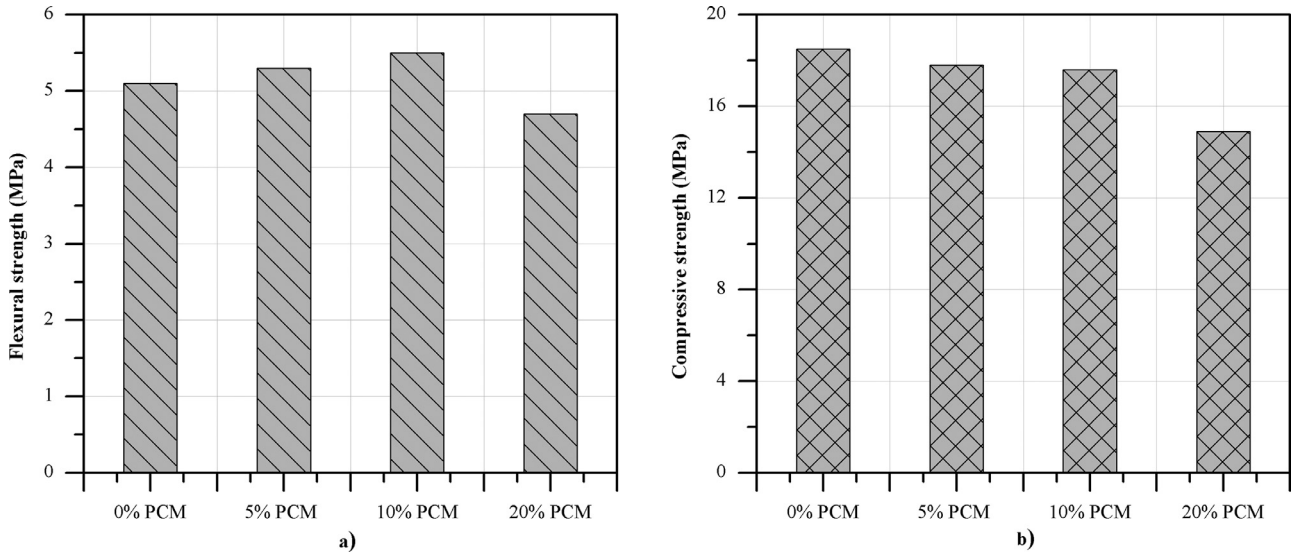


Fig. 8. Mechanical strengths of the mortars: a) Flexural behaviour; b) Compressive behaviour.

