Behavior of cementitious mortars with direct incorporation of non-encapsulated phase change material after severe temperature exposure

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HIGHLIGHTS

- Four cementitious materials with direct incorporation of PCM were developed.
- The PCM used is non-encapsulated paraffin.
- The influence PCM presence at severe temperature exposure was evaluated.
- The PCM incorporation leads to an improvement of the freeze-thaw behavior.
- The behavior at high temperatures is similar to the reference and PCM mortars.

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ABSTRACT

Nowadays, the study of construction solutions capable of withstanding severe conditions, such as temperature exposure, is paramount. Considering the thermal storage capabilities of phase change materials (PCM), this work features the study of four different compositions based on cement and fly ash, with which different contents of non-encapsulated PCM (0%, 5%, 10% and 20%) were combined by direct incorporation. These were tested under low and high temperatures (-18°C , 20°C , 200°C , 400°C and 600°C), through freeze-thaw as well as compressive and flexural tests. Results show that the incorporation of non-encapsulated PCM leads to an improvement regarding freeze-thaw conditions, while maintaining an identical behavior to the reference mortars when subjected to high temperatures.

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1. Introduction

Nowadays, global warming is a critical issue throughout the world, to the point where it represents a danger for Mankind. Dangerous emissions, such as carbon dioxide (CO_2), are the main drivers of this negative climate phenomenon. In this context, the construction sector has largely contributed towards global energy consumption and greenhouse gas emissions. This is aggravated by the elevated energy requirements associated with air conditioning usage, which are expected to increase substantially by 2050 [1].

Mortars comprise an essential construction material, especially given their function and its relation to durability and resistance to factors such as aging and deterioration of buildings [2]. Since build-

ings may be subjected to accidental fires and floods during their lifetime, affecting the performance of materials, in particular indoor lining mortars, the behavior of construction materials to severe temperature conditions is of extreme importance, hence demanding considerable research efforts.

One way to tackle these types of issues and improve the behavior of buildings consists of the employment of functional mortars. Among these, thermal mortars are especially designed to increase the energy efficiency of buildings. Bearing in mind that, in addition to the aforementioned issues, high energy consumption is one of the main problems of modern society [3], it is imperative to study and develop new materials with the ability to further minimize the impact of these problems both from a present and a future viewpoint. On the one hand, phase change materials (PCM) display outstanding thermal regulation capacities due to their ability to absorb and release energy to the environment, and their application has shown that it is possible to decrease the energy

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consumption in buildings, gas emissions to the atmosphere, and negative environmental impacts [4]. On the other hand, there is a growing need to reuse industrial by-products in order to achieve higher levels of sustainability in construction. Thus, increased focus should be placed in the incorporation of waste in the development of sustainable mortars. In this regard, the replacement of Portland cement by fly ash is an already well-known measure in the reuse of this industrial waste, as corroborated by previous studies [5]. Hence, the simultaneous incorporation of PCM and fly ash in mortars not only consists of a measure to increase the energy efficiency of buildings, but it also results in a reduction of the amount of landfilled waste materials [6–8].

Though in recent decades extensive research was carried out concerning the incorporation of PCM into construction materials, the reutilization of fly ash, and the impact of high temperatures on cementitious materials (mortars, concrete), the behavior of cementitious mortars at severe temperatures with direct incorporation of both non-encapsulated PCM and fly ash has not yet been studied. The exposure of building materials to high temperatures has a very significant influence on their properties, since when subjected to this type of action they can exhibit very different behaviors in comparison to normal operating conditions. Indeed, during a fire event, it is possible to verify a very strong thermal gradient in the outer layers of the concrete exposed to heat, which results in severe thermal damage [9]. Currently a large number of published studies reveals a decrease in the mechanical properties of cement-based materials after exposure to high temperatures [7,10,11]. Several efforts have been made to improve the thermal stability of cement composites by incorporating different materials, such as fly ash or ground granulated blast furnace slag. These have shown a good performance in the presence of fire, improving the behavior of materials at high temperatures, due to the capability to retain a higher residual strength and reduce surface cracks [11]. As such, a significant amount of fly ash was adopted in the mortar production throughout this work.

