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Ranking procedure based on mechanical, durability and thermal behavior of mortars with incorporation of phase change materials

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ABSTRACT: Nowadays, considering the high variety of construction products, adequate material selection, based on their properties and function, becomes increasingly important. In this research, a ranking procedure developed by Czarnecki and Lukowski is applied in mortars with incorporation of phase change materials (PCM). The ranking procedure transforms experimental results of properties into one numerical value. The products can be classified according to their individual properties or even an optimized combination of different properties. The main purpose of this study was the ranking of mortars with incorporation of different contents of PCM based in different binders. Aerial lime, hydraulic lime, gypsum and cement were the binders studied. For each binder, three different mortars were developed. Reference mortars, mortars with incorporation of 40% of PCM and mortars with incorporation of 40% of PCM and 1% of fibers, were tested. Results show that the incorporation of PCM in mortars changes their global performance.

KEYWORDS: Mortar; Workability; Mechanical Properties; Durability; Thermal Analysis

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RESUMEN: *Procedimiento de clasificación de morteros con incorporación de materiales de cambio de fase basado en el comportamiento mecánico, durabilidad y comportamiento térmico*. Actualmente, existen varios productos de construcción, siendo importante una adecuada selección, con base en sus principales propiedades y funciones. En esta investigación se aplicó un procedimiento de clasificación desarrollado por Czarnecki y Lukowski, en morteros con incorporación de materiales de cambio de fase (PCM). Este procedimiento transforma los resultados experimentales de las propiedades en un único valor numérico. Los productos se clasifican de acuerdo con sus propiedades individuales o en una combinación optimizada de diferentes propiedades. El principal objetivo de este estudio fue la clasificación de morteros basado en los diferentes aglutinantes con incorporación de diferentes cantidades de PCM. Los aglutinantes utilizados fueran la cal aérea, cal hidráulica, yeso y cemento. Para cada aglutinante se han desarrollado tres morteros, siendo morteros de referencia, con incorporación de 40% de PCM y con incorporación de 40% de PCM y 1% de fibras. Fue observado que la incorporación de PCM en morteros cambia su comportamiento global.

PALABRAS CLAVE: Mortero; Trabajabilidad; Propiedades mecânicas; Durabilidad; Análisis térmico

1. INTRODUCTION

Currently, there are several types of mortars to apply as coating inside buildings, which makes it extremely difficult to select the most appropriate material. The performance of the available generic types under different service conditions needs to be studied. Thus, the need to classify the materials carefully based on a single procedure emerges, in order to clearly show the more interesting behavior, taking into account the exposure ambient and the functions that are important after its application.

Selection of materials is an important part of design in civil engineering. This needs to be made based on the knowledge of the materials properties. Thus, the use of ranking procedure contributes to the selection of the best material available, while establishing an order between the different materials.

Nowadays, there is a huge concern about the high energy consumption verified in the residential sector associated with heating and cooling needs of buildings. Thus, it becomes imperative to implement constructive solutions that increase energy efficiency in buildings. The mortars with incorporation of phase change materials (PCM) emerge as a possible solution in an attempt to solve, or minimize, the massive energetic consumption related to buildings. The use of this material allows the regulation of frequency of temperatures fluctuations, keeping them closer to the desired temperature range for a longer period, or at least reducing the need to use heating and cooling equipment, increasing the thermal inertia (1–3). This technique results in buildings with higher comfort parameters, improving the life conditions of their occupants, and preventing negative environmental impact.

The low thickness achieved with the use of phase change materials, combined with the utilization of flexible construction solution makes it possible to obtain a greater adaptability of the buildings, moving the traditional construction for a more sustainable construction. The incorporation of phase change materials in mortars for coating interior walls allows us to obtain buildings with higher energetic efficiency. Therefore, it is important that the construction industry is innovative and accepts new solutions for solving problems with several years (4). These mortars can be applied not only in the construction of new buildings, but also in rehabilitation operations.

Phase change materials possess the capability to alter their own state as a function of the environmental temperature (5). On the one hand, as the surrounding environmental temperature of PCM increases to its fusion point, a change from a solid state to a liquid state occurs, absorbing and storing the heat energy from the environment. On the other hand, as the temperature decreases to 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 advantages concerning the passive regulation of internal temperature, as well as regarding the increase of thermal inertia (6).

So as to allow for its correct use, the PCM must be encapsulated, otherwise during the liquid phase there is a possibility that it moves from the original area of application. There are two main forms of encapsulation, macroencapsulation and microencapsulation. The former is based in the introduction of PCM into tubes, panels or other large containers. It is usually done in containers with more than 1 cm of diameter and presents a better compatibility with the material, improving the handling in construction (7). Microencapsulation of phase change material consists of covering the particles, with a material (usually a polymer) commonly known capsule, with dimensions between 1 μm and 60 μm. The microcapsules encapsulation process improves the heat transfer, through its large surface area (7, 8). Recently, this problem of encapsulation was solved by using shape-stabilized PCM. These shape-stabilized PCM can be prepared by integrating the PCM into the supporting material. The shape-stabilized PCM are mainly classified as composite PCM and are usually fabricated by embedding PCM into shape stabilization supports such as high density polyethylene, styrene, butadiene, polymethacrylic acid, polystyrene resin, etc. (9).

The incorporation of PCM microcapsules in mortars brings social, economic and environmental benefits, demonstrating a significant contribution to a construction with a higher value of sustainability. The social benefits derive from the increase in thermal comfort inside the buildings. Nowadays, this is an important requirement, frequently demanded by buyers and potential sellers as a fundamental decision parameter. The increase of thermal comfort is achieved by the thermal capacity of the PCM, allowing for the storing and releasing of energy, ultimately keeping the interior temperature sensibly constant, or at least with less variation. The environmental aspect concerns the fossil fuels depletion, given that this technology aims at maintaining constant temperatures inside the building, consequently leading to a decrease on air conditioning equipment usage. The economic benefit is related to the technology adequacy and implementation costs. These should be supported and easily amortized by the user. It may also be noted that the economic benefits of reduced energy consumption and lag times for lower demand are evident, and can be achieved with the use of PCM (4, 10, 11).

Some studies have been published incorporating PCM in construction products. The incorporation of phase change materials in gypsum plasterboard has been the subject of several studies performed, due to its low cost and various possibilities of application (12–15). Darkwa et al. (14), investigated the behavior of two solutions with incorporation of PCM in gypsum plasterboard. In one side the used plasterboard had 12 mm of thickness, fully impregnated with PCM in order to compare with another situation, in which they applied single plasterboards, with 10 mm of thickness, covered by PCM laminate with 2 mm. The amount of PCM incorporated in both cases was the same. The results showed that the use of PCM laminate is more efficient since it contributed to an increase in the minimum temperature. However, other solutions had also been developed like alveolar PVC panels with PCM macroencapsulated, blocks and bricks (7, 16). Cabeza et al. (7), constructed and monitored the behavior of concrete test cells, with and without the addition of 5% of PCM microcapsules. The PCM was incorporated in the concrete used on the roof and south and west walls. During the summer, and without ventilation, a decrease in maximum temperature and a time lag of about 2 hours were recorded.

