

MORTARS WITH INCORPORATION OF PCM BASED IN DIFFERENT BINDERS: MECHANICAL AND THERMAL BEHAVIOR

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Abstract: *Currently we are witnessing a huge concern of society with the parameters of comfort of the buildings and the energetic consumptions. It is known that there is a huge consumption of non-renewable sources of energy. Thus, it is urgent to develop and explore ways to take advantage of renewable sources of energy by improving the energy efficiency of buildings. The mortars with incorporation of phase change materials (PCM) have the ability to regulate the temperature inside buildings, contributing to the thermal comfort and reduction of the use of heating and cooling equipment, using only the energy supplied by the sun. However, the incorporation of phase change materials in mortars modifies its characteristics. The main purpose of this study was mechanical and thermal characterization of mortars with incorporation of PCM in mortars based in different binders. The binders studied were aerial lime, hydraulic lime, gypsum and cement. For each type of binder a reference composition (0% PCM) and a composition with incorporation of 40% of PCM were developed. It was possible to observe that the incorporation of PCM in mortars caused differences in properties such as workability, compressive strength, flexural strength and adhesion, however leads to an improvement of thermal behavior.*

1 Introduction

The energy is an essential factor for economic and social development and for improvement of the quality of life in all countries. It is known that every year the energy powered by the sun that reaches the entire land surface is about 10 000 times higher than the actual energy consumption per year worldwide. Thus, the need to find a way to take advantage of this natural energy source is pressing [1].

The European building sector is responsible for about 40% of the energy consumption [2]. The high growth rate of urban areas and the increase of comfort parameters are the principal reasons responsible for the increase in energy consumption. Thus, presently the concerns related to the energy consumption of buildings are greater than ever, because the energy and environmental security are the major problems in global economy.

It is known that the largest part of the energy consumption in construction industry, specifically in residential sector is associated with the needs for heating and cooling. This problem is related with the excessive use of energy from nonrenewable sources, which cause serious environmental impacts. Therefore, it becomes imperative to obtain a constructive solution that minimizes these consumptions, improving the energetic efficiency of buildings without damaging the environment. In attempt to reach a solution for this problem, it is important define and develop strategies for displacement the consumption from peaks, or hours of greatest demand, to off-peak hours.

The incorporation of Phase Change Materials (PCM) in mortars for the interior appears as a possible solution in an attempt to solve, or at least minimize, the massive energetic consumption related with buildings. The use of this material allows the regulation of temperature inside buildings through latent heat thermal energy storage, using only solar energy as a resource. Thus, the development of new construction materials with incorporation of this material, with the aim to improve the comfort level of the buildings, especially with regard to thermal comfort is urgent.

The phase change materials possess the capability to alter its own state as function of the environmental temperature [3]. In other words, when the surrounding environmental temperature of PCM increases until the materials fusion point, the material suffers a change from a solid state to a liquid state, absorbing and storing the heat energy from the environment. On the other hand, when the temperature decreases until the PCM solidification point, the material alters from the liquid state to solid state, releasing the previously stored energy to the environment. This application could be made in coating mortars of buildings, with advantage in the passive regulation of internal temperature with increase of thermal inertia [4].

The study of mortars with incorporation of PCM has been a target of study and interest for the scientific community. However, the characterization and comparison of different properties of thermal mortars based in different binders is one of the main knowledge gaps. Thus, the main objective of this work was the study of the thermal and mechanical behavior of mortars with incorporation of phase change materials, based on different binders: aerial lime, hydraulic lime, gypsum and cement. Tests were performed with 12 different compositions, evaluating some properties in the fresh and hardened state, such as workability, water absorption by capillarity, water absorption by immersion, flexural strength, compression strength, adhesion, microstructure and thermal behavior.

2 Experimental program

2.1 Materials

The selection of the materials took into account previous works [5-7]. Mortars for interior coatings, based on aerial lime, hydraulic lime, gypsum and cement, were developed in order to understand the influence of adding PCM. The aerial lime used has a purity of 90% and density of 2450 kg/m³. The gypsum used is a traditional one, with high fineness and density of 2740 kg/m³. The hydraulic lime was a natural lime (NHL5) with density of 2550 kg/m³. Cement CEM II B-L 32.5N were also used with density of 3030 kg/m³.

