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INFLUENCE OF INCORPORATION PHASE CHANGE MATERIALS, PCM, GRANULATES ON WORKABILITY, MECHANICAL STRENGHT AND AESTHETICAL APPEARANCE OF LIME AND GYPSUM MORTARS

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Abstract

In a society with a high growth rate of comfort, the need to minimize the currently high energy consumption by taking advantage of renewable energy sources arises. The mortars with incorporation of phase change materials (PCM) have the ability to regulate the temperature inside buildings, contributing for an increase in thermal comfort levels and a reduction of the use of heating, ventilation and air conditioning (HVAC) equipment, using only the energy supplied by the sun. Therefore, the application of phase change materials (PCM) comes as a possible solution in an attempt to solve, or at least minimize, the massive energetic consumption related to buildings. This research intends to understand the influence of microcapsules of phase change materials on mortars. The mortars studied in this work are mixed mortars of lime and gypsum. The proportion of PCM is 0%, 10%, 20% and 30%. In order to minimize some problems associated with cracking of the mortars, the incorporation of nylon fibers and superplasticizer was tested. A study of mechanical characteristics and some sensitivity tests to qualify the cracking of the fifteen compositions were carried out. It can be concluded that the use of PCM microcapsules in mixed mortars of lime and gypsum can be seen as a viable solution for applications in the construction industry once they present a compromise between their strength and aesthetic appearance.

Streszczenie

W społeczeństwie o wysokiej stopie wzrostu komfortu, powstaje potrzeba zminimalizownia wysokiego zużycia energii poprzez wykorzystanie źródeł odnawialnych. Zaprawy z zawartością materiałów zmieniających fazę (PCM) posiadają zdolność do regulowania temperatury wewnątrz budynków, przyczyniając się do zwiększenia poziomu komfortu cieplnego i zmniejszenia wykorzystania ogrzewania, wentylacji i klimatyzacji (HVAC), wykorzystując tylko energię słoneczną. W związku z tym, stosowanie materiałów zmieniających fazę (PCM) może zmniejszać zapotrzebowanie energetyczne budynków. Przedstawione badania miały na celu zrozumienie wpływu mikrokapsułek na przemiany fazowe w zaprawach. Badane zaprawy składały się z wapna i gipsu. Proporcja PCM wynosiła 0%, 10%, 20% i 30% . W celu zminimalizowania niektórych problemów związanych z pękaniem zapraw, wprowadzenie włókna nylonowych i superplastyfikatory. Badanie właściwości mechanicznych i wrażliwości na pękanie przeprowadzono na piętnastu zaprawach. Badania wykazaly, że korzystanie z mikrokapsułek PCM w zaprawach z wapna i gipsu może być realnym rozwiązaniem dla zastosowań w budownictwie.

Keywords: **Phase Change Materials; Lime Mortars; Gypsum Mortars; Workability; Cracking; Mechanical Strength.**

1. INTRODUCTION

Presently, it is possible to verify an increase regarding the concerns related to environmental and living conditions quality. In fact, a huge concern related to the high energy consumption in buildings and the associated negative impacts on the environment have emerged. Thus, there is an urgent need to study and develop new constructive solutions to minimize this problem. The largest part of the energy consumption in the residential sector is associated with heating and cooling needs. Therefore, it becomes imperative to obtain a constructive solution which minimizes these consumptions, improving the level of comfort inside buildings, without damaging the environment. Furthermore, it is important to consider constructive solutions with renewable energy resources providing an improvement in the quality of the buildings, especially in the comfort level of the occupants. The incorporation of phase change materials (PCM) in mortars for the internal coating appears as a possible solution in an attempt to solve, or at least minimize, the massive energetic consumption related to buildings.

Latent heat storage, through the incorporation of PCM, has the following advantages: narrow the gap between the peak and off-peak loads, levelling the energetic demand, decreasing the load in the network and preventing eventual supply failure; reduces operation costs by shifting the energy consumption from peak periods to off-peak periods; contributes to the interior thermal comfort in buildings, by using and storing solar energy (for space heating in the winter) and storing natural cooling by ventilation at night during the summer, thus reducing energy use for heating and cooling [1-3]. The benefit to the interior thermal comfort of buildings is materialized by the change occurring in the PCM. The transferences of energy that occur during the solid-liquid and liquid-solid transitions are generally used to help in the temperature control of the building [2, 4].

It is known that all materials interact with the environment. However, most of them lack the capability to alter their own properties according to the environment characteristics in which they are applied. Phase change materials possess the capability to alter its own state as function of the environmental temperature. 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, with 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.