The study of mortars with incorporation of PCM has been a target of study and interest for the scientific community. However, the application of one ranking procedure for classifying the better performance of the different mortars doped with PCM is one of the main knowledge gaps.

The main goal of this research is the classification of the mortars based on different binders and with incorporation of phase change materials. A ranking procedure that takes into account different properties of the mortars at the same time, based on a function of general performance, was applied. The ranking procedure was based in properties related to the mechanical, durability and thermal behavior. The considered properties were the density, flexural strength, compression strength, adhesion, water absorption by capillarity, water absorption by immersion, freeze-thaw cycles and thermal behavior.

2. RANKING PROCEDURE

Some authors have been applying specific methodologies for classifying different materials, taking into account their functions in the future (17, 18).

Aguiar et al. (18) developed and implemented a ranking procedure of classification of polymeric coatings and hydrophobic agents for concrete protection, in order to determine which is the most convenient to increase the durability of concrete. Thus, the comparison and classification study was applied to epoxy resins, acrylic resins and silicone. The classification performance of these materials was made based on several properties. Ultimately, it was possible to classify a broad range of materials using the same methodology.

Considering that throughout this study several mortars doped with phase change materials have been developed, the need arises to classify these mortars taking into account their behavior based on different properties. The ranking procedure applied in this work was developed by Czarnecki and Lukowshi (17). This methodology is related to the classification of the performance of a material based on a usability function, representing an efficient and convenient procedure for the multi-criteria evaluation. For each performance property y, two values must be selected, y_{better} and y_{worse}, in such a way that the properties of the material should be considered good or satisfactory between these two values. The function d(y) [1] converts the values of y into a performance scale (17, 18):

$$d(y) = e^{-e^{-\left(\frac{y-y_{worse}}{y_{better}-y_{worse}}\right)}} \qquad [1]$$

Where:
$d(y)$ – Function of individual performance;
y – Performance property;
y_{worse} – Worse value of performance properties;
y_{better} – Better value of performance properties.

The functions of individual performance for each property are combined to a complex criterion by one function of general performance [2]:

$$D = \sum_{i=1}^{n} w_i \times d_i \qquad [2]$$

Where:
D – Function of general performance;
W_i – Weigth given to the performance property y_i;
d_i – Function of individual performance of property y_i.

The range of satisfactory values for the individual performance of a specific property is between 0.37 and 0.69. The performance values near 1 are related with a high performance of the material and the performance values near 0 are related with low performance.

Table 1 shows the properties considered in this study. In order to use the general function of performance in mortars, each property must be formulated quantitatively, establishing the values of y_{better}, y_{worse} and w_i.

3. EXPERIMENTAL PROGRAM

3.1. Materials

The selection of the mortars takes into account some previous work (10, 11, 19–21). Mortars were based on the following binders: aerial lime, hydraulic lime, gypsum and cement. The used aerial lime has a purity of 90% and density of 2450 kg/m^3. The used

Table 1. Properties considered in the ranking procedure

	Property	Behavior
1	Density (kg/m^3)	Physical behavior
2	Flexural strength (MPa)	Mechanical behavior
3	Compression strength (MPa)	Mechanical behavior
4	Adhesion (MPa)	Mechanical behavior
5	Capillary absorption coefficient (kg/(m^2·min 0.5))	Durability
6	Water absorption by immersion (%)	Durability
7	Loss of mass in freeze-thaw test (%)	Durability
8	Maximum temperature (°C)	Thermal behavior
9	Minimum temperature (°C)	Thermal behavior
10	Cooling situation lag time (min)	Thermal behavior
11	Heating situation lag time (min)	Thermal behavior

gypsum is a traditional one, with high fineness and density of 2740 kg/m^3. The hydraulic lime is a natural lime (NHL5), with density of 2550 kg/m^3. The used cement is a CEM II B-L 32.5N with density of 3030 kg/m^3.

The used PCM 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/m^3 (Figure 1). It is produced by the Devan Chemicals, with the commercial name of Mikathermic D24. The process of fabrication is polycondensation by addition. This PCM exhibits a transition temperature of 24 °C in the heating cycle and 21 °C in the cooling cycle. Regarding the dimensions of PCM microcapsules, granulometry tests were performed using a laser particle size analyzer. It was possible to observe a particle size distribution between 5.8 to 339 µm and with 80% of particle size between 10.4 to 55.2 µm (Figure 2). The choice of this PCM was based in the temperature transition and the enthalpy. The temperature transition for the selected PCM must be within the desired range of comfort temperatures (20 °C to 25 °C), in order to guarantee both the storage and release of thermal energy. A high enthalpy is also required for maximizing the energy storing capability (3).

The used superplasticizer was a polyacrylate, with a density of 1050 kg/m^3. The used sand has an average particle size of 439.9 µm and a density of 2600 kg/m^3. Finally, polyamide fibers were used with a length of 6 mm and a density of 1380 kg/m^3.

3.2. Compositions

Twelve compositions were studied with the main goal of determining the general performance of the different mortars (Table 2). The used compositions have different contents of PCM and different binders. The water content was established so that the flow value, determined by following the standard EN 1015-3, was 205±5 mm.

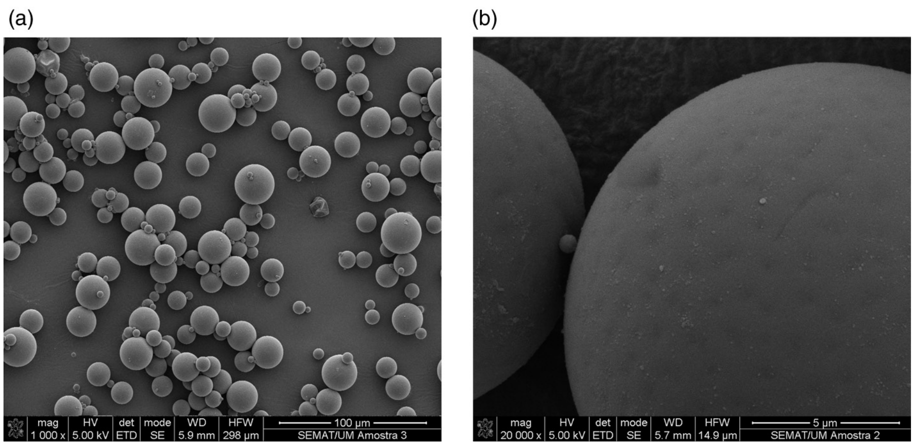

Figure 1. Microscope observation of polymer surface of the microcapsules B: a) enlargement of 1000x; b) enlargement of 20000x.