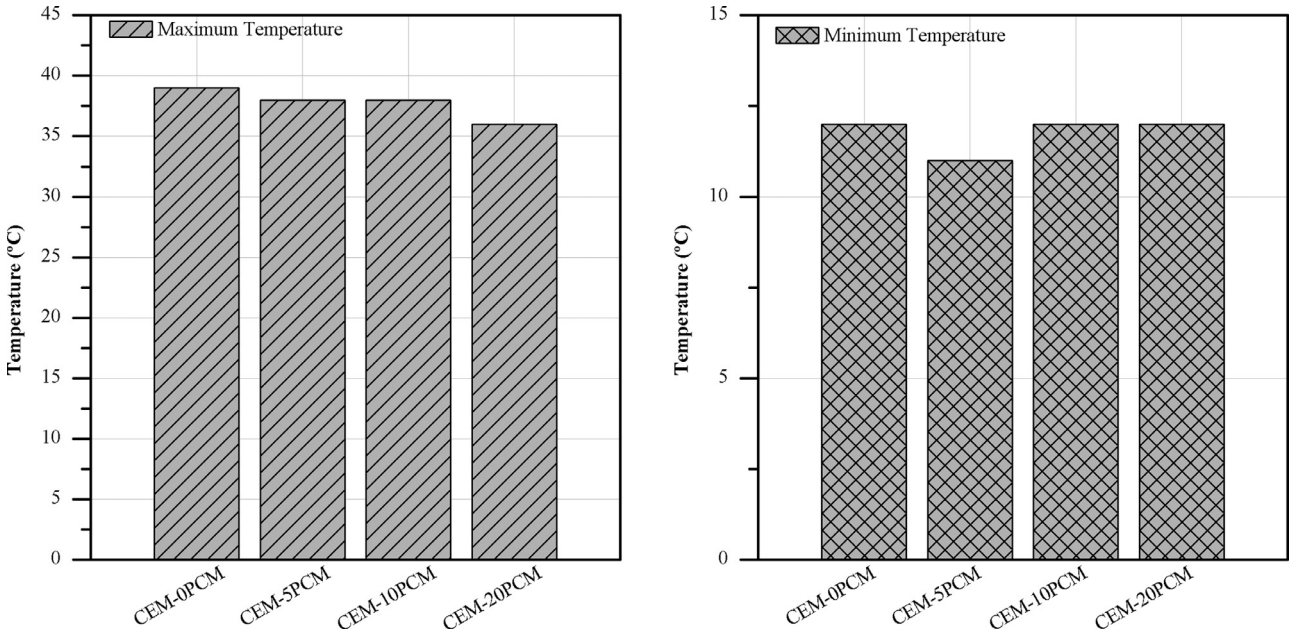


Fig. 10. Maximum and minimum temperatures in summer season.

Table 6
Lag time delay between the extreme temperatures in summer season.

Composition	Lag time delay (min)	
Maximum temperature	Minimum temperature	
CEM-0PCM	0	0
CEM-5PCM	28	0
CEM-10PCM	29	19
CEM-20PCM	48	23

encapsulated PCM resulted in a lag time delay of 28 min for the maximum temperature. The highest values of lag time delay were observed for the mortar with maximum content of PCM (20% of PCM), corresponding to 48 min for the maximum temperature and 23 min for the minimum temperature. It is known that the cost of energy is different in the various periods of the day, especially between day and night, thus this shift to off-peak period leads to a clear economical advantage for the building users, decreasing the energy invoice.

The analysis of the thermal curves presented in Fig. 11 does not deliver sufficient information about the mortars energy performance,

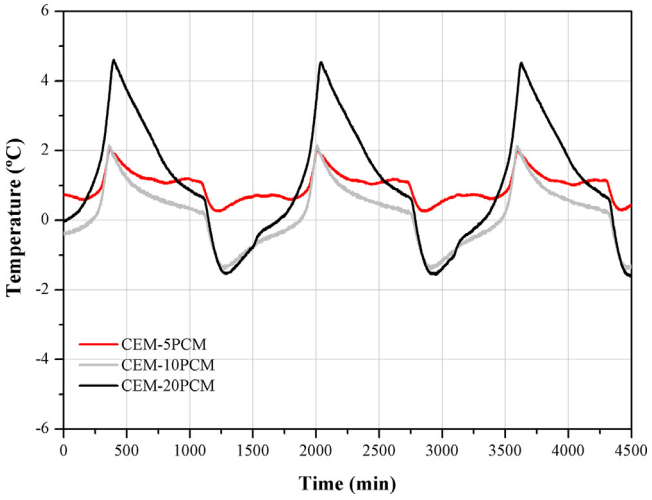


Fig. 11. Thermal gradient of the developed mortars in summer situation.

thus it was determined the thermal gradient, based in Eq. (1). The thermal gradient is the temperature differences in each cell relative to the cell without PCM.

$$\Delta T = T_{REF} - T_{PCM} \quad (1)$$

Where:

T_{REF} - Temperature in the reference test cell (mortar without PCM) (°C);

T_{PCM} - Temperature in the PCM cell (mortars with PCM incorporation) (°C).