For the correct use, the PCM must be encapsulated, otherwise during the liquid phase there is a risk of leakage from the point where it was applied. In this context, there are two main encapsulation types: the microencapsulation and the macro encapsulation.

The macro encapsulation is based on the introduction of PCM into tubes, panels or other large containers. It is usually done using recipients with a diameter larger than 1cm. PCM microencapsulation consists on the placement of small particles with lower molecular weight, coated with high performance polymers. The microcapsules can be spherical or asymmetric and with a variable shape and a diameter of less than 1cm. The advantage of this encapsulation process, comparing with the macro encapsulation, is the improvement of the heat transfer through its greater surface [5, 6].

The incorporation of PCM microcapsules in mortars brings social, economic and environmental benefits. The social benefits derive from the thermal comfort increase inside housings, knowing that nowadays this is a requirement of greater importance and frequently used by sellers and potential buyers as an important decision parameter. The environmental aspect concerns the fossil fuels depletion, assuming that this technology aims at maintaining constant temperatures inside the building, consequently leading to a decrease of air conditioning equipment usage. The economic benefit is noted to the technology adequacy and implementation costs. Therefore, it is intended that the costs associated with its application can be easily supported and amortized by the user. It can also be referred that the economic benefits of the highest energy consumption of off-peak hours are notorious and achievable through thermal storage [7].

Between all the possible applications of phase change materials in buildings, the most interesting is its incorporation in construction materials with the objective of altering their thermal properties. There are a series of possibilities: the PCM may be used as a mean for thermal storage of passive solar heating, by being integrated on the floor, walls or ceilings as well as being an integrating part of the most complex energetic systems, such as heat pumps and solar panels [8]. There are many researchers who have analysed solutions with incorporation of phase change materials in construction.

Castell et al. [9], incorporated small panels containing PCM on cell wall test with different constructive solutions, one being of hollow tile and the other of alveolar brick. Tests were performed on standard cells and on cells with expanded polyurethane enforcement, with and without the PCM panels. According to the performed tests, it was possible to notice that cells containing PCM presented internal conditions of constant temperature and the energy consumption was lower, not only when comparing with cells without PCM, but also with cells with expanded polyurethane. This effect was verified for both constructive solutions.

Darkwa et al. [10], analysed the behaviour of two solutions with PCM incorporation. The authors used 12 mm thick plasterboards with PCM incorporation to make a direct comparison with a condition in which they applied simple 10 mm thick plasterboards coated with 2 mm PCM slides. The amount of PCM infiltrated was, for both cases, 17%. The results showed that the use of laminated PCM is more efficient since it contributes to a 17% increase of the interior minimum temperature. Lai et al. [11], performed a study in which phase change material microcapsules were added to plasterboards with variable percentages of 23%, 30% and 40% of PCM. Based on this work it was possible to conclude that the thermal storage capability increases with the percentage of added PCM.

The main objective of this work was the production of a mixed lime-gypsum mortar with incorporation of PCM polymeric microcapsules, which implies a compromise between workability, mechanical strength and aesthetic appearance. These mortars can be applied not only in the construction of new buildings, but also in rehabilitation procedures.

2. EXPERIMENTAL

2.1. Materials

The studied mortars are based on lime, also incorporating microcapsules of phase change materials, nylon fibers, superplasticizer and gypsum. The PCM microcapsules were synthesized by polymerization process through emulsion and composed by a polymethylmethacrylate and a paraffin nucleus. The product is commercialized in powder (dry) or in emulsion. For this study it was decided to use a dry PCM in order to facilitate its incorporation in already prepared mortars. This PCM has a fusion temperature of about 23°C, enthalpy of 110 kJ/kg, average particle size of 15.40 μm and water content of 2%. The superplasticizer used was a polyacrylate, with a density of 1050 kg/m^3. The sand used has an average particle size of 439.9 μm. The lime used in the compositions was a hydrated lime, with a purity of 90% and density of 1100 kg/m^3. Finally, the gypsum used is a traditional, with high fineness and the fibers used are synthetic fibers of nylon with a length of 6 mm.