The PCM used is composed of a wall in melamine-formaldehyde and a core in paraffin, with temperature transition of about 22.5 °C, enthalpy of 147.9 kJ/kg and a density of 880 kg/m³. The process of fabrication is polycondensation by addition. This material exhibits a transition temperature of 24 °C in the heating cycle and 21 °C in the cooling cycle.

The fibers used are synthetic fibers of polyamide, with a length of 6 mm, with 22.3 µm of thickness and a density of 1380 kg/m³. The superplasticizer used was a polyacrylate, with a density of 1050 kg/m³. Finally, the sand used has an average particle size of 439.9 µm and a density of 2600 kg/m³. Based in granulometric distribution the parameters D10, D50 and D90 were obtained. The D10 corresponds to 0.15 mm, the D50 corresponds to 0.31 mm and the D90 correspond to 0.48 mm.

The dimensions of PCM microcapsules were evaluated by granulometry tests, using a laser particle size analyzer. It was possible to observe a particle size distribution between 5.8 to 339 µm, with 80% of particle size between 10.4 to 55.2 µm and an average particle size of the 44 µm.

2.2 Compositions

For this study twelve compositions were developed taking account the future application of the mortar for interior coating. These compositions were evaluated from the fresh state up to 28 days.

The PCM content was fixed in 0% and 40% of total mass of sand, for mortars based in different binders. In order to overcome some of the problems related with the mortar shrinkage and consequent cracking, polyamide fibers were incorporated. The content of PCM, fibers and superplasticizer was based in previous works [5-7]. The studied compositions are presented in Table 1.

Table 1: Mortars formulation (kg/m³).

Composition	Binder		Sand	PCM	Superplasticizer	Fibers	Water/Binder
AL500-0PCM	Aerial Lime	500	1447.2	0	15	0	0.45
AL800-40PCM	Aerial Lime	800	451.2	180.5	24	0	0.34
AL800-40PCM-F	Aerial Lime	800	425.2	170.1	24	8	0.36
HL500-0PCM	Hydraulic lime	500	1351.1	0	15	0	0.54
HL500-40PCM	Hydraulic lime	500	571.6	228.6	15	0	0.62
HL500-40PCM-F	Hydraulic lime	500	567.2	226.9	15	5	0.62
C500-0PCM	CEM II B-L 32.5R	500	1418.8	0	15	0	0.55
C500-40PCM	CEM II B-L 32.5R	500	644.3	257.7	15	0	0.56
C500-40PCM-F	CEM II B-L 32.5R	500	622.2	248.8	15	5	0.59
G500-0PCM	Gypsum	500	1360.4	0	15	0	0.56
G500-40PCM	Gypsum	500	540.1	216.0	15	0	0.70
G500-40PCM-F	Gypsum	500	535.8	214.3	15	5	0.70

2.3 Test procedures

The workability tests were performed based on the flow table method stated by the European standard EN 1015-3 [8]. The resulting value within the test was only considered when between 200-220 mm.

The water absorption by capillarity tests were performed based on the European standard EN 1015-18 [9]. The samples were obtained by cutting the prismatic specimens with dimensions of 40×40×160 mm³, previously subjected to flexural tests. After their preparation all the specimens were stored during 7 days in polyethylene bags and subsequently placed in the laboratory at regular room temperature (about 22°C) during 21 days. For each composition, 3 specimens were prepared, resulting in 6 samples after flexural tests. The quantification of absorbed water was performed by conducting successive weightings of the specimens. These weight measurements were made according to a previously established weighting plan, beginning with the first contact of the specimens with water.

The water absorption by immersion tests were based in the specification LNEC E 394 [10]. The samples were obtained by cutting the prismatic specimens with dimensions of 40×40×160 mm³, previously subjected to flexural tests. After their preparation all the specimens were stored during 7 days in polyethylene bags and subsequently placed in the laboratory at regular room temperature (about 22°C) during 21 days. Initially the specimens were dried in oven until the constant mass. Subsequently, they were saturated with resource to a container with water at a temperature of 20±3°C. Finally, after saturation it was determined the hydrostatic mass.