Regarding to Fig. 11, it was possible to observe that the incorporation of non-encapsulated PCM leads to a regulation in the interior temperature of buildings. It was also possible note that the presence of higher PCM content leads to an increase in the thermal gradient. The mortar doped with 20% of PCM presents a more advantageous thermal behaviour, due to the higher difference between the extreme temperatures of about 5 °C in the maximum temperature and 2 °C in the minimum temperature when compared with the reference mortar (0% PCM).

In order to obtain more information about the thermal behaviour the cooling and heating needs were calculated based in Eq. (2). Thus, the amount of energy exceeding the temperature comfort range during one day was determined. The amount of energy exceeding 25 °C is associated with the cooling needs. On the other hand, the amount of energy lower than 20 °C is relative to the heating needs.

$$N = \frac{\rho_{cv} \int_{t_0}^{t_i} T(t)dt}{\Delta t} \quad (2)$$

Where:

N - Cooling or heating needs (J/m^3);

ρcv - Volumetric capacity of the air (J/m^{3}K);

t_0 - Initial time (min);

t_i - Final time (min);

$T(t)$ - Representative function of the temperature curve (K.h);

Δt – Time (h).

Table 7 shows the climatization needs for the different mortars. It was observed that even though there was a decrease in the extreme temperatures and in the climatization needs (Fig. 11). The incorporation of 10% of free PCM causes a decrease of about 6% in the heating needs and 13% in the cooling needs.

Table 7
Climatization needs in summer situation for comfort temperature (20 °C to 25 °C) (J/m3).

Composition	Heating needs	Cooling needs
CEM-0PCM	252,750	268,997
CEM-5PCM	252,212	254,209
CEM-10PCM	248,173	243,394
CEM-20PCM	237,824	234,111

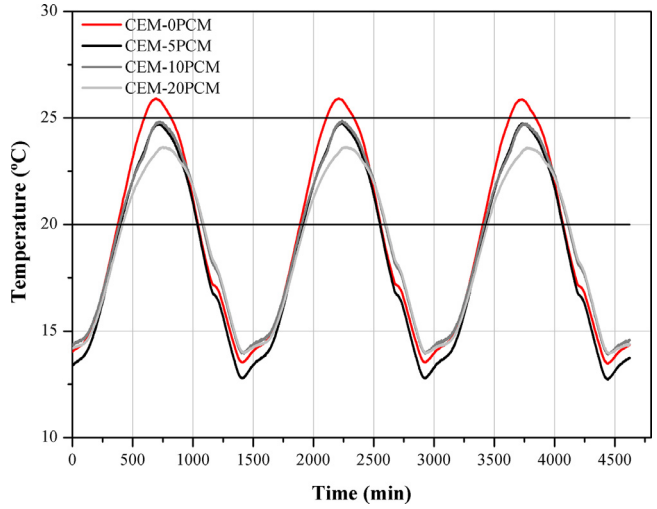


Fig. 12. Thermal behaviour of the developed mortars in spring situation.

5.2. Spring

Regarding to the spring season, once again it was verified that the addition of non-encapsulated PCM in mortars results to an improvement in the thermal behaviour, compared to the mortars without PCM (Fig. 12). The same behaviour presented for the summer season was verified. However, in this season, it was possible to observe a higher PCM influence in the cooling situation. It was not found a PCM mortar with temperature curve inside the cells superior to 25 °C, which consequently eliminates the cooling needs. However, regarding to the heating situation, it was also observed an increase in the minimum temperature. It should also be noted that the effect of the thermal

Table 8
Lag time delay between the maximum and minimum temperatures in spring season.