2.2. Formulations

In order to obtain the final composition, for future application on thermal tests in probe cells an experimental campaign was realized, with the main goal of characterizing the produced compositions, under a mechanical point of view. The compositions tested in this study were based on the information available in the Patent PCT/PT2009/000072 [12]. Throughout this work, for the studied mortars the PCM content varied between 0%, 10%, 20% and 30%. In order to overcome some of the problems related to the mortar shrinkage and consequent cracking, nylon fibers, superplasticizer and gypsum were incorporated. Fifteen different compositions were studied belonging to 4 different series. The composition groups resulted from the incorporation of different materials. Series 1 corresponds to mortars with different additions of PCM and constant content of superplasticizer. On the other hand, series 2 relates to PCM mortars containing superplasticizer and fibers. Series 3 corresponds to PCM mortars with superplasticizer, fibers and 10% of gypsum and finally, in the fourth series, only the gypsum content varies, while the PCM, fibers and superplasticizer amount remains constant (Table 1).

For each composition without PCM , it was decided not to include superplasticizer due to its dispersive effect, which caused a slight segregation of the mortar.

The mixture procedure and specimens preparation was performed in accordance with the EN 1015-11 standard [13]. To evaluate the mechanical properties (compression and flexural strength) of all the different compositions, 3 prismatic specimens with 40×40×160 mm^3 were prepared. After their preparation, all the specimens were stored for 7 days in polyethylene bags and subsequently placed in the laboratory at regular room temperature (about 22°C) for 51 days.

3. TESTING RESULTS AND DISCUSSION

3.1. Workability

The workability tests were performed in order to have an adequate workability for handling the devel-

Table 1.
Composition of mortar (PCM, superplasticizer, and fibers as % of total mass of solid particles; gypsum and sand as % of binder mass)

Series	Compositions	PCM	Super plasticizer	Fibers	Gypsum
1	SP0PCM	0	0	-	-
	SP10PCM	10	1	-	-
	SP20PCM	20	1	-	-
	SP30PCM	30	1	-	-
2	FSP0PCM	0	0	0.1	-
	FSP10PCM	10	1	0.1	-
	FSP20PCM	20	1	0.1	-
	FSP30PCM	30	1	0.1	-
3	GFSP0PCM	0	0	0.1	10
	GFSP10PCM	10	1	0.1	10
	GFSP20PCM	20	1	0.1	10
	GFSP30PCM	30	1	0.1	10
4	GFSP20PCM20G	20	1	0.1	20
	GFSP20PCM30G	20	1	0.1	30
	GFSP20PCM40G	20	1	0.1	40

Table 2.
Amount of water added to the mortar (in % of total mass of solid particles)

Series	Compositions	% Water
1	SP0PCM	23
	SP10PCM	18.5
	SP20PCM	29
	SP30PCM	45
2	FSP0PCM	23
	FSP10PCM	18.5
	FSP20PCM	30
	FSP30PCM	45
3	GFSP0PCM	23.5
	GFSP10PCM	19.2
	GFSP20PCM	31
	GFSP30PCM	47
4	GFSP20PCM20G	31
	GFSP20PCM30G	32
	GFSP20PCM40G	32

oped mortars. These tests were performed based on the flow table method stated by the European standard EN 1015-3 [14]. The adequate values were only considered when between 160-180 mm.

Depending on the incorporation of PCM microcapsules, it was possible to verify changes in the content of water added to the mortar. According to Table 2 and Figure 1, it was possible to observe that, during the mixture process, the need for a higher content of water increases with the increase of incorporated PCM microcapsules. An increase of 10% in the PCM corresponds to an increase in the amount of water of about 52%. This situation can be explained by the reduced particle size of the used PCM and by the water absorption characteristics of the polymeric wall of the microcapsule.

The incorporation of fibers did not cause any alteration in the content of water added to the mortar, although there was a slight reduction in the obtained diameter.