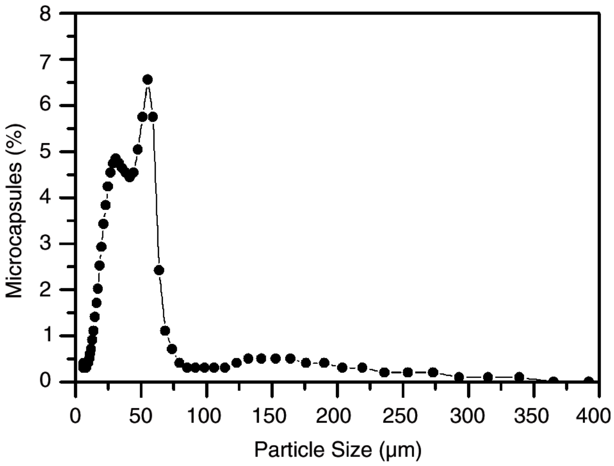

FIGURE 2. Particle size distribution of PCM microcapsules.

3.3. Test Procedures and Results

3.3.1. Density

Regarding the density of the different mortars, a reduction of its value with the incorporation of PCM microcapsules was observed (Figure 3). The incorporation of 40% of PCM caused a decrease in mortar density of about 30% for all tested binders. This behavior can be explained by the low density of the PCM, as well as the increase in the water quantity used to produce these mortars. The incorporation of fibers did not cause changes in the density, since the content used in each composition is low.

3.3.2. Flexural and compression strengths

The mixture procedure and specimen preparation for the compression and flexural tests followed the standard EN 1015-11 (22). For each composition, 3 prismatic specimens with 40×40×160 mm^3 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 50N/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.

According to the results (Figure 4) it was possible to observe a decrease in flexural strength caused by the introduction of PCM microcapsules. The incorporation of 40% of PCM microcapsules resulted in a decrease of flexural superior to 35%, with exception of aerial lime based mortars, which increase about 64%. This behavior can be justified by the high quantity of binder into these mortars.

Regarding the compression strength (Figure 5), all tested binders 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 20% when compared to the reference mortar.

The incorporation of polyamide fibers in mortars led to an increase in the flexural strength of about 51% for aerial lime based mortars. The mortars based on hydraulic lime, gypsum and cement did not show any influence associated with this addition. The improvement observed essentially for aerial lime based mortars is related to the capacity of fibers to oppose the formation of cracks. These can be due to high quantity of binders into these mortars. Concerning the compression strength, it was possible to verify a significant increase in aerial lime based mortars. The remaining binders showed

TABLE 2. Mortar formulations (kg/m^3)

Composition	Binder		Sand	PCM	SP	Fibers	Water/Binder
CA500-0PCM	Aerial lime	500	1447.2	0	15	0	0.45
CA800-40PCM	Aerial lime	800	451.2	180.5	24	0	0.34
CA800-40PCM-F	Aerial lime	800	425.2	170.1	24	8	0.36
CH500-0PCM	Hydraulic lime	500	1351.1	0	15	0	0.54
CH500-40PCM	Hydraulic lime	500	571.6	228.6	15	0	0.62
CH500-40PCM-F	Hydraulic lime	500	567.2	226.9	15	5	0.62
C32.5N500-0PCM	CEM II B-L 32.5N	500	1418.8	0	15	0	0.55
C32.5N500-40PCM	CEM II B-L 32.5N	500	644.3	257.7	15	0	0.56
C32.5N500-40PCM-F	CEM II B-L 32.5N	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

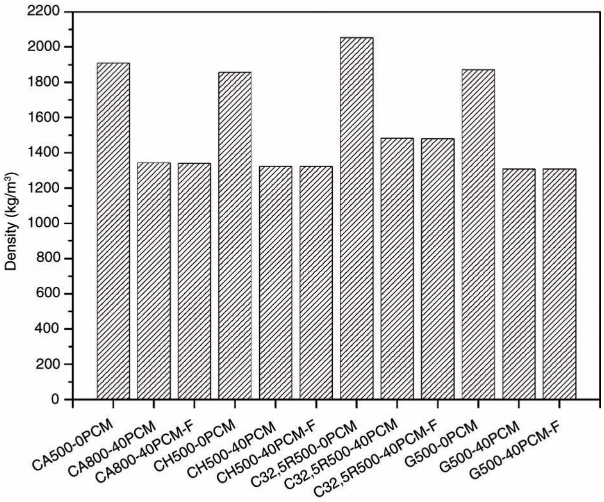

FIGURE 3. Density of the different mortars.

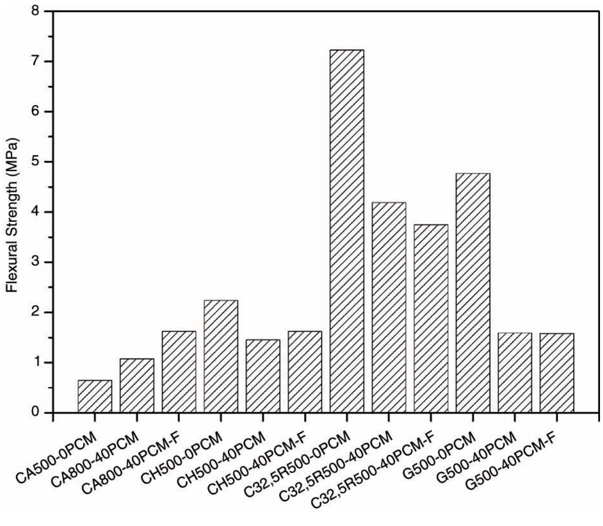

FIGURE 4. Flexural strength of the different mortars.

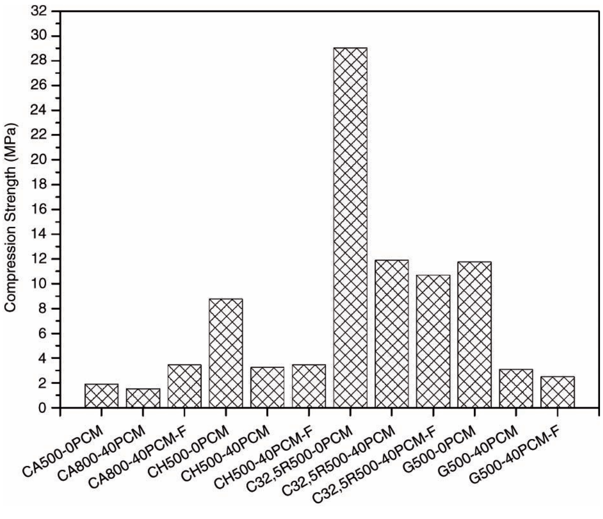

FIGURE 5. Compression strength of the different mortars.

a residual decrease in the compressive strength. In these cases it is possible to consider that the incorporation of polyamide fibers was not beneficial.