The flexural and compressive behavior was determined based in the standard EN 1015-11 [11]. For each composition, 3 prismatic specimens with 40×40×160 mm³ were prepared. After their preparation all the specimens were stored during 7 days in polyethylene bags and subsequently placed in the laboratory at regular room temperature (about 22°C) during 21 days. The flexural tests were performed with load control at a speed of 50 N/s. Compressive tests were realized through the application of a load on the specimen with resource to a metallic piece, rigid enough to make the vertical load uniform. The specimens used for the test were the half parts resulting from the flexural test. The compressive tests were performed with load control at a speed of 150 N/s.

The thermal behavior was tested in a climatic chamber, with a law of temperatures representative of the season to be analyzed. For each composition a small-scale test cell made with an insulating material (extruded polystyrene) with 3 cm of thickness were developed. These cells have a dimension of 200 mm × 200 mm × 200 mm. The cells were coated on the inside with a mortar layer of 1 cm. The thermocouples were placed inside for temperature measurement and were connected to a data acquisition system. During these tests the PCM reached the phase transition (between 21 and 24 °C) storing and releasing the energy from the environment. The aim was to measure the impact of incorporation of PCM in the interior temperatures.

3 Test results and Discussion

3.1 Workability

The workability tests were performed with the main goal of verifying the adequacy of application of the developed mortars. According to Figure1, it was possible to verify an increase in water/binder ratio with the incorporation of PCM microcapsules. The incorporation of 40% of PCM microcapsules causes an increase in the amount of water of about 15% for hydraulic lime based mortars, 25% for gypsum based mortars and 5% for cement based mortars. This can be explained by the reduced particle dimension of the used PCM. However, the incorporation 40% of PCM in aerial lime based

mortars led to a decrease in the quantity of water added to the mixture. This behaviour is related to the presence of higher dosage of binder and consequently higher quantity of superplasticizer, because it was necessary to increase the content of binder to obtain an adequate mechanical classification. For the used range of fibers fraction, the incorporation of this material in the mortars with PCM did not cause significant changes in the amount of water added to the mortar.

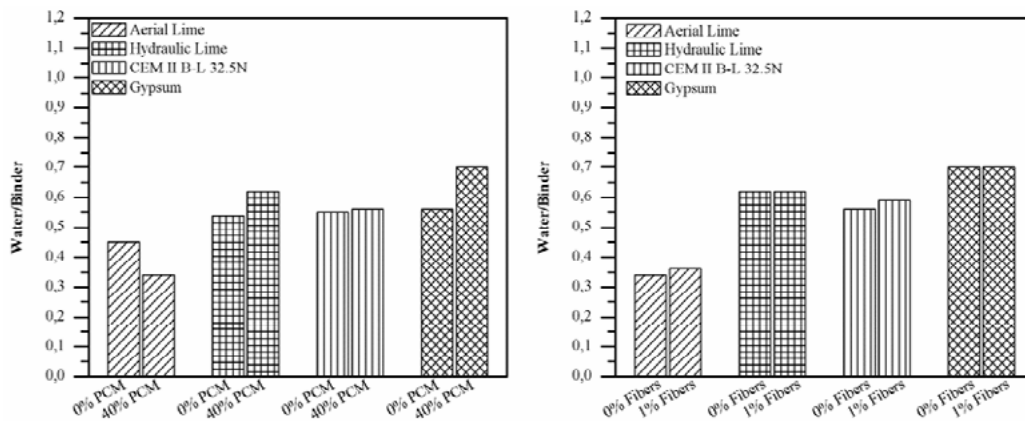


Figure 1: Water/binder ratio of developed mortars: a) Variation with PCM content; b) Variation with fibers content

3.2 Flexural and compressive behavior

According to the results, it was possible to observe a decrease in the flexural and compressive strengths caused by the introduction of PCM microcapsules in mortars. This behaviour can be justified by the increase of the water/binder ratio due to the introduction of a higher content of PCM which caused higher porosity in mortars. Concerning the flexural strength (Figure 2), the incorporation of 40% of PCM microcapsules resulted in a decrease superior to 35%, with exception of aerial lime based mortars which increase 64%.