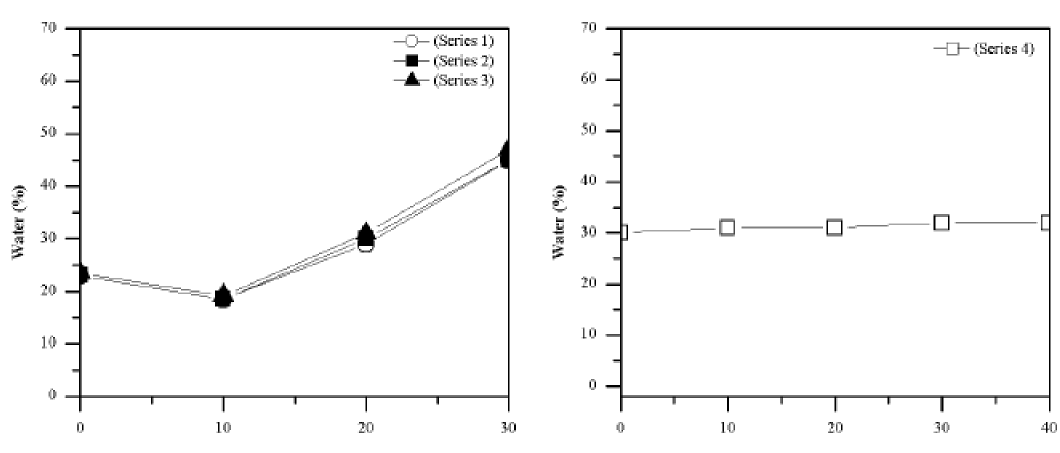

Figure 1.
Content of water, % (constant workability)

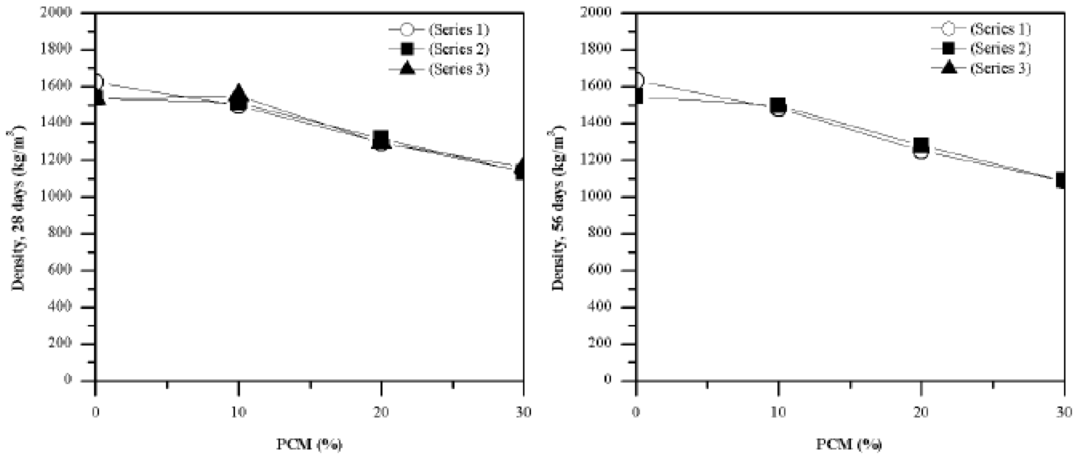

Figure 2.
Density of mortars (series 1, 2 and 3)

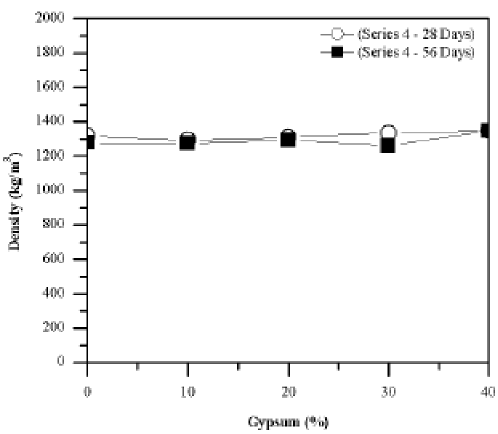

Figure 3.
Density of mortars (series 4)

The incorporation of 10% of gypsum (series 3) caused a slight increase in the necessary water content. For mortars tested in series 4, an increase of 20% of gypsum, resulted in an increase of about 3% of the mixing water.

The compositions without PCM incorporation, exhibited a higher percentage of water in all cases, and this can be explained by the absence of superplasticizer, which contributes to the water reduction in the remaining compositions.

3.2. Density

In regard to the density of the different formulations and series tested, it was possible to observe a reduction of its value with the increase of the PCM percentage (Figure 2), caused by the low mass content of the incorporated material. Contrary to the addition of PCM microcapsules, the introduction of a higher content of gypsum (Series 4) leads to a slight increase of the mortar density (Figure 3). The incorporation of fibers (Series 2) and 10% of gypsum (Series 3) does not affect the results and the compositions maintained the same tendency, therefore only the influence related to the amount of PCM incorporated was verified (Figure 2).

3.3. Mechanical Behaviour

The flexural and compressive behaviour was evaluated based on EN 1015-11. The specimens used for the flexural test were prismatic with dimensions of 40×40×160 mm^3. The tests were performed with load control at a speed of 10 N/s. Compression tests were realized through the application of a load on the specimen with resource to a metallic piece, rigid enough to make the vertical charge uniform. The specimens used for the test were the half parts resulting from the flexural test. The compression tests were performed with a load control at a speed of 50 N/s.