The majority of recent research related to PCM in construction elements focused on the encapsulation technique in gypsum plaster boards [12–14], concrete and mortars [7,15–17], as well as PVC panels, blocks and bricks [6,18]. Cunha et al. [4,6,19] developed several studies regarding the incorporation of PCM microcapsules in mortars based on different binders (cement, aerial lime, hydraulic lime and gypsum). In these studies, it was possible to observe a decrease in the mechanical behavior of the mortars (flexural strength, compression strength, and adhesion), together with an increase in the microporosity and thermal performance, as evidenced by the decrease in climatization needs. However, in some studies, the cost of construction materials doped with microencapsulated PCM is very high, representing an obstacle for the practical application of the technology. In fact, some of the most relevant drawbacks related with encapsulation include the cost of PCM acquisition, production time of construction materials, material cost and adaptation of materials to the technique. Yet, while the encapsulation technique encompasses the addition of PCM to the construction materials in a polymeric microcapsule with dimensions lower than 60 μm , the direct incorporation technique consists of adding the PCM without any type of encapsulation, ultimately comprising a simpler and more economical way to use PCM in construction solutions.

Regarding the simultaneous incorporation of PCM and fly ash, only a reduced number of studies can be found, most of which resort to PCM microcapsules. This research gap urgently calls for the study and development of functional construction materials based in simple techniques, as well as in economical and sustainable raw materials, with high potential of thermal performance and reuse of industrial waste. Hence, whereas the adoption of direct incorporation of non-encapsulated PCM appears as a possi-

ble solution to minimize the high energetic consumption at low cost, the use of industrial waste further reduces the costs related to raw materials.

Although its potential as a method to decrease the energy dependence of buildings is as promising as it is innovative, the study of the direct PCM incorporation technique still remains undeveloped. In fact, since PCM features the ability to regulate temperature inside the buildings, it also has influence on the temperature observed during the curing process, which may originate changes in the different properties of cementitious mortars. In addition, it is essential to evaluate the behavior of mortars with incorporation of non-encapsulated PCM at several temperatures, which may occur in the event of a disaster or accident. Thus, the main objective of this research is the study of the behavior of several mortars with incorporation of free and pure PCM when exposed to low temperatures, by means of freeze-thaw cycles, as well as to high temperatures, by resorting to compressive and flexural tests at 200 °C, 400 °C and 600 °C. The temperature range selection was based on the observation of the behavior of mortars at different temperatures outside of normal operating temperatures.

2. Experimental program

2.1. Materials

The selection of the materials used in this work took into account previous research developed by the authors related to the incorporation of PCM in mortars for interior lining [4,6,8]. The adopted materials were Portland cement, fly ash (Table 1), aggregates (sand A and sand B) and non-encapsulated PCM. The densities of the different used materials are presented in Table 2. The aggregate was composed by sand A (Fig. 1) and sand B (Fig. 2), with average particle sizes of 439.9 μm and 762 μm , respectively. The main drive behind the adoption of both sands is to obtain a more extensive granulometric curve. The selected PCM is pure paraffin with temperature transition between 20 and 23 °C and enthalpy of 200 kJ/kg.

2.2. Mixtures

Four different cement mortars were prepared with different contents of non-encapsulated PCM (0%, 5%, 10% and 20%) (Table 3). The addition of the PCM replaced part of the aggregate's mass. The used aggregate was composed by 50% of sand A and 50% of sand B. In turn, the binder is comprised of 40% cement and 60% fly ash. The reasoning behind this choice is related to the improvement of the thermal stability [11] and the thermal regulation effect of the cementitious mortars [6]. It is also important to note that, since these mortars are lining interior mortars, the classification of CSII based in the EN NP 998-1:2010 [20] is sufficient for their intended application. Thus, it was possible to incorporate high percentages of fly ash without

Table 1
Chemical composition of fly ash.

