Materials Research. 2023; 26(suppl. 1):e20230068
DOI: https://doi.org/10.1590/1980-5373-MR-2023-0068

Thermal Performance Investigation of Phase Change Materials in Concrete Blocks Masonry

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Received: January 15, 2023; Revised: September 26, 2023; Accepted: October 25, 2023.

Mortars containing phase change materials (PCMs) were tested to determine their applicability to the thermal control of buildings. One mini-wall prototype was coated with mortar without PCM, whereas the three other prototypes were coated with mortar added with 5%, 10%, and 15% PCM. All specimens were subjected to visual analysis, scanning electron microscopy coupled with energy dispersive X-ray analysis, and differential scanning calorimetry. Thermal analysis was conducted using K-type thermocouples under irradiation by 1000 W halogen lamps. Compared with the other samples, the sample containing 15% PCM required more water in the mixture to achieve a good consistency. Compared with the reference mortar containing 0% PCM, specimens containing 5%, 10%, and 15% PCM showed greater thermal delay. The results of this study reveal that the use of PCM in buildings might lead to significant energy savings.

Keywords: *Thermal performance, Addition, Shrinkage, Concrete blocks, Masonry.*

1. Introduction

Global economic growth has led to an increase in the consumption of electricity, which is mainly obtained from non-renewable sources. High electricity consumption has directly affected the population and environment[1]. The construction sector lacks definitions regarding the environmental impact of energy consumption in buildings, which occurs throughout their life cycle from construction to operation and maintenance[2].

Phase change materials (PMCs) are considered highly suitable for building construction and rehabilitation owing to their ability to transfer heat while changing phase at a given temperature[3-6]. A PCM is a substance that can store and release heat energy as it changes in phase from solid to liquid and from liquid to solid, respectively. A wide range of phase transition temperatures can be achieved by modifying the chemical structures of PCMs. Organic paraffin, a commercially available material, can have a phase transition temperature between 10 and 70 °C, with a latent heat capacity of approximately 200–250 J/g[7]. Organic PCMs are the most common type of PCMs because they are chemically stable, do not undergo cooling, are neither corrosive nor toxic, and have a high latent heat of fusion[8]. These materials have been applied in the claddings of building facades to render buildings more energy efficient, avoiding the need for heat generation/absorption systems, such as air conditioning systems, which have high energy consumption[9].

No references in the literature are available on the applications of the Thermoball®[10] PCM used in this work as additives in cementitious materials. The relevant studies are limited to its use as an additive for painting and lining other industrial surfaces, such as clothes and metals.

In-depth studies on the applications of PCMs to civil construction must be conducted to provide greater comfort and economic advantages to users by increasing the thermal inertia of building materials and reducing the need for heating and cooling equipment. If building materials, especially facade lining, are properly designed with PCMs and sized and applied appropriately, significant economies of scale can be generated for users and buildings produced with these materials could be of greater value, as they are more sustainable.

This study aimed to investigate the thermal behavior of mortars blended with different percentages of PCM when applied to concrete blocks. The structural viability of the mortar–PCM specimens was examined by visual analysis and scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM/EDS). In addition, the thermal viability of the specimens was studied via differential scanning calorimetry (DSC) and thermal analysis using K-type thermocouples under irradiation with 1000 W halogen lamps.

2. Materials and Methods

General-use industrial mortar sourced from Quartzolit® from Saint Gobain, Brazil[11] was used in this investigation, and the PCM microcapsules were supplied by Insilico®, from Seoul, South Korea[11]. The properties of the mortar and microcapsules are shown in Table 1. The experimental scheme and materials used are presented in Figure 1.

Mini-wall specimen compartments measuring 400 × 400 × 140 mm^3 were constructed to simulate the conventional walls of multi-story buildings. The constituent blocks had dimensions of 140 × 390 × 190 mm^3 and 140 × 190 ×

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190 ^{mm3}, and they were laid with a 10 mm-thick layer of the commercial mortar between them.