The binder which presented lower losses of flexural and compressive strength was the cement CEM II 32.5N B-L. In contrast, the binder which showed higher sensitivity to the incorporation of PCM microcapsules, and consequently higher losses in the mechanical properties, was the aerial lime. This behavior can be justified by the increase of water/binder ratio caused by the introduction of a higher content of PCM, which caused higher porosity in mortars.

3.3.3. Adhesion

Regarding the adhesion tests, the mixture procedure and specimens preparation followed the standard EN 1015-12 (23). For each studied composition 5 circular test areas with a diameter of 50 mm were prepared. Following 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.

It was possible to estimate the adhesion of the mortars at 28 days, when applied to a ceramic substrate frequently used in the construction industry to perform masonry. The tests were performed only for the reference compositions (0% PCM) and those with incorporation of 40% of PCM and 1% of polyamide fibers, since the compositions with incorporation of 40% of PCM and without addition of fibers showed cracks in surface related to shrinkage, making impossible to perform these tests.

According Figure 6 it is possible to observe a decrease in adhesion with the incorporation of PCM microcapsules. The incorporation of 40% PCM leads to a decrease in the value of adhesion of about 33%.

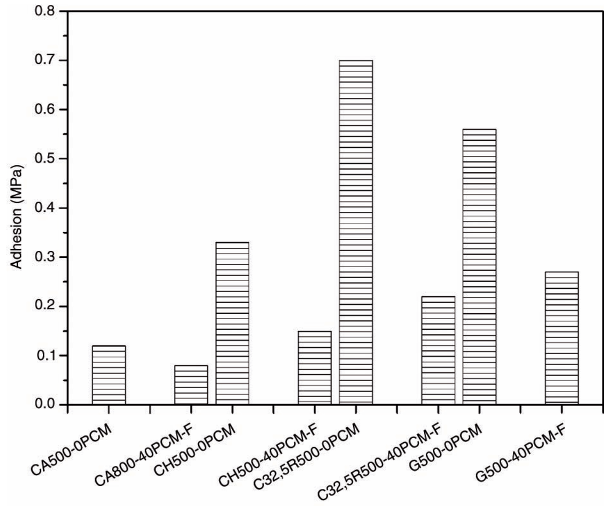

FIGURE 6. Adhesion of the different mortars.

3.3.4. *Water absorption by capillarity*

The water absorption by capillarity tests were performed based on the European standard EN 1015-18 (24). The samples were obtained by cutting the prismatic specimens with dimensions of 40×40×160 mm^3, using flexural tests. 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 in specimens. These weight measurements were accomplished according to a previously established weighting plan, beginning with the first contact of the specimens with water. The obtained results allowed us to determine the water absorption by capillary of the different mortars. The capillary absorption coefficient was determined according to expression [3]:

$$C = \frac{M_2 - M_1}{\sqrt{t_f - t_i}} \quad [3]$$

Where:
C – Capillary absorption coefficient (kg/(m^2·min$^{0.5}$));
M_1 – Weight of the specimen in contact with water at the instant 10 minutes (kg/m^2);
M_2 – Weight of the specimen in contact with water at the instant 90 minutes (kg/m^2);
t_f – Final time, instant 90 minutes (min);
t_f – Initial time, instant 10 minutes (min).

On the one hand, according to Figure 7, 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 main purpose of incorporating 1% of polyamide fibers was to control shrinkage in the developed mortars. Their presence in mortars caused a decrease in the capillary absorption coefficient of about 4% in the aerial lime based mortars, 13% in the gypsum based mortars, and 63% in the cement based mortars. The hydraulic lime based mortars did not present any change 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 water/binder ratio.

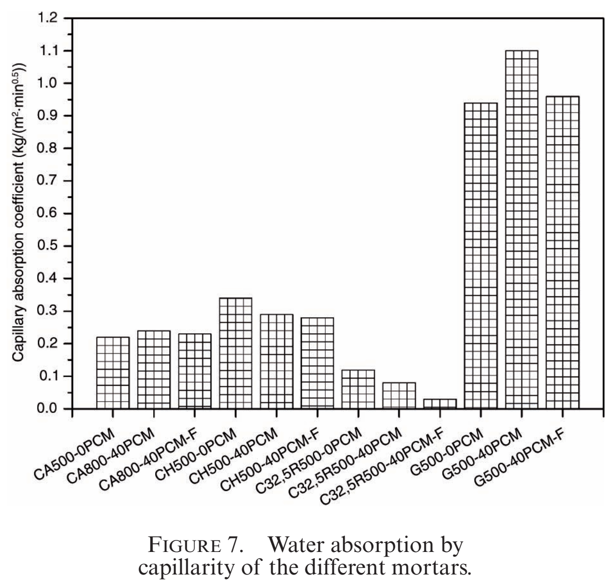

Figure 7. Water absorption by capillarity of the different mortars.

3.3.5. *Water absorption by immersion*

The water absorption by immersion tests were based in the specification LNEC E 394 (25). The samples were obtained by cutting the prismatic specimens with dimensions of 40×40×160 mm^3, using flexural tests. For each composition, 3 specimens were prepared, resulting in 6 samples after flexural tests.

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, the hydrostatic mass was determined.

The obtained results allowed us to determine the water absorption by immersion of the different mortars. This was determined according to the expression [4]:

$$W = \frac{M_1 - M_3}{M_1 - M_2} \quad [4]$$

Where:
W – Water absorption by immersion (%);
M_1 – Mass of saturated specimen (g);
M_2 – Hydrostatic mass of saturated specimen (g);
M_3 – Mass of dried specimen (g).

Regarding Figure 8, 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 did not undergo any change. It was also possible to identify that the gypsum based mortars and hydraulic lime based mortars presented the higher water absorption values. Yet, the cement based mortars showed a lower water absorption.

3.3.6. *Freeze-thaw tests*

These tests consist of submitting the specimens to cycles of positive and negative temperatures. Note that when there are negative temperatures, the water

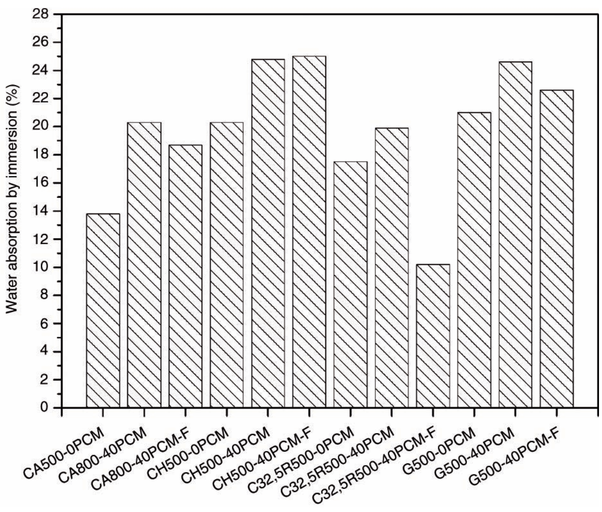

FIGURE 8. Water absorption by immersion of the different mortars.