Regarding the compressive strength (Figure 3), all tested mortars showed also a significant decrease with the incorporation of PCM. The incorporation of 40% of PCM microcapsules revealed a decrease in the compressive strength at least 19% when compared to the reference mortar, justified by the presence of higher content of water. The incorporation of 1% of polyamide fibers did not conduct to significant variations in the compressive and flexural strengths.

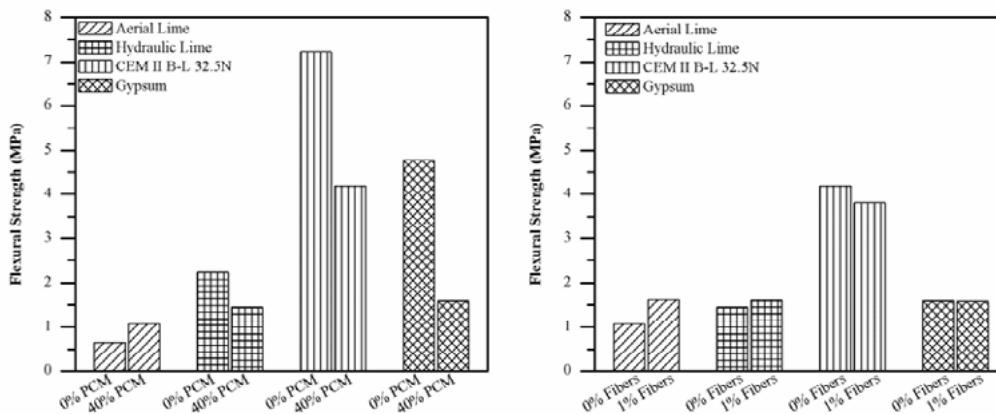


Figure 2: Flexural strength of developed mortars: a) Variation with PCM content; b) Variation with fibers content.

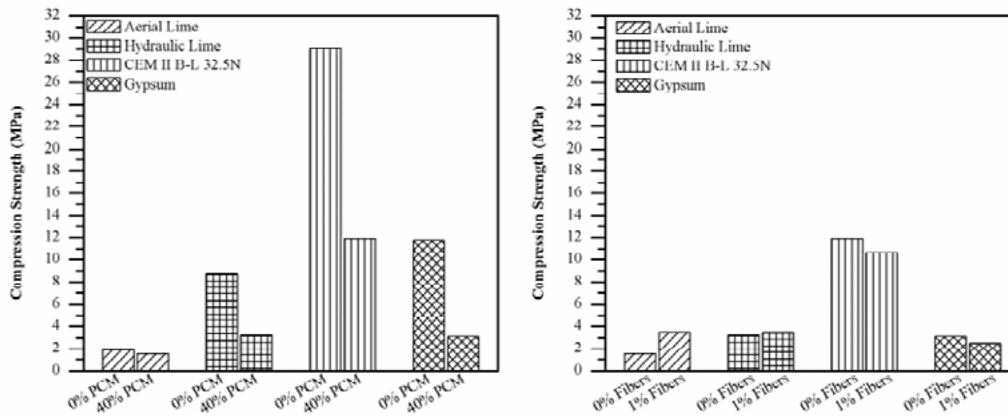


Figure 3: Compression strength of developed mortars: a) Variation with PCM content; b) Variation with fibers content.

3.3 Water absorption

The water absorption of mortars was evaluated based in the water absorption by capillarity and water absorption by immersion.

The water absorption by capillarity coefficient is related with the velocity of water absorption and the dimensions of pores. Thus, higher coefficients reveal the existence of a larger amount of pores with small size and consequently an increase in water absorption velocity. Regarding to Figure 4 it was possible to verify that the incorporation of 40% of PCM caused a decrease in the capillary absorption coefficient of 15% in hydraulic lime based mortars and 33% in the cement based mortars. On the other hand, it was also possible to observe an increase in capillary absorption coefficient of 9% for aerial lime based mortars and 17% for gypsum based mortars.