Chemical component	(%)
Silicon oxide (SiO_2)	49.12
Aluminum oxide (Al_2O_3)	27.30
Iron oxide (Fe_2O_3)	8.19
Calcium oxide (CaO)	2.36
Magnesium oxide (MgO)	1.42
Sulfates (SO_3)	1.30
Potassium oxide (K_2O)	3.34
Sodium oxide (Na_2O)	0.99
Titanium oxide (TiO_2)	2.32

Table 2
Densities of the materials.

Material	Density (kg/m^3)
Cement CEM II B-L 32.5N	3030
Fly Ash	2420
Sand A	2600
Sand B	2569
PCM	760 (solid state) 700 (liquid state)

Fig. 1. Particle size analysis – Sand A.

compromising the required mechanical performance. The development of these formulations took into account previous work developed by the authors related to the incorporation of PCM in mortars for interior coating [4,6,8].

2.3. Testing procedures

The mortars were tested in order to evaluate their behavior at severe conditions. A general classification was developed based in different tests, Standards and other works, namely: workability [21], density [8], water absorption by capillarity [22], water absorption by immersion [23], microscope observations [6,7] and thermogravimetric tests (DSC-TGA) [8]. Regarding the behavior at high temperatures, flexural and compressive tests [24] were developed at different temperature ranges. In turn, the behavior at low temperatures was assessed by means of freeze-thaw tests [25].

3. Test results and discussion

3.1. Workability

Workability tests were performed in order to obtain a resulting value of 180 ± 5 mm, based on the flow table method. These tests allowed for the ascertainment of the optimal water content in view of obtaining the same workability for the different mortars. Table 3 reveals a decrease in water content with the increase of PCM incorporation, due to its liquid state, which increases the flow table diameter.

Fig. 3 shows the water-binder ratio present in the different mortars. The incorporation of a higher PCM content resulted in a decrease in the water-binder ratio. Indeed, the incorporation of 5% PCM led to a decrease of about 8% in the water content added to the mortar. This behavior is associated to the fact that the PCM is incorporated in its liquid state and can function as an agent to obtain a homogeneous mortar. The use of PCM in liquid state is also the cause of the verified increase in the liquid-binder ratio for higher PCM contents (Fig. 4). Although the PCM does not work as an agent for the hydration of the binder, it contributes towards obtaining a greater workability.

3.2. Density

A decrease in the density of the mortars could be observed with the incorporation of non-encapsulated PCM (Fig. 5). In fact, the incorporation of 5% of non-encapsulated PCM leads to a decrease of about 11% in the density of the prepared mortars, which decreases even further with the incorporation of higher PCM contents. This behavior is associated with the decrease in the water-binder ratio of the mortars doped with PCM, induced by the addition of non-encapsulated PCM in its liquid state. Additionally, while it has been previously established that the free PCM can operate as a workability enhancement agent, its density is inferior in comparison to the density of water.

Fig. 2. Particle size analysis – Sand B.

Table 3
Formulation of the mixtures (kg/m³).

Mixture	Cement	Fly Ash	Sand A	Sand B	PCM	Water
CEM-0PCM-NE	200	300	659.1	659.1	0	300
CEM-5PCM-NE	200	300	583.6	583.6	58.4	275
CEM-10PCM-NE	200	300	526.2	526.2	105.2	252.5
CEM-20PCM-NE	200	300	442.3	442.3	176.9	215

Fig. 3. Water-Binder ratio of the mortars.

Fig. 4. Liquid-Binder ratio of the mortars.

Fig. 5. Density of the mortars.

porosity of the PCM mortars, which becomes more evident with the incorporation of a higher content of PCM. This behavior can be justified by the fact that PCM is added to the mortars during its production in liquid form, allowing it to distribute freely in the mortar matrix.