Composition	Lag time delay (min)	
Maximum temperature	Minimum temperature	
CEM-0PCM	0	0
CEM-5PCM	11	6
CEM-10PCM	25	29
CEM-20PCM	59	37

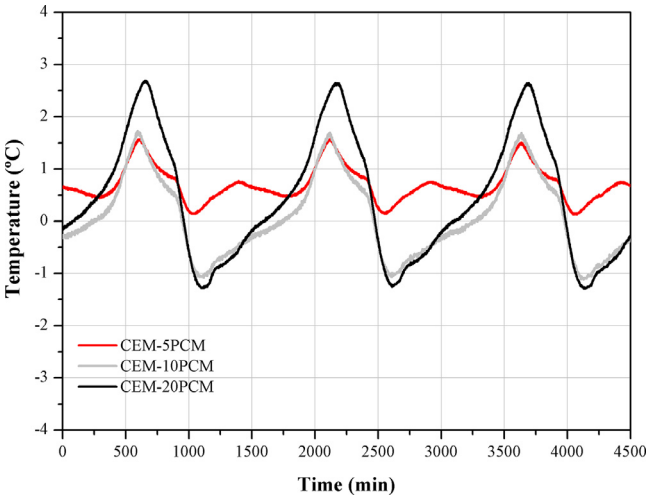


Fig. 14. Thermal gradient of the developed mortars in spring situation.

Table 9
Climatization needs in spring situation for comfort temperature (20 °C to 25 °C) (J/m3).

Composition	Heating needs	Cooling needs
CEM-0PCM	253,932	262,369
CEM-5PCM	253,466	0
CEM-10PCM	252,341	0
CEM-20PCM	244,571	0

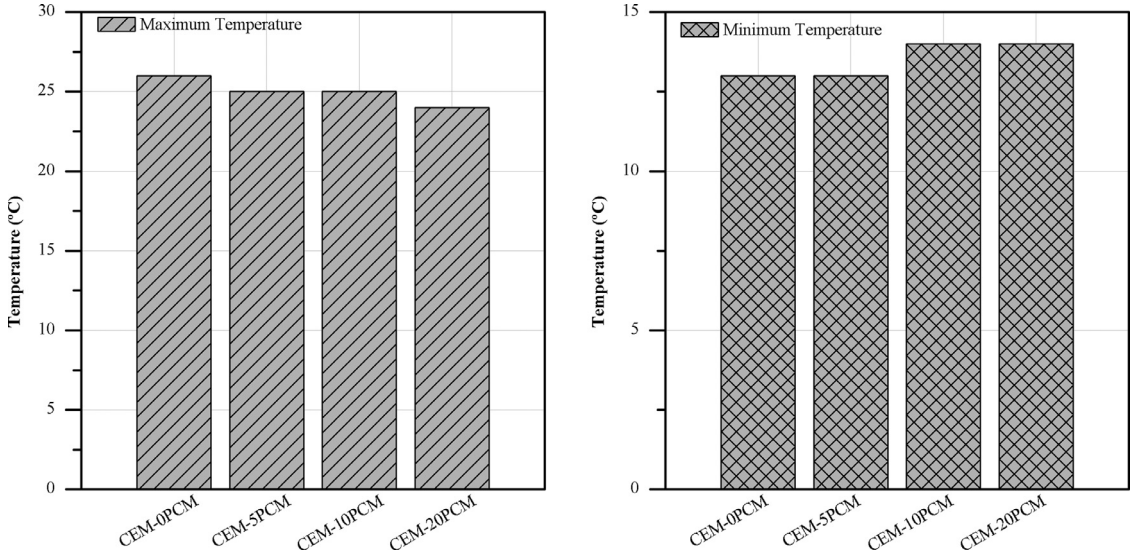


Fig. 13. Maximum and minimum temperatures in spring season.

Table 10
Daily and monthly climatization needs (J/m3).

Composition	Summer Daily climatization needs	Summer Monthly climatization needs	Spring Daily climatization needs	Spring Monthly climatization needs
CEM-0PCM	521,747	15,652,410	516,301	15,489,030
CEM-5PCM	506,421	15,192,630	253,466	7,603,980
CEM-10PCM	491,567	14,747,010	252,341	7,570,230
CEM-20PCM	471,935	14,158,050	244,571	7,337,130

Table 11
Montly climatization needs (KWh/m3).