The incorporation of 1% of polyamide fibers had the main objective of reduce the shrinkage in the developed mortars. Their presence in mortars caused a decrease in the capillary absorption coefficient of 13% in the gypsum based mortars and 63% in the cement based mortars. The lime based mortars presented a slight decrease in the capillary absorption coefficient with the incorporation of fibers. This situation can be explained by the ability of fibers to reduce porosity of the mortars, reducing the effect of the presence of a higher ratio water/binder.

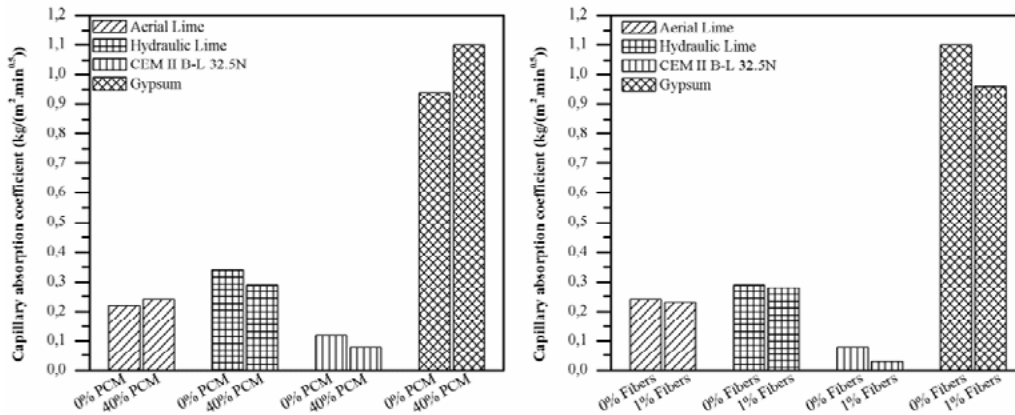


Figure 4: Capillary absorption coefficient: a) Variation with PCM content, b) Variation with fibers content.

Figure 5 shows the behavior of the studied mortars during the 9 days of testing. According with the results of the coefficient of water absorption by capillarity, it was possible to observe once again that the gypsum based mortars have a faster saturation process presenting all specimens saturated after 150 minutes in contact with water and the higher values of water absorbed. The cement based mortars and the aerial lime based mortars showed a slower velocity of saturation and the lowest values of water absorbed. Thus, it is possible to conclude that the gypsum based mortars presented higher content of pores with small dimensions.