Four types of mortar were prepared to coat blocks external face with 10 mm-thick layers, which were named according to the PCM addition: Ref – without PCM, T1 – with 5%, T2 – with 10%, and T3 – with 15% of PCM addition, respectively.

The inner face of the concrete bricks was not insulated, and the external faces of all specimens were painted with white acrylic paint.

Table 1. Data of the mortar and PCM microcapsules used in this study.

PCM microcapsules	InSilico Thermoball®
Average diameter	15 microns
Lining Material	Melamine-Polyoxymethylene
Encapsulated material	Paraffin
Melting temperature	28º C
Enthalpy	170 to 175 J/g
Mortar	Quartzolit® Multimass Mortar for general use
Composition	Cement, mineral aggregates and special additives
Water dosage (recommendation)	135 ml/kg
Apparent dry density	1.50 kg/cm^3
Density of fresh mortar	1.80 kg/cm^3
Consumption	17 kg/m^2/cm
Type of mixture	Mechanical

A box was fabricated to establish an internal insulated space to avoid spurious results arising from other external heating or cooling influences on the opposite face of the mini-walls. This box was made of 15 mm-thick plywood and internally insulated with 30 mm of polystyrene.

The thermal gradient signals of specimens placed inside the box were acquired by three K-type sensors with the software and hardware necessary for data acquisition at the acquisition rate of 8 Hz because of the long time necessary to evaluate a temperature change of approximately 1.5 °C.

The mass of water added to each mixture increased as the PCM percentage increased, as shown in Figure 2.

In this study, the authors developed a method of testing, since there was no used the real solar conditions along the time to have control of the external boxes conditions of temperature and relative humidity. After the calculation of the solar radiation, was proposed first, the use of two 400W infrared lamps, that were not efficient due to the time spent for heating the external wall face.

To provide more power in less time to avoid the radiation transfer to the ambient, two 1000 W halogen lamps (Figure 3a) were employed as radiation sources. Temperature sensors (K-type thermocouple) and ThermData 0.0.1® software were used to measure the heat transmitted throughout the prototypes, and the data were analyzed using Origin 8.1. Three sensors were positioned diagonally over each prototype, as shown in Figure 3b. The samples (mass, 3 ± 0.5 mg) were subjected to DSC, which was performed over the temperature range of 0–100 °C at a heating rate of 5 °C/min under a nitrogen

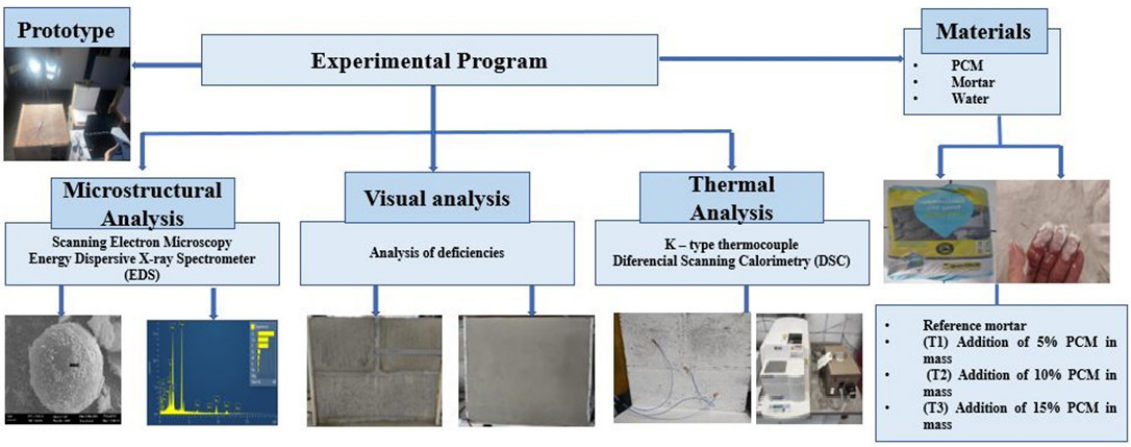

Figure 1. Flowchart of the experiments.