According to the results (Table 3 and Figure 4 to 9) it was possible to verify that the mechanical behaviour reveals an improvement with the addition of PCM microcapsules.

For the 28th day, the addition of 10% of PCM leads to an increase of about 300% in the flexural strength and an increase of about 330% of the compression strength. These values were obtained comparing the compositions without incorporation of phase change

Table 3.
Mechanical strength of mortars

Series	Compositions	Flexural strength (MPa)		Compression strength (MPa)	
		28 Days	56 Days	28 Days	56 Days
1	SP0PCM	0.17 [10.98]	0.47 [13.89]	0.25 [8.09]	0.53 [10.03]
	SP10PCM	0.67 [12.26]	1.43 [4.32]	1.54 [8.92]	2.51 [13.36]
	SP20PCM	0.93 [11.22]	1.47 [2.70]	2.22 [6.09]	3.28 [4.83]
	SP30PCM	0.81 [5.19]	1.24 [20.43]	2.47 [3.24]	3.62 [5.92]
2	FSP0PCM	0.16 [13.68]	0.20 [28.28]	0.40 [14.82]	0.47 [7.00]
	FSP10PCM	0.86 [13.44]	1.22 [12.73]	1.74 [8.03]	2.51 [14.7]
	FSP20PCM	0.72 [10.57]	0.96 [9.29]	1.79 [5.99]	2.41 [6.35]
	FSP30PCM	0.82 [15.75]	0.84 [9.44]	2.22 [2.84]	2.69 [5.75]
3	GFSP0PCM	0.15	0.34 [4.56]	0.25 [4.0]	0.72 [8.55]
	GFSP10PCM	0.72 [2.90]	1.69 [3.03]	1.77 [5.33]	3.38 [4.91]
	GFSP20PCM	0.93 [5.80]	1.40 [16.36]	2.03 [4.27]	3.07 [4.26]
	GFSP30PCM	0.62 [6.98]	0.53 [15.91]	1.74 [7.54]	2.70 [4.96]
4	GFSP20PCM20G	1.36 [4.52]	1.40 [11.19]	2.27 [10.6]	3.33 [5.20]
	GFSP20PCM30G	0.73 [12.53]	1.34 [14.00]	1.78 [5.7]	3.20 [4.83]
	GFSP20PCM40G	1.01 [12.72]	1.30 [3.61]	2.00 [11.7]	3.23 [2.46]

In parentheses, the coefficient of variation is presented

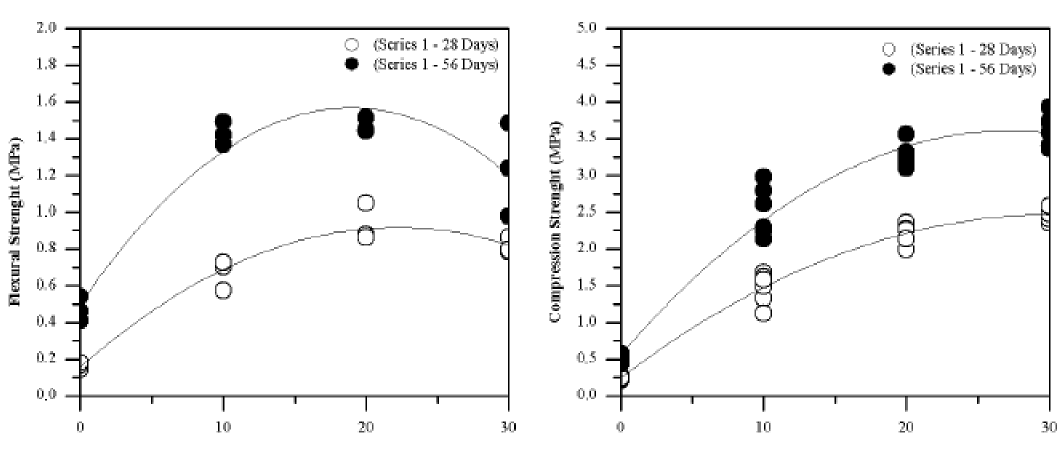

Figure 4.
Mechanical strength vs. content of PCM, % (series 1)