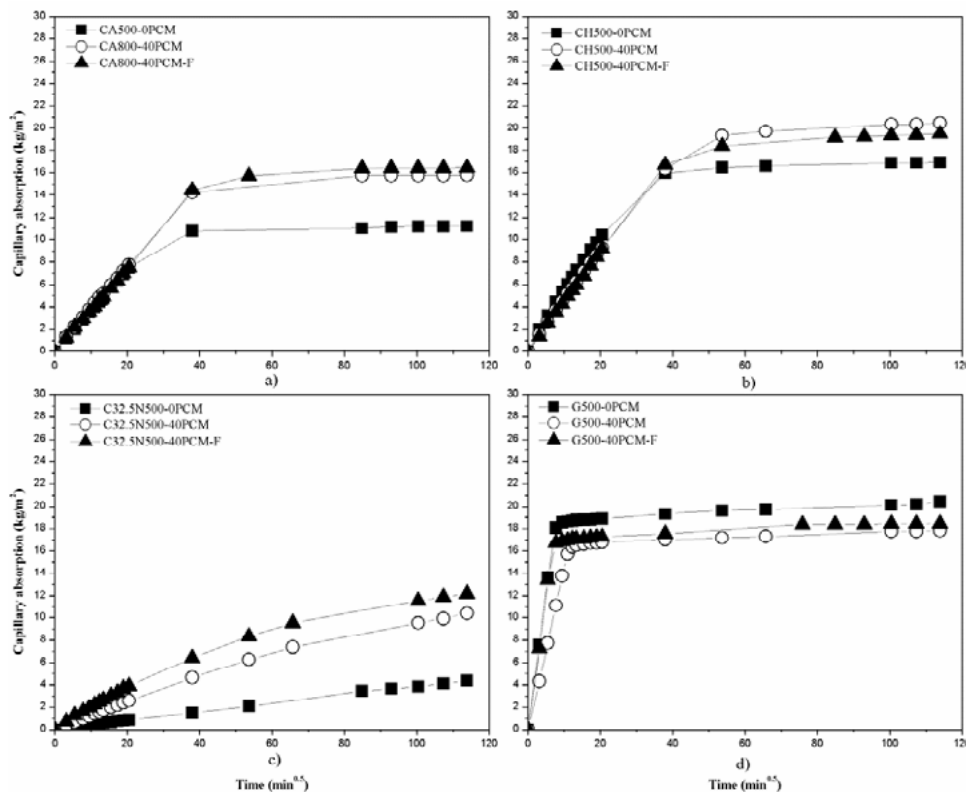


Figure 5. Water absorption by capillarity: a) Aerial lime based mortars, b) Hydraulic lime based mortars, c) Cement based mortars, d) Gypsum based mortars.

The water absorption by immersion is related to the presence of pores with higher dimensions in

mortars. According to Figure 6, it was possible to observe that the incorporation of 40% of PCM microcapsules in mortars caused an increase in water absorption greater than 14%. However, the incorporation of 1% polyamide fibers resulted in a decrease of water absorption greater than 8%, with the exception of hydraulic lime based mortars, which value did not suffer any change. It was also possible to identify that the gypsum based mortars and hydraulic lime based mortars presented the higher water absorption values. On the other hand, the cement based mortars showed lower water absorption. These results are connected with the flexural and compressive behavior, because the increase in the porosity leads to a decrease in the mechanical properties.

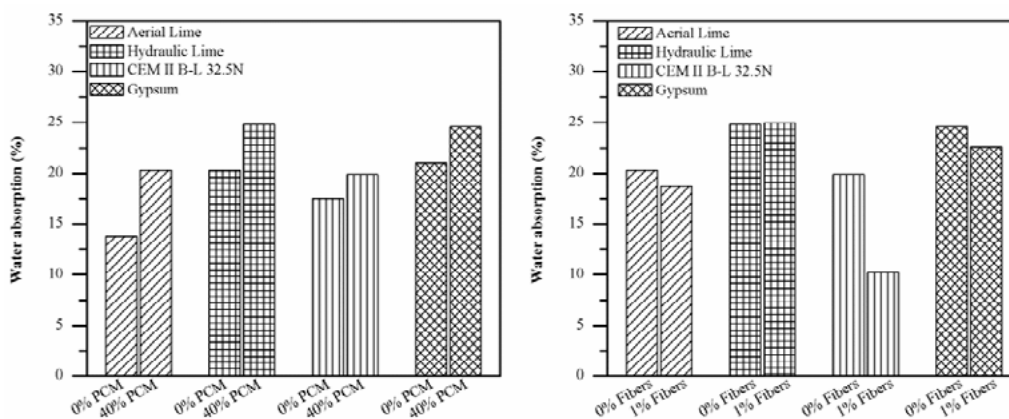


Figure 6: Water absorption by immersion: a) Variation with PCM content, b) Variation with fibers content.

3.4 Thermal behavior

It is known that the external temperature influence significantly the behavior of the PCM, since that this material has a great influence in areas where winter and summer are more rigorous [12-14]. Thus, based on weather data, a campaign of tests was conducted with the aim of evaluate the thermal behavior of mortars with incorporation of PCM in Portugal. The weather data was obtained with resource to a meteorological station installed in the University of Minho in Guimarães, Portugal.

During these tests the different seasons of the year were evaluated, however the study of the extreme situations is the most interesting for the study of the PCM behavior. For the spring situation the range of temperature analyzed was between 12°C and 29°C. In the autumn the temperatures considered were between 17°C and 34°C. To simulate the winter the law of temperatures presented a minimum of 5°C and a maximum of 22°C. In this situation the observation of the effect of PCM was not possible, since the melting point of the material was not achieved. In order to study this situation it would be necessary the use of a heating system. Thus, in this study the thermal behavior of PCM in a summer situation was evaluated, since the range of temperature was wider. Figure 7 shows the temperature law used to simulate a typical summer day. In this analysis the minimum temperature reached was 11 °C and the maximum temperature was 44 °C. To simulate the summer 3 cycles were performed and each cycle was composed by 24 hours.