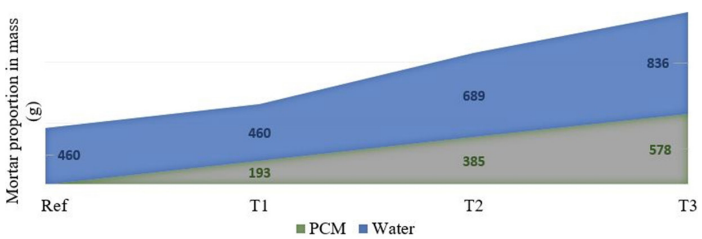

Figure 2. Proportion of added water related to the amount of PCM in the mortar.

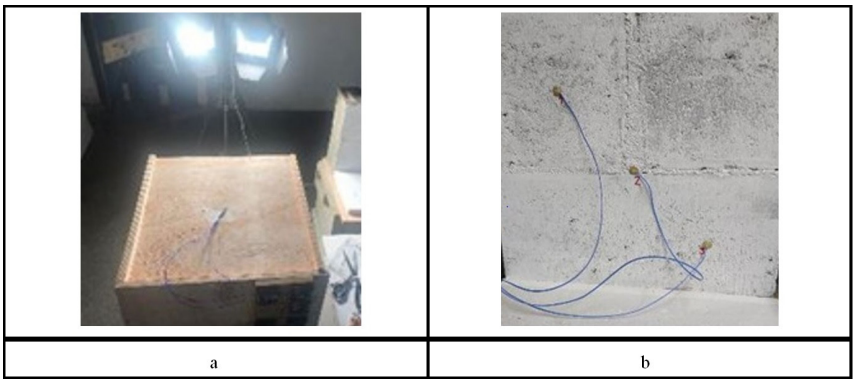

Figure 3. (a) Set used in the study. (b) Positioning of sensors.

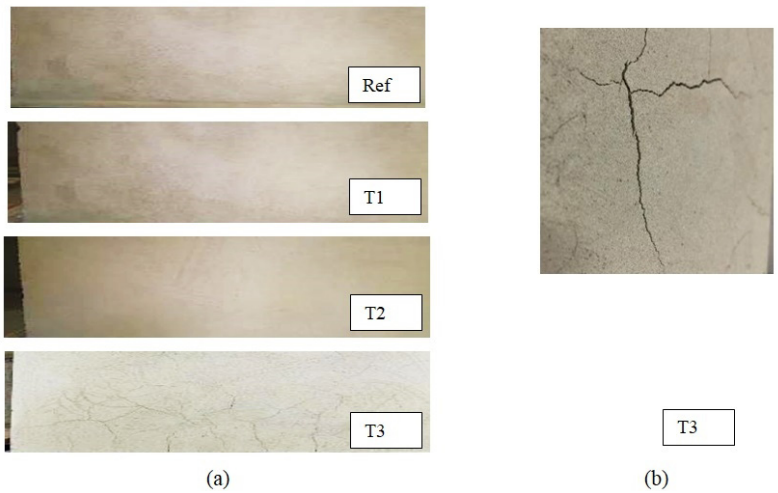

Figure 4. (a) Visual results of the mortar prototypes. (b) Pronounced map-shaped crack of prototype T3.

atmosphere. A pure PCM sample was also analyzed to verify the melting point provided by the manufacturer. SEM-EDS analysis was performed to identify the constituent materials of the samples.

3. Results and Discussion

3.1. Visual analysis

The mortar applied to the prototypes presented rapid and uniform hardening; this characteristic was maintained over time in samples Ref and T1 (Figure 4a). These samples did not develop cracks. Specimen T3 showed several cracks (Figure 4a), with T3 showing more serious damage in terms of both quantity and dimensions (Figure 4b).

The cracks observed were mainly caused by shrinkage during the hardening of the mortar, which is an undesirable phenomenon during the hardening of cementitious materials. When the water used to hydrate the paste is lost to the surface of the microcapsules, reductions in resistance and crack formation may occur. The map-shaped cracks shown in Figure 4b are usually caused by a lack of or inadequate cure. Studies indicate that the addition of microspheres with diameters between 1 and 25 μm increases the water demand of the mixture.