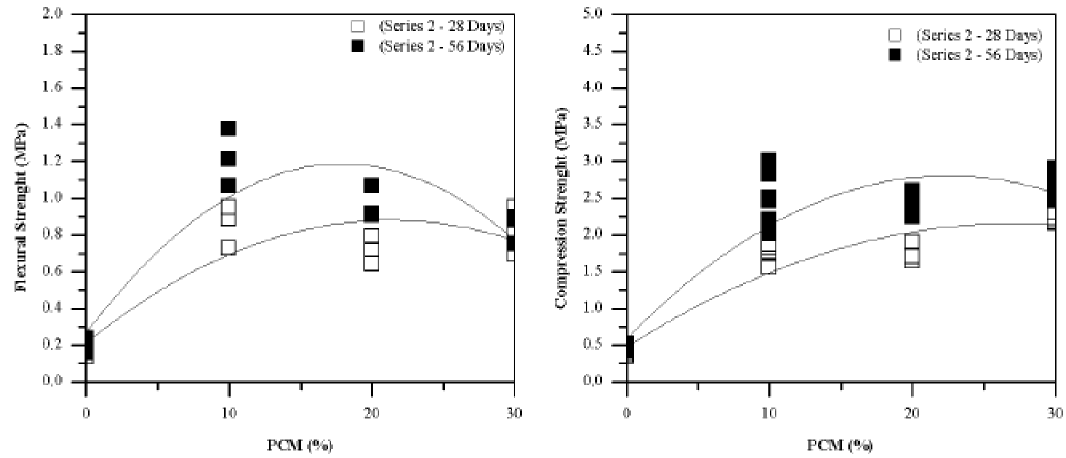

Figure 5.
Mechanical strength vs. content of PCM, % (series 2)

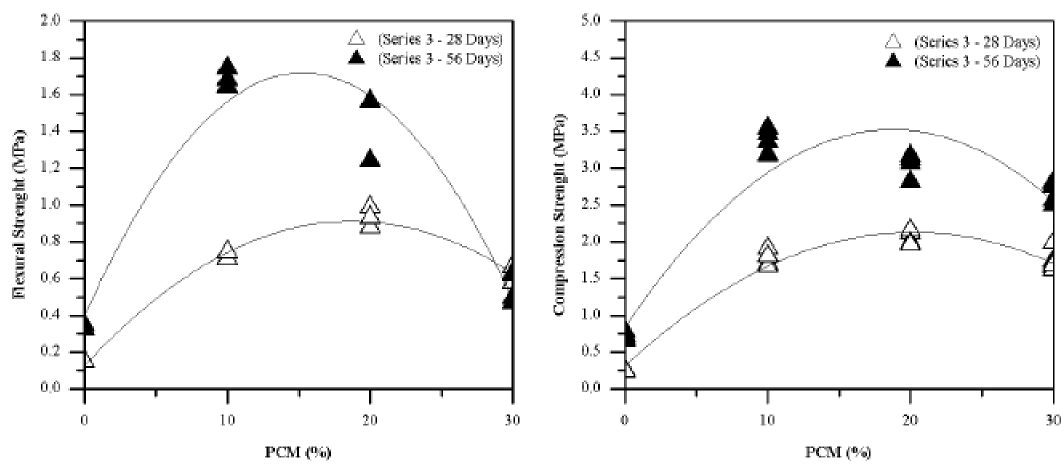

Figure 6.
Mechanical strength vs. content of PCM, % (series 3)

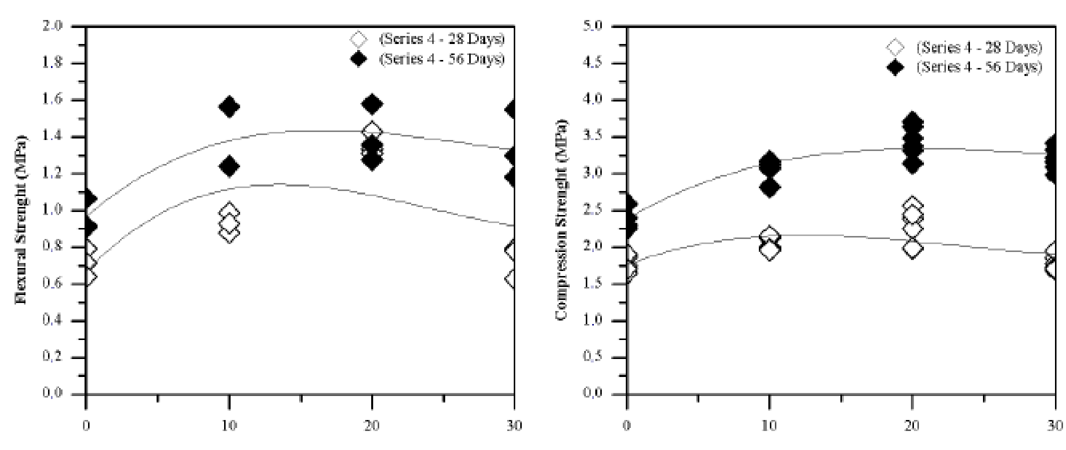

Figure 7.
Mechanical strength vs. content of gypsum, % (series 4)