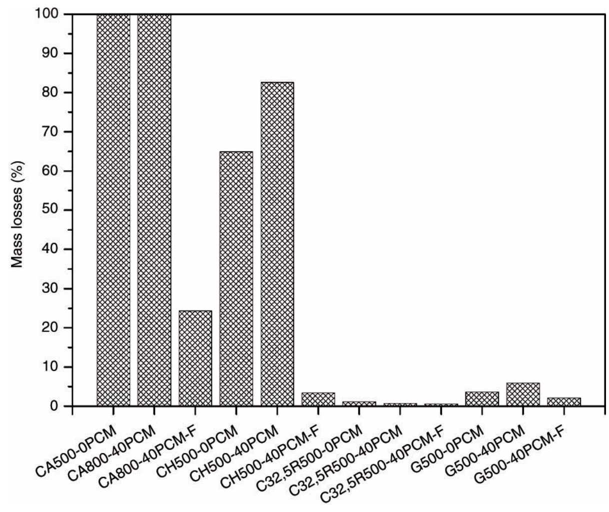

FIGURE 9. Mass losses in the freeze-thaw tests.

inside the structure of the mortars freezes and consequently increases its volume. If the pores of the mortar are not saturated, the problems that can arise are minimal, since the volume of frozen water is inferior to the volume of the pores.

However, if the pores are saturated, the resulting increase in volume causes a pressure increase on the microstructure of mortars, which can cause cracking and even the partial destruction of the specimens.

The freeze-thaw tests were conducted based in the standard CEN/TS 12390-9 (26). The equipment used for the tests was programmed with a law temperature and humidity. Each freeze-thaw cycle has duration of 24 hours, a total of 56 cycles were performed. During each cycle of freeze-thaw, temperature ranges between to the maximum of 24 °C to the minimum of −18 °C.

In order to account for the variation of mass, each sample was individually placed in a container able to contain its mass losses, resulting from the degradation verified during the freeze-thaw cycles. The quantification of mass losses was performed by conducting successive weightings of the specimens. These weight measurements were made according to a previously established plan of weighting, beginning in the first cycle.

Figure 9 shows the total degradation experienced by the specimens of the different tested compositions. It was observed that the incorporation of PCM generally resulted in higher losses of the material during the freeze-thaw action, demonstrating that the incorporation of PCM microcapsules in mortars results in a higher susceptibility to its effect. This behavior is related with the ease that the aggressive agents have to penetrate into the mortar, and can be evidenced by the increase in porosity with the incorporation of PCM. Moreover, the incorporation of fibers in all tested mortars allowed for the observation of a decrease in mass loss, associated with a higher resistance to the passage of the aggressive agents, which once again is confirmed by the decrease of mortar porosity, caused by the introduction of polyamide fibers.

3.3.7. Thermal Behavior

The thermal behavior was tested in a climatic chamber, with temperatures law 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 was developed. These cells have dimensions of 200 mm ×200 mm ×200 mm. The cells were coated on the inside with a mortar layer of 1 cm. 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 in the interior temperatures of incorporation of PCM in the mortars. The setup of the thermal tests is shown in Figure 10.

It is known that the external temperature significantly influences the behavior of the PCM, since this material has a great effect in areas where winter and summer are harsher (28, 29). Thus, based on weather data, a campaign of tests were 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, different seasons of the year were evaluated. However, extreme situations are the most interesting for the study of the PCM behavior.

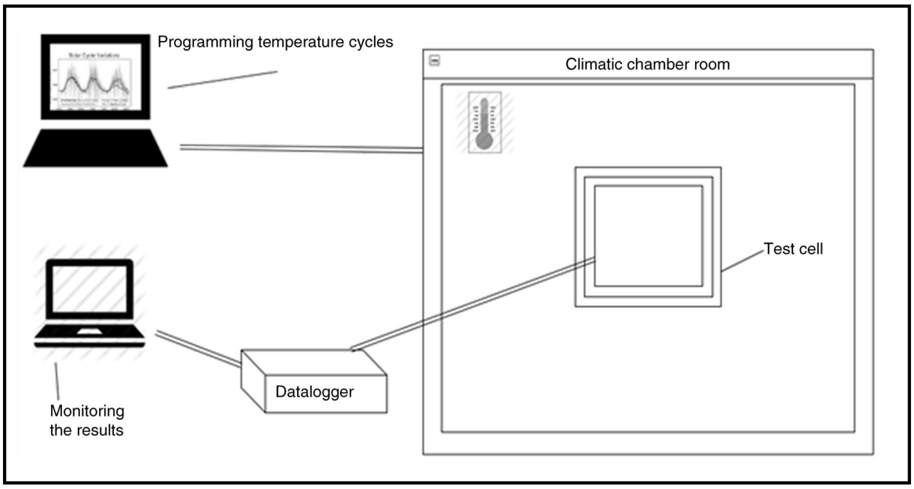

FIGURE 10. Setup of the thermal tests, adapted from Kheradmand et al. (27).

For simulation of winter conditions, 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 the mortars with PCM in summer conditions was evaluated, since the range of temperature was wider. Figure 11 shows the temperatures 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 conditions, three cycles were performed and each cycle had duration of 24 hours.

According to Figure 12 it is 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 and 1% of polyamide fibers were tested, since the compositions with incorporation of 40% of PCM and without addition of fibers showed cracks in surface, making it impossible to perform these tests.

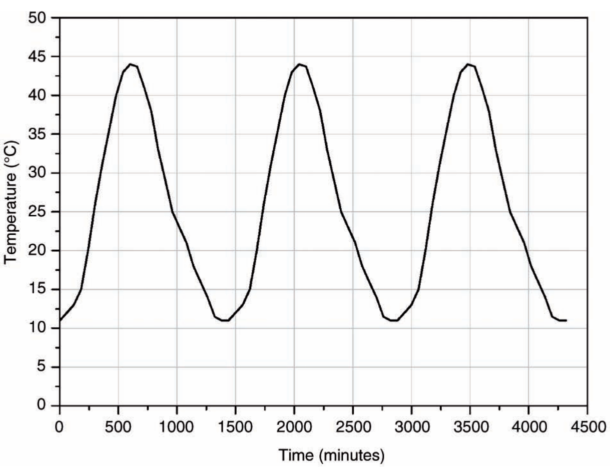

FIGURE 11. Law of temperatures for summer simulation.

For all compositions with PCM, it was observed that the temperature curves evolved in a different way when compared with the temperature curve of the reference mortar. For the cooling situation, i.e. when the temperature exceeds 25 °C, the mortars with PCM showed lower maximum temperature. A similar behavior was verified for the heating stage, i.e. 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.

The reference cell always shows 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 the positive effect of the PCM in all tested compositions was verified, since cells with PCM did not reach such extreme temperatures as the reference test cell (0% PCM), and the temperature inside remains stable for a longer period. 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, were observed. This means that a shortest operation time of heating, cooling, and air conditioning systems is verified when the composite materials with PCM are used, and that effective energy saving can be achieved.