3.2. SEM-EDS analysis

The scanning electron micrographs shown in Figure 5 reveal the rupture of some microcapsules following their mechanical mixing with the mortar. Microcapsule rupture releases the PCM into the mortar, leading to a loss of its function and interferences with microcapsule–matrix adherence.

Figures 6a-c show the adherence of the PCM to the mortar matrix. The PCM in t T2 and T3 adhered well to the mortar matrix but that in sample T1 did not. The low adherence between the microcapsules and matrix in T1 may be due to the low water content of the mixture, which leads to poor hydration. Figure 6d shows an image of sample T3; good homogeneity between the microcapsules and mortar can be observed. The PCM microcapsules crystallized onto the surface of the concrete, thereby ensuring good adherence.

EDS analysis was performed to verify the composition of sample T3, which showed two microcapsular regions.

The first remained intact after the mixing of the mortar and PCM microcapsules (Figure 7a), whereas the second showed broken PCM microcapsules (Figure 7b). The first region was composed of 8.7 wt% silica (Si) and 65 wt% carbon (C). The second region was composed of a larger amount of Si (44%), which is the constituent material of the mortar, and a smaller amount of C (17%), which is because of the PCM (paraffin). These results indicate that the rupture of PCM microcapsules leads to the loss of this material into the mixture and reductions in homogeneity afforded by the solid microcapsules.

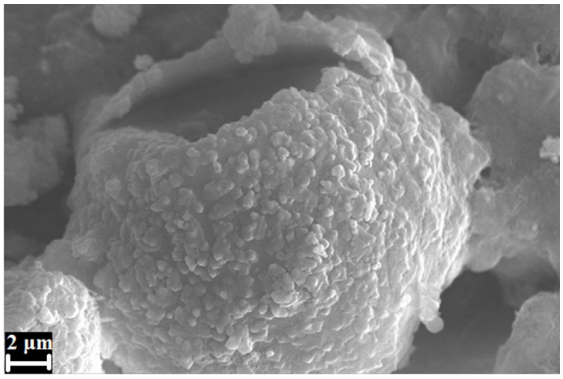

Figure 5. Damaged PCM.

3.3. DSC analysis

The melting point of the pure material was identical to that provided by the manufacturer. Figure 8 depicts the peak melting points of pure PCM, which showed the most significant peak, as well as those of the Ref, T1, T2, and T3 mixtures. The mortars with added PCM showed the same endothermic peak when the temperature reached 28 °C, indicating the influence of PCM on the melting point of the samples.

Variations in the PCM microcapsule content of the cementitious matrix influenced the heat storage capacity of the resulting materials. The heat storage capacity of the samples showed a nonlinear increase, with the mortar containing 15% PCM exhibiting optimal results. When the results of pure PCM (not mixed with mortar) and T1 were compared, the melting enthalpy of the mixed sample markedly decreased from 181 to 5.84 J/g, which is equivalent to a decrease in heat storage of approximately 97%. With samples T2 and T3, the heat storage decreased by approximately 93% and 81%, respectively. This finding demonstrates that increases in the amount of PCM added to the mortar considerably increase the amount of heat present