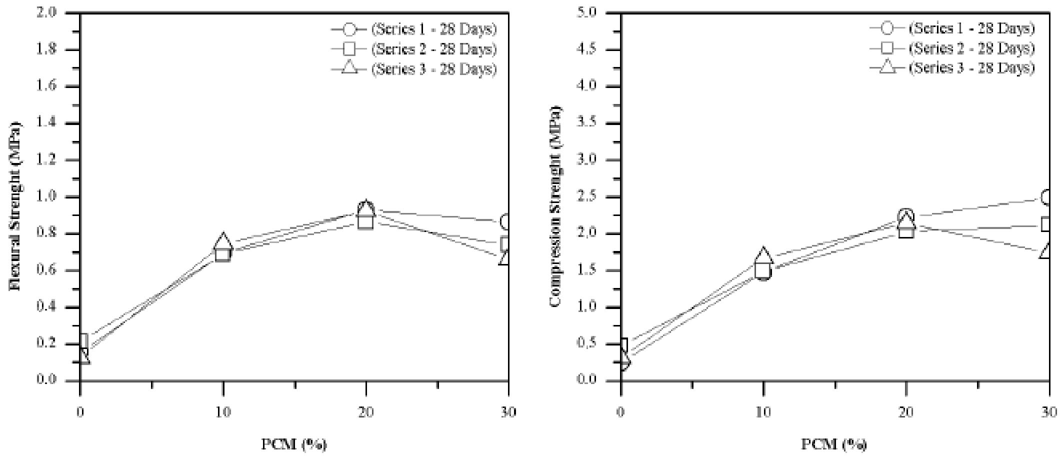

Figure 8.
Mechanical strength vs. content of PCM, % (series 1, 2 and 3-28 days)

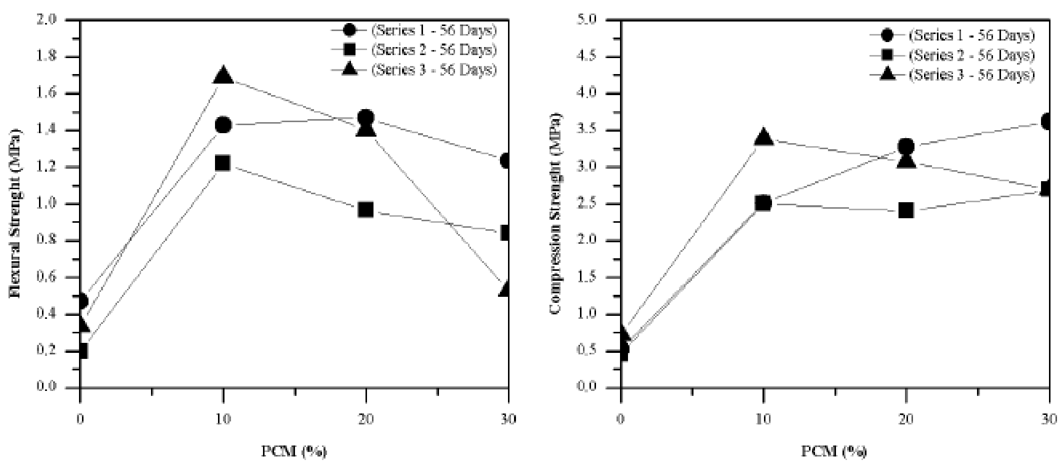

Figure 9.
Mechanical strength vs. content of PCM, % (series 1, 2 and 3- 56 days)

materials with the composition with 10% of PCM, for series 1, 2 and 3.

For the 56th day, it was possible to observe an increase in flexural strength of more than 25%, except for the composition FSP30PCM of series 2, that increased only 2%. For the composition GFSP30PCM, there was a decrease of about 14%. For the compressive strength of these compositions, the increase was about 20%. However, for the composition GFSP0PCM and SP0PCM this increase was greater than 100%. These values were obtained comparing the results for the compositions after 28 days with the results after 56 days.