The gypsum based mortars exhibit 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 13). However, in all compositions, it was possible observe an increase in the minimum temperature, and a decrease in the maximum temperature.

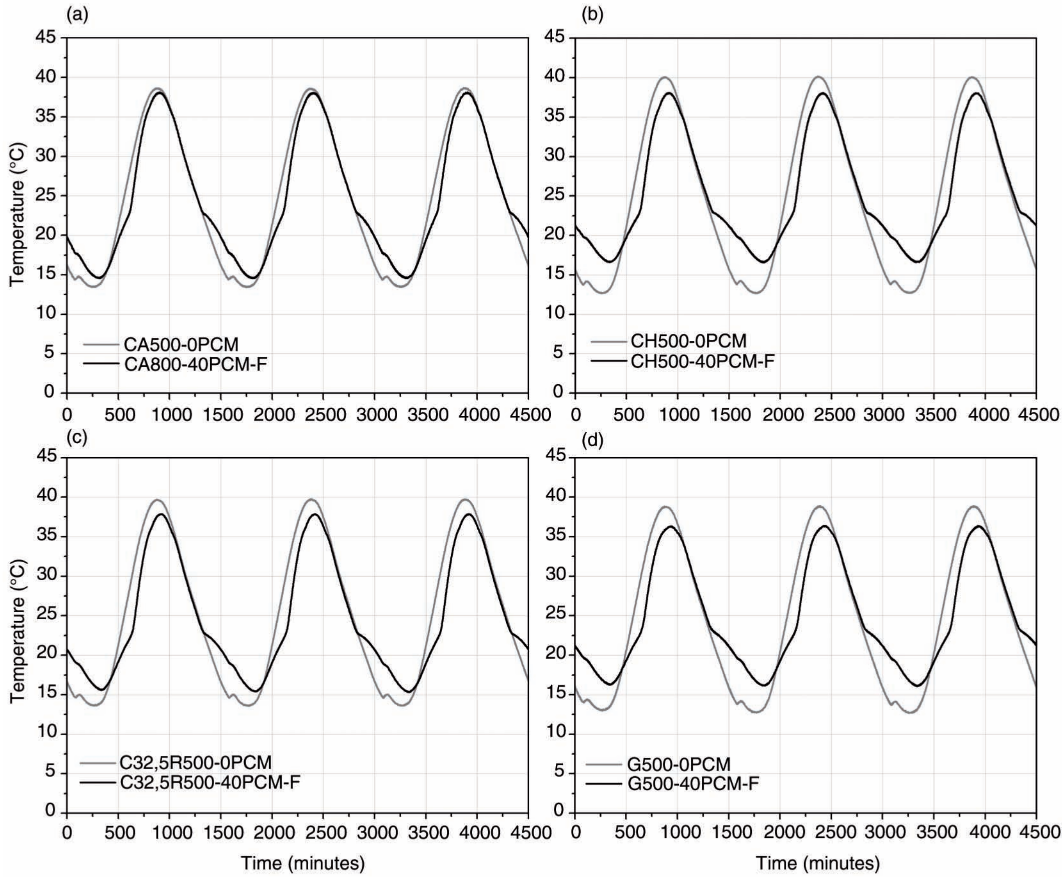

FIGURE 12. Thermal behavior in summer of developed mortars: a) Aerial lime based mortars, b) Hydraulic lime based mortars, c) Cement based mortars, d) Gypsum based mortars.

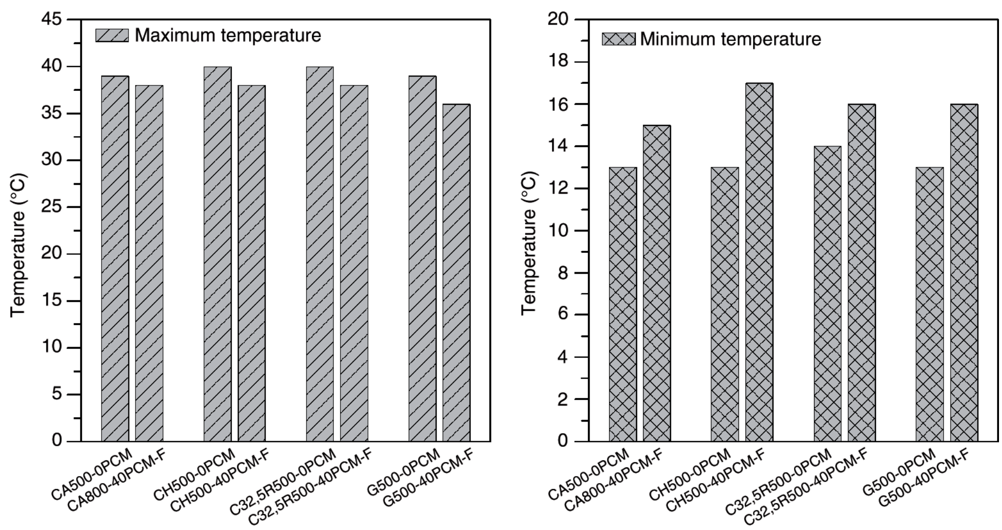

FIGURE 13. Maximum and minimum temperature achieved with the different mortars.

During these tests, 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, was also observed (Table 3). It is know that the major part of residential buildings electricity consumption is used for space

TABLE 3. Lag time between maximum and minimum temperatures with developed mortars

	Lag time (min)	
Binder	**Cooling situation**	**Heating situation**
Aerial lime	30	60
Hydraulic lime	60	70
Cement	40	80
Gypsum	55	85

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.

4. RANKING OF MORTARS

The rankings of the tested mortars were established using the procedure previously presented. Based on the presented results, it was possible to determine the best and worst performance of each property, for each studied mortar. The results obtained are reported in Table 4.

In this study, it was decided to establish different rankings based on the main properties related to the mechanical, durability and thermal behavior. The three properties related to the mechanical behavior were the flexural strength, compression strength and adhesion. The durability was considered with regard to the water absorption by capillarity, water absorption by immersion and freeze-thaw resistance. This choice was based in the standard NP EN 998-1, which considers these as the most important properties for mortars for interior coating (30). The thermal behavior was considered based on the maximum and minimum temperatures achieved during the tests, and in the lag times verified during the cooling and heating situations.

TABLE 4. Worse and better values of properties

Property	y_{worse}	y_{better}
Density (kg/m^3)	2054	1308
Flexural strength (MPa)	0.65	7.23
Compression strength (MPa)	1.53	29.05
Adhesion (MPa)	0	0.7
Capillary absorption coefficient (kg/(m^2·min$^{0.5}$))	1.1	0.03
Water absorption by immersion (%)	25	10.2
Loss of mass in freeze-thaw test (%)	100	0.6
Maximum temperature (°C)	40	36
Minimum temperature (°C)	13	17
Cooling situation lag time (min)	30	60
Heating situation lag time (min)	60	85

Table 5 presents the individual performance of each property for each composition. Taking into account the differences between the mortars, it was possible to establish multiple levels of comparison. Thus, different classifications based on different weighting factors for each property were realized. In this study, the applicability of different mortars was disregarded for the ranking, since this is exactly the same interior lining of buildings, independently of the used binder.