Fig. 7 shows the microstructure of the mortars doped with non-encapsulated PCM at transition temperature (20 °C). In this regard, the same behavior could be observed in both the transition temperature (Fig. 7) and the −18 °C temperature (Fig. 6). Indeed, the incorporation of higher contents of PCM leads to a decrease in the porosity of the mortars, due to the superficial coating of the materials present in the mortar matrix. However, the fact that a greater amount of hydration crystals with angular form can be observed (Fig. 7b) to Fig. 7d)) indicates a lower quantity of PCM. This can be justified by the fact that, at this temperature, the PCM remains in a transition state, part of which is still in the solid state and part in the liquid state. Yet, any material in liquid state was removed from the sample by vacuum during the tests as a consequence of the characteristics and requirements of the experimental equipment (Scanning Electron Microscope).

3.3. Microstructure

Microstructure observations were performed for all the developed mortars at two different temperature ranges, −18 °C (Fig. 6) and 20 °C (Fig. 7), in order to observe the mortars with PCM in both their solid state and transition state, respectively.

Fig. 6 showed a significant alteration in the microstructure of the mortars containing the non-encapsulated PCM. In the reference mortar (Fig. 6a)), a more crystalline microstructure was observed, evidenced by the presence of a large amount of hydration crystals with angular form. However, in mortars with PCM incorporation (Fig. 6b) to Fig. 6d)), it was possible to identify a more compact microstructure: the non-encapsulated PCM coated the entire mortar matrix, providing a protective layer of the crystalline structure observed in the reference mortar. The PCM present in the mortars was thoroughly aggregated in the hydrated crystals and aggregates in the matrix. Thus, it was also possible to observe a decrease in the

3.4. Thermogravimetric tests (DSC-TGA)

Thermogravimetric tests were performed in order to understand the influence of the addition of non-encapsulated PCM in the mortars. Figs. 8–11 shows the thermogravimetric curves of the different mortars with various PCM contents. It was possible to observe that the incorporation of non-encapsulated PCM leads to an increase in the peak points of the curves. It is also important to note that the peak points are more expressive with the incorporation of higher PCM contents.

Regarding the reference mortars without PCM incorporation (Fig. 8), it was possible to identify two peak points at 104.3 °C and 730.4 °C. The first peak point (104 °C) is related to the evaporation of uncombined chemical water. Usually, this evaporation can occur up to approximately 105 °C in two different stages. The first stage is related to the evaporation of the uncombined water present in mortar pores with high dimensions, typically taking

Fig. 6. Microstructure observations at -18°C , enlargement of 25000 $\times$: (a) Reference mortar (0% PCM); (b) Mortar with 5% of non-encapsulated PCM; (c) Mortar with 10% of non-encapsulated PCM; (d) Mortar with 20% of non-encapsulated PCM.

place between 35°C and 70°C . The second stage concerns the water present in the pores with lower dimensions, the capillary pores, which occurs between 70°C and 105°C . The second peak point (730.4°C) concerns the decarbonation of calcium carbonate (CaCO_3) [8,26–29].

Bearing in mind Figs. 9–11, it was possible to identify 4 peak points for the mortars with incorporation of non-encapsulated PCM. This indicates that the incorporation of free and pure PCM leads to changes in the hydration products of the cement mortars. Similarly to the reference mortars, the first peak point (108.6°C , 104.3°C and 104.8°C) is related to the evaporation of uncombined chemical water. The second peak point, at around 200°C (200°C , 202.2°C and 212.2°C), is directly related with the presence of PCM, since this peak corresponds to the PCM flash point [30]. The third peak point (447.8°C , 437°C and 436.9°C) is associated with the dehydroxylation of calcium hydroxide ($\text{Ca}(\text{OH})_2$) [26]. According Anjos et al. [26], the loss of mass between the 425°C and 550°C , corresponds to the decomposition of $\text{Ca}(\text{OH})_2$ into calcium oxide and water ($\text{CaO} + \text{H}_2\text{O}$). Finally, as previously mentioned, the fourth peak point (721.7°C , 719.6°C and 723.9°C) is related to the decarbonation of calcium carbonate (CaCO_3) [8,26–30].

According to these results, the presence of calcium hydroxide in mortars doped with non-encapsulated PCM could be observed. Thus, one can infer the existence of a delay in the hardener process, which can be justified by the fact that the PCM interferes in the contact between cement and water, as well as between fly ash and calcium hydroxide, retarding the hardener reactions. The interference caused by the PCM in the contact between binder, water, and calcium hydroxide can be justified by the fact that the non-encapsulated PCM freely coats the entire matrix of the mortar, remaining adherent to the cement hydration products, the fly ash, and the aggregates (Figs. 6 and 7).