According to Figure 8 it was possible observe the behavior of different mortars in a summer situation. For each binder a composition without PCM and a composition with 40% of PCM were tested.

For all compositions it was possible to observe that when the temperature achieves the temperature

range between 20°C and 25°C, the phase change of the PCM occurs and the thermal behavior of the PCM mortar begins to evolve in a different way from the temperature curve of the reference mortars. For the cooling situation, ie when the temperature exceeds 25 °C, the mortars with PCM showed a higher cooling rate and lower maximum temperature. The same was verified for the heating stage, ie when the temperature is lower than 20 °C, being possible to verify an increase in the minimum temperature for the mortars with PCM, evidencing a reduced need for heating. When the temperature lies near the indoor thermal comfort zone, the cells exhibit similar temperature values. The effect of heat storage and heat release is detected only when the temperature diverges from the thermal comfort zone.

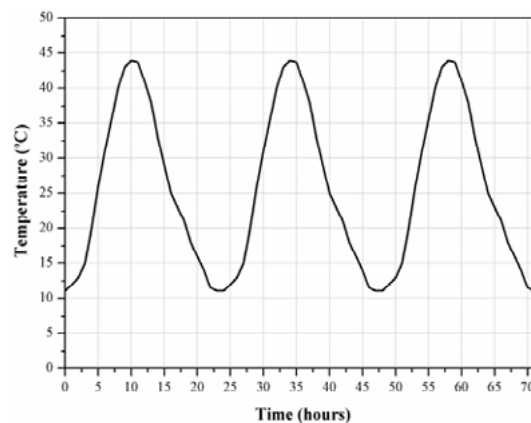


Figure 7: Law of temperatures for summer simulation.

The reference cell has always the highest and the lowest temperature. Thus, it was possible to verify the beneficial effect of the incorporation of PCM in mortars for interior coating.

It is important to note that in all tested compositions it was possible verify the positive effect of the PCM. Since cells with PCM did not reach such extreme temperatures as the reference test cell (0% PCM), the temperature inside remains stable for a longer period. It was possible observe a decrease of maximum temperature superior to 5% in the cooling situation and an increase in the minimum temperature superior to 14% in the heating situation. This mean a shortest operation time of HVAC systems when the composite materials with PCM are used and effective energy saving can be achieved.

The gypsum based mortars exhibits the best thermal performance, reducing the maximum temperatures during the cooling situation in 8% and increasing the minimum temperatures during the heating situation in 23%, when compared to the composition without PCM (Figure 9). However in all compositions it was possible observe an increase in the minimum temperature and a decrease in the maximum temperature.

During these tests it was also observed a lag time of maximum and minimum temperatures higher than 30 minutes during the cooling situation and higher than 60 minutes during the heating situation (Table 2). It is know, that the major part of residential buildings electricity consumption is used for space heating and cooling, varying greatly during day and night and leading to differentiate tariffs. Thus, the shift to off-peak periods of this consumption presents a clear economical advantage.