In order to take into account the different properties, four evaluations were made. The first one considered the mechanical behavior as the most important. The second one considered the durability as the most important aspect. The third considered the thermal behavior as the most important aspect. In these evaluations, the main properties possess a greater calculation factor. However, the remaining properties of the mortars were not disregarded. It is important obtain a mortar with high mechanical strength, adequate durability, and high thermal performance for application in the construction industry. Thus, different weighting factors were allocated in the different classifications. Finally, the fourth classification considered the global behavior by assigning the same importance to all properties.

4.1. Ranking based on the mechanical behavior

Table 6 show the weight factors considered for the ranking based on the mechanical behavior.

Figure 14 presents the global performance of the mortars. It is possible to observe that cement based composition without PCM (C32.5N500-0PCM) have the better performance, since these present high values for all dominant properties. The composition with lower performance is the aerial lime with incorporation of PCM (CA800-40PCM), since it shows relatively low compressive and flexural strengths, and it was even impossible to perform the adhesion tests. A decrease in the global performance of mortars incorporating 40% of PCM superior to 11% was verified, with exception of aerial lime based mortar. This situation can be explained by the decrease of the mechanical properties of mortars with incorporation of PCM. The incorporation of 1% of fibers caused a positive effect in the global performance of mortars, evidenced by an increase higher than 16%. This situation is related not only to an increase in mechanical strength of mortars with incorporation of fibers, but also with the best performance in the properties related with the durability, since these were also taken into consideration in this classification.

4.2. Ranking based on the durability

Table 7 shows the weight factors considered for the ranking based on the durability.

Table 5. Individual performances of different properties

d_i	Density	Flexural strength	Compression strength	Adhesion	Capillary absorption coefficient	Water absorption by immersion	Loss of mass in freeze-thaw test	Maximum temperature	Minimum temperature	Cooling situation lag time	Heating situation lag time
CA500-0PCM	0.44	0.37	0.37	0.43	0.64	0.63	0.37	0.46	0.37	0.37	0.37
CA800-40PCM	0.68	0.39	0.37	0.37	0.64	0.48	0.37	0.37	0.37	0.37	0.37
CA800-40PCM-F	0.68	0.42	0.39	0.41	0.64	0.52	0.63	0.55	0.55	0.55	0.61
CH500-0PCM	0.46	0.46	0.46	0.54	0.61	0.48	0.5	0.37	0.37	0.37	0.37
CH500-40PCM	0.69	0.41	0.39	0.37	0.63	0.37	0.43	0.37	0.37	0.37	0.37
CH500-40PCM-F	0.69	0.42	0.39	0.45	0.63	0.37	0.68	0.55	0.69	0.69	0.64
C32.5N500-0PCM	0.37	0.69	0.69	0.69	0.67	0.55	0.69	0.37	0.46	0.37	0.37
C32.5N500-40PCM	0.63	0.56	0.5	0.37	0.68	0.49	0.69	0.37	0.37	0.37	0.37
C32.5N500-40PCM-F	0.63	0.54	0.49	0.48	0.69	0.69	0.69	0.55	0.62	0.6	0.68
G500-0PCM	0.46	0.59	0.5	0.66	0.42	0.47	0.68	0.46	0.37	0.37	0.37
G500-40PCM	0.69	0.42	0.39	0.37	0.37	0.38	0.68	0.37	0.37	0.37	0.37
G500-40PCM-F	0.69	0.42	0.38	0.51	0.42	0.43	0.69	0.69	0.62	0.67	0.69

Figure 15 presents the global performance of the mortars. It was observed that the cement based composition with incorporation of PCM and fibers (C32.5N500-40PCM-F) have the best performance. In contrast, the hydraulic lime and gypsum based mortars with incorporation of 40% of PCM (CH500-40PCM and G500-40PCM) showed the lowest performance. It was observed that the incorporation of 40% PCM caused some fragility in the global performance of the mortars, resulting in a decrease exceeding 5%. This situation can be explained by the lower resistance of compositions with PCM to the freeze-thaw tests, and the increase in water absorption by immersion, allowing an easier penetration of aggressive agents. The incorporation of fibers appears to be quite positive, resulting in an increase in the global performance of the mortars in more than 17%. This behavior is associated with decreased water absorption by immersion, and the lower losses of mass during the freeze-thaw actions.

4.3. Ranking based on the thermal behavior

Table 8 shows the weight factors considered for the ranking based on the thermal behavior.

Figure 16 presents the global performance of the mortars. It was possible observe that the gypsum and cement based mortars with incorporation of 40% of PCM and 1% of fibers (G500-40PCM-F and C32.5N500-40PCM-F) have the best performance. In contrast, the aerial lime, hydraulic lime and gypsum based mortars with incorporation of 40% of PCM (CA500-40PCM, CH500-40PCM and G500-40PCM) showed the lowest performances. This situation can be explained by the impossibility of carrying out the tests of thermal behavior in mortars with PCM and without fibers, because of its high cracking. It was observed that the incorporation of 40% PCM and 1% of polyamide fibers caused an improvement in the global performance of the mortars, resulting in an increase higher than 29%.

Table 6. Weight factors for the ranking based on mechanical behavior

Property	w_i
Density (kg/m^3)	0.05
Flexural strength (MPa)	0.2
Compression strength (MPa)	0.2
Adhesion (MPa)	0.2
Capillary absorption coefficient (kg/(m^2·min$^{0.5}$))	0.05
Water absorption by immersion (%)	0.05
Loss of mass in freeze-thaw test (%)	0.05
Maximum temperature (°C)	0.05
Minimum temperature (°C)	0.05
Cooling situation lag time (min)	0.05
Heating situation lag time (min)	0.05

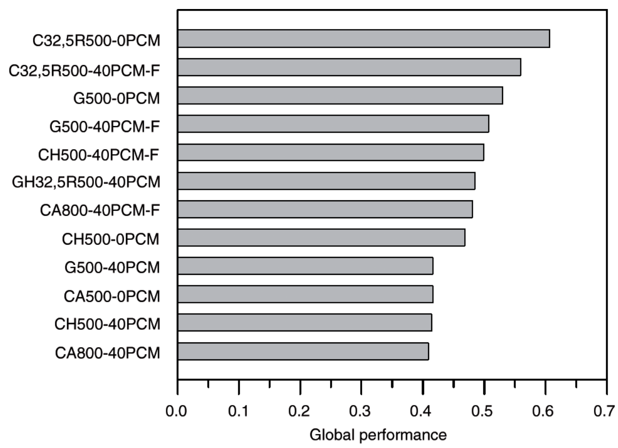

Figure 14. Global performance ranking based on the mechanical behavior.