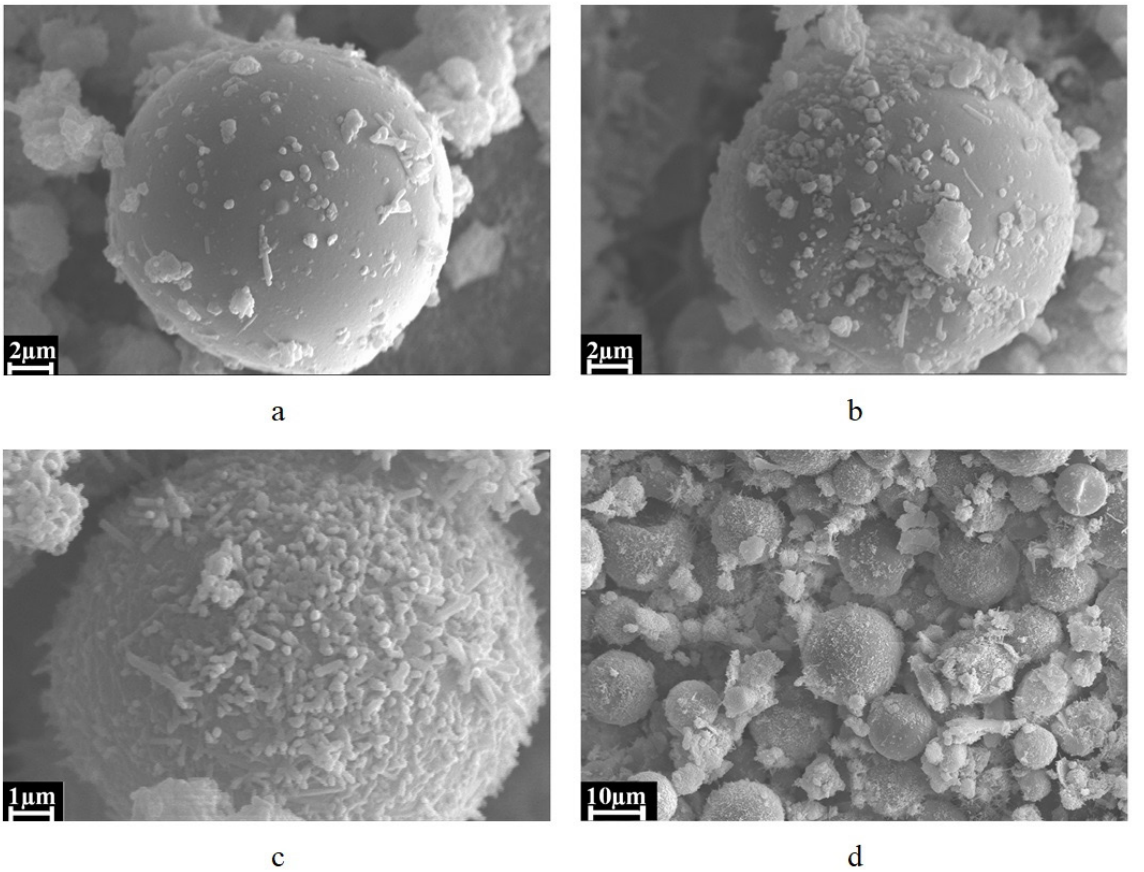

Figure 6. Percentage of addition T1, T2 and T3 respectively in (a), (b) and (c-d).

in it. The melting points of pure PCM and all samples are shown in Table 2. These melting points are consistent with the manufacturer's data.

The phase transition temperatures of the mortar samples decreased when compared with that of pure PCM.

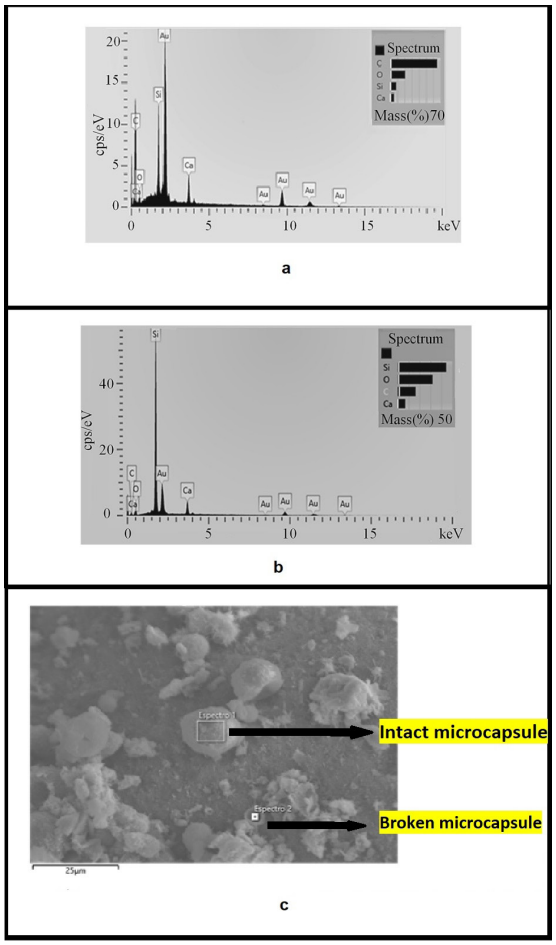

Figure 7. (a) EDS 1- intact microcapsules. (b) EDS 2 – broken microcapsules. (c) SEM image of the EDS analysis.