Furthermore, it is important to note that the mass loss associated with the dehydroxylation of calcium hydroxide and decarbonation of calcium carbonate are very similar for all the PCM mortars, which indicates that the delay in the hardener process is directly related to the presence of PCM and not with its content. As mentioned in Section 2.2, the PCM was added to the mortar replacing the aggregate according to its mass. However, in order to better understand the thermogravimetric results and the possibility of PCM losses during the procedure, handling, and curing of the mortars, the quantity of PCM present in each mortar in relation to the solid material was calculated. Table 4 shows the PCM content in

Fig. 7. Microstructure observations at 20 °C, enlargement of 25000×: (a) Reference mortar (0% PCM); (b) Mortar with 5% of non-encapsulated PCM; (c) Mortar with 10% of non-encapsulated PCM; (d) Mortar with 20% of non-encapsulated PCM.

Fig. 8. Thermogravimetric test for the mortar without PCM incorporation.

Fig. 9. Thermogravimetric test for the mortar with incorporation of 5% of non-encapsulated PCM.

Fig. 10. Thermogravimetric test for the mortar with incorporation of 10% of non-encapsulated PCM.

Fig. 11. Thermogravimetric test for the mortar with incorporation of 20% of non-encapsulated PCM.

Table 4
PCM content, related to the mass of solid constituents.

Mixture	Theoretical PCM content (%)	Real PCM content (%)
CEM-0PCM-NE	0	0
CEM-5PCM-NE	3.38	3.57
CEM-10PCM-NE	6.34	5.42
CEM-20PCM-NE	11.3	7.91

relation to the mass of solid materials that comprise the mortars (i.e., cement, fly ash and sand). From this table, one can easily infer that the incorporation of a higher PCM content leads to a higher PCM loss. Indeed, the incorporation of a 20% of non-encapsulated PCM leads to a maximum PCM loss of about 30%. This is a consequence of the fact that the matrix of the mortars reaches its maximum support capacity once the PCM is added to the hydration salts and the particles present in the microstructure of the mortar. Conversely, inferior PCM contents do not origin significant losses.

3.5. Water absorption

The behavior of mortars at severe conditions, as well as their durability, is greatly affected by the associated water absorption capacity, since the latter is related to the ease of penetration of

aggressive agents in mortars. In fact, the penetration capacity of the aggressive agents is influenced by the water-binder ratio, the binder fineness, the workability, and the curing conditions. Hence, water absorption by capillarity and immersion are extremely important parameters, especially in the case of mortars incorporating non-encapsulated PCM, since the addition of PCM in this work was carried out in its liquid state and subsequently stored in the mortar pores.

The incorporation of non-encapsulated PCM in the mortars prompted a decrease of water absorption coefficient (Fig. 12). As a matter of fact, the incorporation of 5% of PCM leads to a decrease of about 60% in the aforementioned coefficient. This is justified by the fact that PCM is deposited on the particles of the mortars, creating a protective layer. When coating these particles, the PCM causes a reduction of the existing voids between the different mortar constituents, which consequently results in a decrease in the porosity. As such, it can be concluded that the PCM is stored in the mortar, preventing any risks associated with changing its intended position after application in its liquid phase.

Furthermore, it was possible to observe a decrease in water absorption by immersion of about 18% with the incorporation of 5% of non-encapsulated PCM (Fig. 13). Higher levels of PCM incorporation resulted in a greater reduction in water absorption by immersion. Thus, this supports the conclusion that the pure PCM is stored in the mortar matrix, which comprises a natural form of PCM encapsulation.