Table 7. Weight factors for the ranking based on durability

Property	w_i
Density (kg/m^3)	0.05
Flexural strength (MPa)	0.05
Compression strength (MPa)	0.05
Adhesion (MPa)	0.05
Capillary absorption coefficient (kg/(m^2·min$^{0.5}$))	0.20
Water absorption by immersion (%)	0.20
Loss of mass in freeze-thaw test (%)	0.20
Maximum temperature (°C)	0.05
Minimum temperature (°C)	0.05
Cooling situation lag time (min)	0.05
Heating situation lag time (min)	0.05

Table 8. Weight factors for the ranking based on thermal behavior

Property	w_i
Density (kg/m^3)	0.05
Flexural strength (MPa)	0.05
Compression strength (MPa)	0.05
Adhesion (MPa)	0.05
Capillary absorption coefficient (kg/(m^2·min$^{0.5}$))	0.05
Water absorption by immersion (%)	0.05
Loss of mass in freeze-thaw test (%)	0.05
Maximum temperature (°C)	0.16
Minimum temperature (°C)	0.16
Cooling situation lag time (min)	0.16
Heating situation lag time (min)	0.16

This behavior is related to the storage and release energy capacity of the PCM.

4.4. Ranking based on all properties

Table 9 shows the weight factors considered for the ranking based on all properties.

Figure 17 presents the global performance of the mortars. It was possible observe that the cement based mortars with incorporation of 40% of PCM and 1% of fibers (C32.5N500-40PCM-F) have the best performance. In contrast, the aerial lime, hydraulic lime and gypsum based mortars with incorporation of 40% of PCM (CA800-40PCM, CH500-40PCM and G500-40PCM), and the aerial lime based mortar without the incorporation of PCM (CA500-0PCM), showed the lowest performance.

5. CONCLUSION

The use of this ranking procedure enables the establishment of comparisons between the studied mortars in all analyzed cases. The quantification of the material selection criterion makes the choice more objective, and independent on subjective feelings or opinions. The set of criteria can be extended to take into account other aspects or characteristics of mortars. The insertion of such criteria could drastically change the ranking of the products. This ranking procedure certainly presents a valuable tool for evaluation of performance of different materials.

Regarding the ranking based in the mechanical behavior and durability, the cement based mortars presented a better performance compared with the mortars based in other binders. This situation can be justified by the high mechanical strengths, low losses of mass during the freeze-thaw tests, and lower water absorption by immersion. The worst global performance was presented by the aerial lime and hydraulic lime based mortars, due to the lower mechanical strengths, and higher losses during the freeze-thaw tests. In these rankings, it was concluded that the reference mortars, and the mortars with incorporation of PCM and fibers presented, in all situations, a better performance, compared with the mortars with incorporation of PCM only.

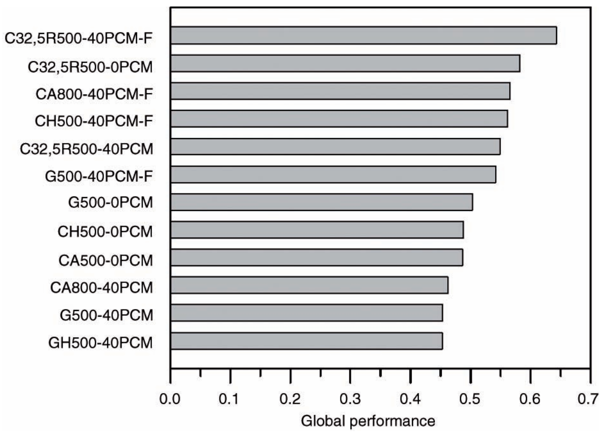

Figure 15. Global performance ranking based on the durability.

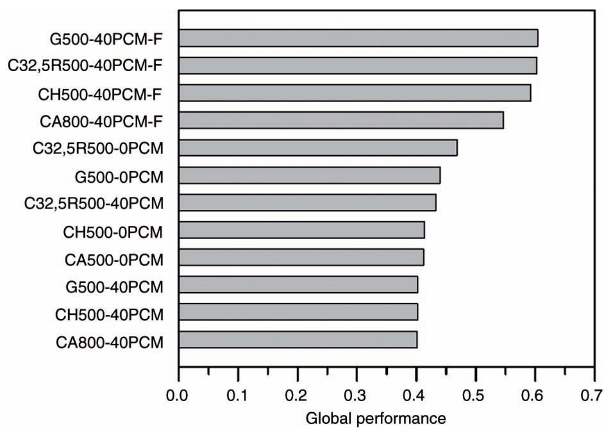

Figure 16. Global performance ranking based on the thermal behavior.

TABLE 9. Weight factors for the global ranking

Property	w_i
Density (kg/m^3)	0.09
Flexural strength (MPa)	0.09
Compression strength (MPa)	0.09
Adhesion (MPa)	0.09
Capillary absorption coefficient (kg/(m^2·min$^{0.5}$))	0.09
Water absorption by immersion (%)	0.09
Loss of mass in freeze-thaw test (%)	0.09
Maximum temperature (°C)	0.09
Minimum temperature (°C)	0.09
Cooling situation lag time (min)	0.09
Heating situation lag time (min)	0.09

According to the ranking based on the thermal behavior, it was observed that the mortars with incorporation of PCM and fibers always showed a better performance when compared to the reference mortars. The cement based mortars with incorporation of PCM and fibers showed the best results. This result is justified not only by the good thermal performance of the mortar, but also by its good mechanical behavior and durability.

Globally, with respect to the ranking based in all properties, it was verified that the cement based mortars showed the best performance, and the aerial lime based mortars the worst performance.

Finally, it can be concluded that the mortars with incorporation of PCM and fibers, even with a lower global performance in some cases compared with the reference mortars, always present a good performance, allowing us to assure their suitability for the construction industry with greater facility and safety.

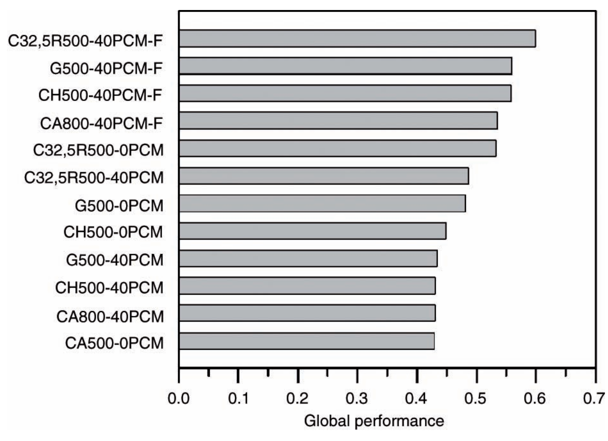

FIGURE 17. Global performance ranking based on the all properties.

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