Composition	Summer	Spring
CEM-0PCM	4.35	4.30
CEM-5PCM	4.22	2.11
CEM-10PCM	4.10	2.10
CEM-20PCM	3.93	2.04

regulation is more evident in mortars with higher content of PCM. Thus, the mortar with 20% incorporation of non-encapsulated PCM presents the best thermal behaviour.

With respect to the extreme temperatures (Fig. 13), it was verified a decrease in the maximum temperature of about 5% and an increase in the minimum temperature of about 3%, with the addition of 5% of non-encapsulated PCM.

As previously mentioned, there was also a time lag delay between the maximum and minimum temperatures recorded for reference mortars (0% PCM) and for the mortars with PCM incorporation (Table 8). The incorporation of 5% of non-encapsulated PCM resulted in a lag time delay of 11 min for the maximum temperature and 6 min for the minimum temperature. The mortar with 20% of PCM incorporation revealed a more evident lag time delay, about 59 min for the maximum temperature and 37 min for the minimum temperature.

Fig. 14 shows the thermal gradient of the PCM mortars. Once again it was verified a regulation in the interior temperature of buildings due to the PCM presence. It was also observed that the mortar with addition of 20% of PCM shows a temperature difference of about 3 °C in the heating situation and around 1.5 °C in the cooling situation when compared with the reference mortar (0% PCM), showing the higher potential for temperature regulation.

The climatization needs were also determined (Table 9). It was observed that the incorporation of non-encapsulated PCM leads to the cooling needs elimination. Concerning to the heating needs, it was verified a decrease of about 5% due to the incorporation of 20% of PCM. Thus, it was possible to determine a decrease in the climatization needs of 51%, due to the incorporation of 5% of non-encapsulated PCM (Tables 10,11).

In all the tests, it was possible verify that in the PCM test cells the extreme temperatures are lower compared to the reference cell. On the other hand, the internal temperature remains stable for a longer period of time. Thus, it was possible to predict a lower necessity of heating and cooling equipment, due to the decrease of climatization needs. The PCM incorporation in mortars shows to be effective in energy saving. The mortars with non-encapsulated PCM incorporation showed a higher heating or cooling rate, an lower maximum temperature and a higher minimum temperature.

6. Conclusion

This study shows that it is possible to incorporate non-encapsulated phase change material in cement and fly ash mortars for interior coating.

About workability it was observed that the incorporation of non-encapsulated PCM causes an increase in the liquid-binder ratio, since the incorporation of PCM was performed in its liquid state.

It was identified a reduction in the water absorption (capillarity and immersion) due to the PCM incorporation. This behaviour is related to the total or partial pores occupation with PCM.

Concerning to the mechanical behaviour (flexural and compressive strengths) of the mortars, it can be concluded that the incorporation of 5% and 10% of PCM did not cause significant changes. However, the incorporation of a higher PCM content causes a higher reduction in the mechanical strengths. This behaviour is related to the presence of a higher liquid content in the mortars, due to the fact that the PCM is incorporated in the liquid state. This performance can also be justified by the PCM occupation in the mortar pores. On the other hand, the mortars presented a high resistance class, taking into account their compressive behaviour, which indicates the existence of good conditions for their applicability and functionality.

About the thermal behaviour, it was verified a decrease of the extreme temperatures and a significant lag time delay with the incorporation of non-encapsulated PCM. The incorporation of a high PCM content leads to a better thermal performance. Thus, it can be verified that the mortar with 20% of PCM incorporation presented the highest thermal performance, with mechanical behaviour compatible with the application as interior mortars in buildings, revealing the more interesting performance. It was also observed a decrease in the climatization needs in the summer season and a more expressive decrease in the spring season, since the cooling needs were eliminated and the cost of climatization decrease about 50%, compared to the reference mortar.

Based in this study it can be concluded that the incorporation of non-encapsulated phase change materials in mortars for interior coating can be seen as a viable and economical solution to improve the energy efficiency of the buildings.

7. Author statement

All authors may have contributed in multiple tasks.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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