3.6. Behavior at high temperatures

The behavior of the mortars at high temperatures was assessed by means of flexural and compressive tests at different temperature ranges, namely 20 °C (reference temperature), 200 °C (Fig. 14), 400 °C and 600 °C. Temperature range selection took into account the simulation of the behavior of mortars when exposed to an accidental fire action. It is important to note that submitting the mortars to 800 °C temperatures leads to the destruction of the specimens for both the reference mortars and the PCM mortars. In all temperature tests, the mortars with 28 days of aging were submitted to the corresponding temperature range for four hours by resorting to an oven.

According to Fig. 15, the incorporation of PCM leads to a slight decrease in flexural strength in all tested temperatures. This becomes more evident for contents of 20% of non-encapsulated PCM. Moreover, a more pronounced decrease in the compressive strength could also be observed in the mortars with the PCM incor-

Fig. 12. Water absorption by capillarity coefficient of the mortars.

Fig. 13. Water absorption by immersion of the mortars.

poration. The incorporation of 5% of PCM results in a decrease in compressive strength higher than 20% in the reference temperature range (20 °C). This is related to the delay associated with the hardener reactions, and with the presence of a higher liquid-binder ratio in the mortars, since the PCM is added to the mortar in liquid state, contributing towards the increase of pores in the mortars. However, it is important to note that these pores are totally or partially occupied with PCM, which accounts for less significant influence of the latter in the flexural strength.

Regarding to the effect of the temperature, one can straightforwardly perceive that the mortars submitted to temperatures of 200 °C show an improvement in the flexural and compressive behavior, compared to the reference temperature (20 °C). This occurrence is related to the curing process of the binders, in which

the temperature accelerates the hardener process of the cementitious materials. However, the exposure of the cementitious mortars to temperatures of 400 °C and 600 °C causes a significant decrease in their flexural and compressive behavior. As a matter of fact, submitting the cementitious mortars to a 400 °C and 600 °C has triggered a decrease in their flexural strength superior to 26% and 71%, respectively. Similarly, the compressive strength of the mortars has sustained a decrease superior to 12% for a temperature exposure of 400 °C, and 39% for a temperature exposure of 600 °C, in comparison to the reference temperature (20 °C). On the one hand, this response stems from the development of micro cracks in the mortars, originated by the high internal vapor pressure and by the thermal gradient between the internal and external layers of the specimens [7,31,32]. These micro cracks lead to a decrease in the cross section resistance area, resulting in the aforementioned impact on the flexural and compressive strengths [33]. On the other hand, it is important to note that the exposure of the cementitious mortars to a temperature range of 425–550 °C leads to a decomposition of calcium hydroxide (Ca(OH)_2) into calcium oxide and water ($\text{CaO} + \text{H}_2\text{O}$), which also causes a reduction in the mechanical strengths [26,34].

3.7. Behavior at low temperatures

The study of the effect of low temperature on the mortars was based in freeze-thaw tests. After 28 days of curing of the mortars, they were submitted to 56 test cycles. The duration of each cycle was 24 h, and the temperature ranged from −18 °C to 24 °C. The degradation suffered by the mortars was measured taking into account the mass losses sustained in each cycle.

Freeze-thaw tests consist of subjecting the specimens to cycles of positive and negative temperatures. When negative temperatures occur, the water inside the mortar freezes, and consequently

Fig. 14. Mortars submitted to 200 °C.

Fig. 15. Flexural and compressive behavior at high temperatures.

Fig. 16. Mortar with incorporation of 10% of PCM submitted to freeze-thaw tests.

Fig. 17. Variation of the specimens mass during the freeze-thaw tests.

increases its volume. Although the risk is reduced in cases where the pores of the mortars are not saturated (i.e. the volume of the frozen water is inferior to the volume of the pores), in cases in which saturation has been reached the increase in volume resulting from freezing increases the pressures exerted on the walls of

Table 5
Mass loss of the mortars during the freeze-thaw tests (%).