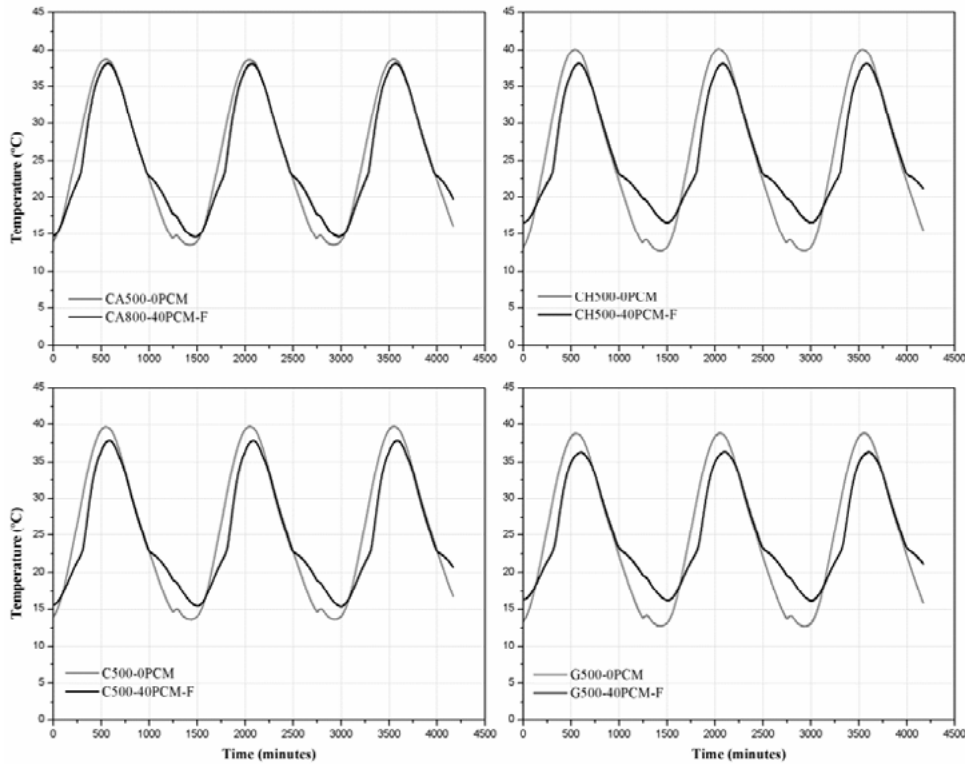


Figure 8: Thermal behavior in summer of developed mortars: a) Aerial lime based mortars, b) Hydraulic lime based mortars, c) Cement based mortars, d) Gypsum based mortars.

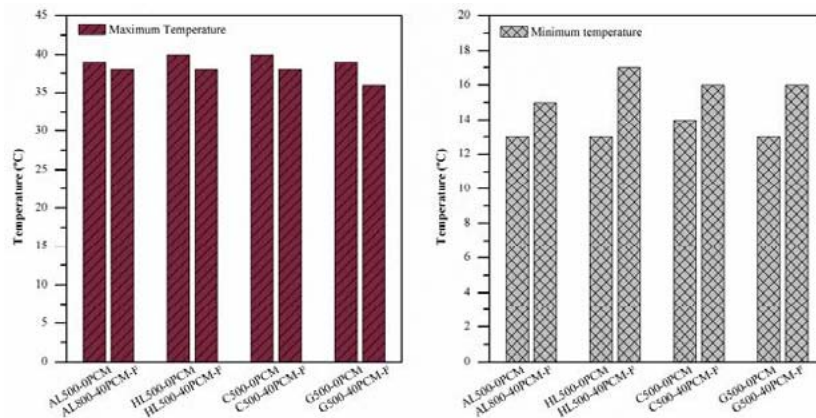


Figure 9: Maximum and minimum temperature achieved with the different mortars.

Table 2: Lag time between maximum and minimum temperatures with developed mortars.

Binder	Lag time (minutes)	
	Cooling situation	Heating situation
Aerial Lime	30	60
Hydraulic Lime	60	70
CEM II B-L 32.5R	40	80
Gypsum	55	85

4 Conclusion

This study allowed a comparison of the mechanical and thermal behavior of mortars with incorporation of PCM based in different binders. Based on the obtained results, it can be concluded that the addition of PCM in mortars caused significant changes in their properties in fresh and hardened state.

Regarding workability, it was verified that the incorporation of PCM caused an increase in the amount of water added to the mortar in order to give a suitable workability. This increase in the ratio water/binder is related to the fineness characteristics of PCM, requiring more water to obtain a homogeneous mortar. On the other hand, the incorporation of PCM microcapsules in mortars caused an increase in water absorption, revealing a higher porosity of these mortars. The study of mechanical strengths showed a decrease with the incorporation of PCM, which is a consequence of the higher porosity.

According to the thermal behavior, the use of mortars with incorporation of PCM proved to be an efficient strategy to develop sustainable buildings, due to the reduction of extreme temperatures and the time delay of the peaks. Thus, it is possible reduce the energy demand, the fossil fuel depletion and the environmental impact associated with the heating and cooling systems.

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6 References

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