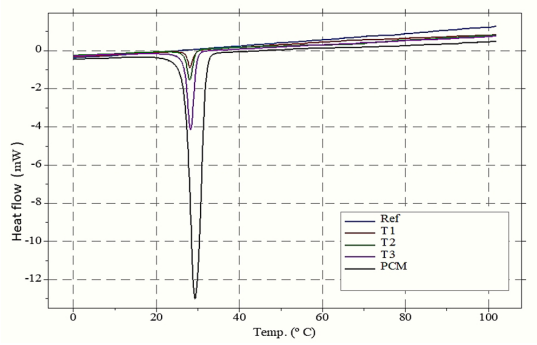

Figure 8. DSC test with melting points for each treatment and for pure PCM.

3.4. Results of thermal radiation testing

Figures 9a-d present the thermal analysis results of Ref. T1, T2, and T3, respectively.

The temperature and time results were normalized to enable the accurate comparison of the average results by wall and specimen because the start time and test duration for each specimen differed owing to differences in the time required to reach the peak temperature in the insulated compartment. Figure 10 shows the average normalized temperature and time results of all specimens.

As shown in Figure 10, among the specimens, T3 may be considered the most efficient in terms of time to increase, stabilize, and decrease the temperature to room temperature. T1 required approximately 3 h (9000 s) to achieve the maximum temperature and decrease it. This time is similar to the time required by the sample to release the heat completely to the external environment. T3 was the second most efficient sample. The time required by this sample to achieve peak heating was approximately 2.5 h (7250 s). However, it required the same time as T1 to achieve heat release to the external environment.

As shown in Table 3, the most efficient specimen in terms of thermal inertia and time to absorb and release heat radiation is T2. Although the temperature of this specimen increased rapidly over less than 90 min, it presented the lowest thermal gradient among all specimens prepared. Indeed, the thermal gradient of T2 was 44% lower than that of T1 and 56% lower than that of T3.

Having determined the ability of T2 to not only absorb and release heat but also retain the external temperature of the material, the results must be carefully verified because this study is a preliminary investigation on the use of Thermoball® PCM as a mortar additive.

Table 2. Melting point of the samples.

Study treatments	Fusion (°C)
PCM	29.2
T1	28.1
T2	28.0
T3	28.2

Table 3. Normalized temperature versus time results of the specimens.

Specimen		Time (s)	Temp. (°C)
Ref.	Min.	0.000	0.000
	Max.	2132.167	0.748
	Final	3673.750	-0.007
T1	Min.	0.000	0.000
	Max.	9247.500	1.743
	Final	18611.167	-0.011
T2	Min.	0.000	0.000
	Max.	5350.433	1.152
	Final	17192.333	-0.135
T3	Min.	0.000	0.000
	Max.	7249.167	2.032
	Final	16545.000	0.009