Cycle	0% PCM	5% PCM	10% PCM	20% PCM
0	0	0	0	0
2	20	16	20	15
3	20	16	20	15
6	20	16	20	15
7	20	15	20	15
13	19	15	19	15
16	18	14	18	15
17	21	14	18	15
20	37	14	18	15
22	100	13	17	15
23	100	10	18	15
28	100	11	30	15
29	100	45	46	15
34	100	100	58	15
35	100	100	59	15
37	100	100	86	15
42	100	100	100	15
43	100	100	100	20
48	100	100	100	20
51	100	100	100	28
57	100	100	100	28
58	100	100	100	37
62	100	100	100	53
65	100	100	100	100

the pores (i.e., in the microstructure of the mortars). This may lead to cracking and even partial destruction of the element under analysis. In turn, throughout the process of defrosting, the amount of water previously crystallized resumes its initial volume. In the course of this process, two different situations can occur: the partial, or the total drying of the specimens due to the change of phase to gas and the absorption of a new quantity of water by capillarity.

Figs. 16 and 17 depict the behavior of the mortars during the freeze-thaw cycles. In this regard, the mortar with incorporation of 20% of non-encapsulated PCM presents a higher resistance to the freeze-thaw action, since it does not show a significant mass loss in the first cycles of the test. Contrariwise, the most sensitive mortar to this type of aggression is the mortar without PCM incorporation, as the complete loss of specimens during the first test cycles was significant. Table 5 shows the mass losses suffered during the test cycles. It was possible to observe that the mass loss was more prominent and slower for the mortars with PCM incorporation. Additionally, the total loss of the mortar with incorporation of 20% of PCM occurs in the cycle 65 and the total mass loss for the reference mortar (0% PCM) in the cycle 22. This reveals that the incorporation of phase change material led to lower losses of material during the action of the freeze-thaw, demonstrating that the incorporation of non-encapsulated PCM enhances the mortars towards becoming less susceptible to this type of action. Such is related to the lower water-binder ratio present in the PCM mortars, together with a decrease in the dimensions and quantity of pores in the mortar matrix.

4. Conclusion

This study evaluated the behavior of cement mortars with direct incorporation of PCM at severe temperatures, comprising a considerable advance in the state of knowledge on the subject.

The incorporation of pure and free PCM leads to a decrease in the water-binder ratio and an increase in the liquid-binder ratio due to the fact that PCM is incorporated in its liquid state. Note that, for this reason, it can function as an agent to obtain a homogeneous mortar, contributing towards a greater workability. Moreover, a decrease in the density of the mortars with the incorporation of non-encapsulated PCM was also verified, which can be explained by the decrease in the water-binder ratio of the mortars doped with PCM, together with the lower density that characterizes the PCM.

There was also a decrease in the water absorption coefficient, allied with a decrease in the water absorption by immersion in the mortars with incorporation of non-encapsulated PCM. This behavior can be justified by the fact that the PCM is deposited on the microstructure particles, hence decreasing the porosity by partially or totally occupying the pores of the mortar.

In addition, the mechanical behavior of the developed mortars was affected by the PCM incorporation, originating a decrease in the flexural and compressive behavior. Such can be related to the presence of a higher liquid-binder ratio in the PCM mortars and the delay of the hardener reactions.

Concerning the behavior of the PCM mortars when exposed to high temperatures (200 °C, 400 °C and 600 °C), it was possible to observe an improvement in the flexural and compressive behavior at a temperature exposure of 200 °C, due to the fact that the temperature accelerates the hardener process of the cement and fly ash. However, exposure to higher temperatures causes a significant decrease in the mechanical behavior of the mortars, resulting from the development of micro cracks in the mortars, and the subsequent decrease of the cross section resistance area.

Regarding to the behavior at low temperatures, it was possible to verify a higher resistance to the freeze-thaw action, due to the

lower water-binder ratio and porosity inherent to the PCM doped mortars.

Briefly, it can be concluded that, on the one hand, the incorporation of non-encapsulated PCM improves the performance of mortars against the freeze-thaw action. On the other hand, the incorporation of PCM in mortars exposed to high temperatures slightly decreases the mortars performance, while maintaining a similar behavior to the reference mortars (0% PCM). Thus, the incorporation of 10% PCM can be considered an optimal solution, as it leads to a better overall performance when taking both behaviors into account.

Declaration of Competing Interest

None.

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