The approximations made in Figures 4 to 7, were based on second-degree polynomials, with an approximation degree of more than 75%.

The incorporation of more than 20% of gypsum in the mortars caused a slight reduction of its mechanical strength, as shown in Fig. 7.

Fig. 8 presents the summary of the mechanical properties for the 28th day in which it was possible to verify that, for PCM content equal or less than 20%, there are no significant changes for the tested series. The behaviour is different for the incorporation of more than 20% of PCM. A slight decrease in the flexural strength in all the tested compositions was observed. The compression strength remains fairly constant for series 1 and 2. In series 3, a slight reduc-

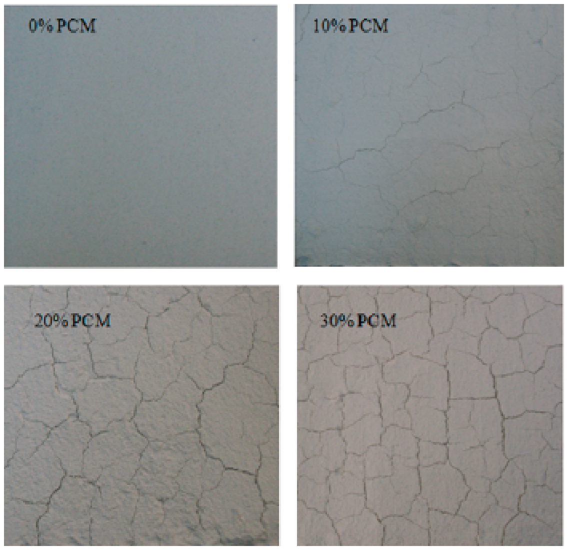

Figure 10.
Cracking observed in series 1

tion with 30% of PCM was noticed. Nonetheless, the value obtained for a PCM content of 30% is higher than the value presented for the mortar without PCM, which allows for the inference of the beneficial effect caused by the incorporation of PCM in mortars. However, the more advantageous content of PCM to add to the mortar is around 20%.

Fig. 9 presents the summary of the mechanical properties for the 56th day. It was possible to verify that the flexural strength decreases for series 2 and 3, for quantities exceeding 10% of PCM. The compression strength for series 3 shows a slight decrease in its value for quantities of incorporation of PCM higher than 10%. For series 1 and 2, it was possible to verify a slight increase in compression strength for PCM incorporation of 30%.

The increase in mechanical strength is related to the increase of porosity caused by the higher water content. This increase in porosity benefits from the carbonation of the lime present in the mortars, which cause an increase in the mechanical strength. However, after a certain content of incorporated PCM the carbonation is not enough to compensate the increase of porosity.

3.4. Sensitivity tests

Sensitivity tests were performed with the goal of measuring the cracking caused by the PCM incorporation. For that, a multilayer system was applied over bricks. It was carried out with a levelling coat without the incorporation of PCM having a thickness of 1.5cm and a finishing coat of 0.5cm with the incorporation of the different percentages of PCM microcapsules.

It was possible to verify that the mortars without the addition of PCM did not show any type of cracking. However, for mortars with phase change materials additions, major problems related to cracking were detected and the effect was rather significant, as shown in Figure 10. With the purpose of solving this problem, fibers were added to the mortars and an effective decrease in the cracking was verified. However, the problem was not entirely solved. As such, a new testing series was performed, this time incorporating 10% of gypsum. These tests confirmed that the gypsum addition was sufficient to solve the problems related to cracking in mortars with the incorporation of 10% of PCM content. Therefore, a last test campaign was performed with the incorporation of higher amounts of gypsum, 20%, 30% and 40%. With an incorporation of 40% of gypsum, it was possible to incorporate 20% of PCM without any cracking related problem

4. CONCLUSIONS

Based on these results, it can be concluded that the use of PCM microcapsules in lime based mortars can be seen as a viable solution for applications in the construction industry. It is possible to achieve a viable compromise between their strength and esthetical appearance. The results of the sensitivity tests show that the combined use of fibers and gypsum is a good solution to solve problems related to cracking caused by the incorporation of phase change materials. It was even possible to verify the need for an increase of the necessary water with the increase of PCM percentage, in order to obtain a suitable workability. The compression and flexural strength measured in each performed test showed a tendency for their improvement with a greater incorporation of PCM microcapsules.

The mortar with 60 % of aerial lime and 40 % of gypsum with incorporation of PCM microcapsules is more interesting because it showed an excellent compromise between high mechanical strengths and good aesthetical appearance.

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