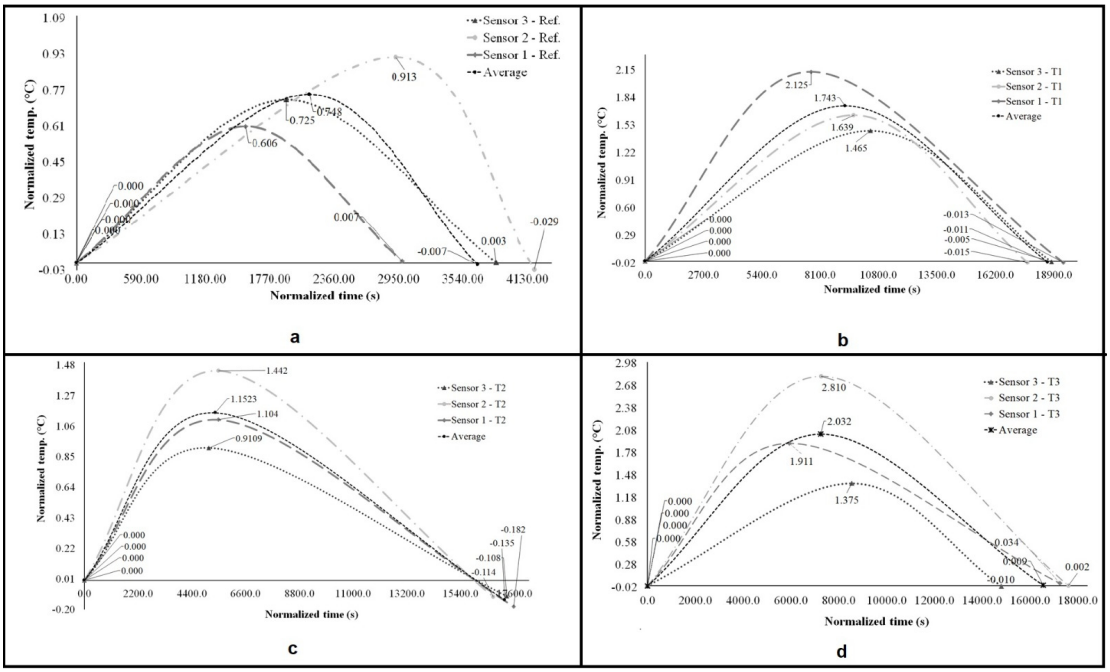

Figure 9. 'a' to 'd' – Results achieved by thermal analysis conducted on each specimen.

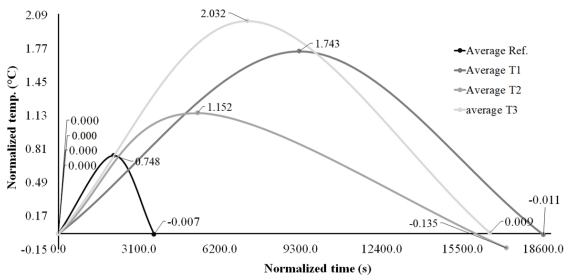

Figure 10. Average normalized results by percentage of PCM mixed with the mortar.

4. Conclusions

The addition of microcapsules with a melting point of 28 °C was proven to be an efficient means to increase the thermal inertia of mortars; thus, these materials could be used in the facade of buildings constructed in tropical countries. The results also revealed that the interaction between the two materials leads to significant changes in the properties of the hardened mortar by increasing the surface area of the particles and, consequently, changing their rheology.

Figure 10 and Table 3 show that the PCM affects two different mortar properties. First, PCM addition changes the time required by the mortar to achieve maximum heat transfer. Second, the PCM could modify the ability of the mortar to block heat transfer from the exterior to the interior of a compartment. The mortar bearing 10% PCM (T2) may reasonably be supposed to be the most effective specimen because the time it required to absorb and release heat energy was longer than those of T1 and T3. This capability is beneficial for its practical applications in tropical countries, as the solar radiation received by buildings in such countries over the period of 12:00–6:00 p.m. is greater than that received by similar structures in other regions of the world.

Further research on similar systems must be conducted to consider the effects of shadowing, such as that observed in high-density urban areas, and assess how the PCM can affect the mechanical strength of mortars and their rheology, as this study was conducted in the geographic region delimited by the latitudes 22°26′12″ S and 24°26′12″ S, where the Tropic of Capricorn is the central latitude. In addition, the influence of the proportion of PCMs in mortar mixtures should be investigated to determine how the PCM ratio influences the curing process.

5. Acknowledgments

The authors thank the Department of Physics, São Paulo State University, Ilha Solteira campus, for allowing the use of their SEM microscopy facilities. They also thank the staff at the multi-user laboratory of the State University of Londrina for allowing the use of their DSC facilities.

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