Chapter 8

Development of Clay Plasters Containing Thermoregulating Microcapsules for Indoor Walls

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Abstract

This work shows the technical feasibility of incorporating phase change materials (PCMs) into clay plastering mortars to improve the thermal properties of the building envelopes. Due to the absence of regulated and internationally agreed-upon norms for clay mortars containing thermoregulating microcapsules (MPCMs), two tests following UNE-EN-998-1:2010 and UNE-EN-1015, were designed to provide the greatest similarity to its final application. Three different dosages 5, 10, and 15 wt% of MPCM relative to the dried mortar weight were used. Fresh mortars were physically characterized to determine its consistency, apparent density, period of workability and open time, and occluded air content. Physical and mechanical characteristics were determined for hardened mortar. The thermal characteristics of the specimens were analysed by using a differential scanning calorimetry, obtaining their apparent specific heat capacities and the enthalpy curves. Building simulation software is a fundamental tool for designing buildings with almost zero energy consumption. In this study, three identical architectural models were simulated. The reference building had inner coatings of clay-based mortar, mortar with 15% added material, and a conventional gypsum mortar. These buildings were subjected to the same exposure and radiation conditions, which allowed the result to be compared to evaluate the effect of incorporating the PCM.

Keywords: phase-change materials (PCMs), clay plaster, thermal energy storage (TES), energy demand

1. Introduction

One of the greatest problems facing society today is energy consumption and environmental pollution. One of the main consumers of energy is the domestic sector, which in the European

Union (EU), for example, represents 25% of the total energy [1]. In fact, given the direct (use of housing) and indirect (materials manufacturing, transport, construction, demolition, etc.) energy costs, it is estimated that the construction industry in developed countries consumes up to 40% of the total energy [2].

The residential sector accounts for 25% of the total energy consumption in the EU and 19% in Spain [3]. Construction, considered part of the industrial sector, accounted for approximately 1 and 2% of the energy consumed in the EU and Spain, respectively, in 2014, according to data from the 2016 edition of Eurostat. The energy consumed in the residential sector combined with all other construction totals 40% of the energy consumed [4].

This is why the future of construction and building cannot be contemplated without designing buildings that consume almost no power, that is, zero-energy buildings (ZEBs). In this regard, legislation related to energy savings in buildings is being implemented around the world. In the EU, [4] on energy efficiency in buildings (EPBD) was approved; its objective is buildings with almost zero-energy consumption in 2020, and more recently [5] on energy efficiency has emphasized the rehabilitation of the building stock of member states.

Some of the strategies to follow for achieving these objectives are reducing the energy demand of air-conditioning systems and searching for materials with smaller carbon footprints through life cycle assessment and life cycle energy analysis [6]. Such strategies must be considered in a more relevant way in the areas of the planet with considerable daily variations in temperature that cause notable differences in energy consumption between day and night. Such variations lead to periods of maximum load and of less activity (with the latter generally between midnight and early morning). If heat or cold thermal energy could be stored at convenience and released into the indoor environment during the moments of greatest demand, some or all of the load peaks could be displaced and other “passive” strategies could be exploited. In this way, energy is managed effectively, which provides economic and environmental benefits.

Indeed, passive conditioning in buildings that store thermal energy by means of phase changes (i.e., latent heat) is an increasingly common trend. It is not surprising, therefore, that during the last years, many studies have been published on the use of phase-change materials (PCMs) in buildings [7–9].

PCMs are substances that, through exothermic and endothermic processes derived from their change of state, are capable of storing large amounts of energy in the form of latent heat and exchanging it with the environment when thermal conditions require it. Among the various changes of state, the solid–liquid has the best characteristics for being used in building construction attending to the small volume change that occurs. According to their nature, PCMs are classified into three broad groups: inorganic, organic and eutectic mixtures; hydrated salts and paraffin are the most common compounds [10]. The main methods of incorporating PCMs are the direct, immersion and encapsulation methods. A detailed description of such systems can be reviewed in [11]. There are two types of encapsulation: macroencapsulation and microencapsulation. In the former, the PCM is packed in tubes, bags, spheres, panels or other containers and then incorporated into the building material. The latter method, microencapsulation, involves small PCM particles being enclosed in a thin film of a high-molecular-weight polymer that must be physical-chemically compatible with both the PCM and the building materials.

The first applications of PCMs to heating and cooling buildings described in the literature date back three decades [12]. In recent decades, a broad spectrum of work has focused on incorporating PCMs to store energy as latent heat into building materials such as plaster and cement walls, roofs, floors, sandwich panels, among others [7, 13]. However, as noted by [14], some difficulties remain in reliable applications, practical uses and validation through modeling processes [15, 16]. In this sense, some studies, such as the one by [17], have characterized and studied the behavior of PCMs embedded in compacted earth elements. However, although these properties are valued, authors do not numerically model the construction element within a complete architectural framework.

In that way, new trends are emerging that vindicate these construction systems, which have been developed by adapting to the climate of each region for years. Bioconstruction tries to relate the natural environment to the urban habitat by promoting the use of materials with practically no environmental impact and conceiving of architecture as a discipline that must be adapted to the environment and not the other way around. The use of new technologies and materials allows to recover the use of other traditional materials, such as earth (soil), which makes them more energy efficient and compliant with the requirements of the elements and current construction systems, thereby reducing the impact on the natural environment.

In this sense, clay presents itself as a material capable of satisfying these new needs. It is natural, recyclable and abundant in most regions of the world. Handling it does not require more resources than the ones used for extraction, and there is no need for transport or firing processes, which ensures that its environmental impact is much lower than that of other construction materials [18].

Since there has been no literature referred to the use of clay plasters containing thermoregulating microcapsules to passive buildings applications, the goal of this work is to study the technical feasibility of incorporating these materials into clay-plastering mortars to improve the thermal properties of the resulting building, contributing to its energy efficiency and habitability. In that way, three different composites containing 5, 10 and 15 wt% of microencapsulated phase-change materials (MPCMs) were synthesized and characterized. Due to the absence of regulated and internationally agreed-upon norms for clay mortars containing thermoregulating microcapsules, two tests following European Normative [19–27], which refers to mortars for masonry, were designed to provide the greatest similarity to its final application. Finally, energetic effects of incorporating PCMs into the coating mortar were simulated and a comparative analysis of the variation of the energy demand was made and based on an architectural model.

2. Materials and methods

The clay-based mortar lining used in this study consists of illite-kaolinite clays, siliceous sands at different granulometries and fiber (straw) without additional chemical additives. This commercial clay was supplied by the company Ecoclay®. The technical characteristics of the material are shown in **Table 1**.

Spherical microcapsules containing Rubitherm® RT27 with a shell from LDPE and EVA-mSD-(LDPE·EVA-RT27) were obtained following the method described in the Patent EP2119498 in a pilot plant spray drying. These microcapsules have an average particle size of 30 μm and a latent heat of 98.14 J/g (**Figure 1**).

The thermal properties of the microcapsules and the clay-based mortars were characterized by differential scanning calorimetry (DSC). Analyses were performed in the range from 0 to 40°C at a heating rate of 5°C/min. The PCM began to accumulate at a temperature of 5.33°C, ending at 32.71°C. In this temperature range, there was a total accumulation of 83.41 J/g, which is the heat storage capacity produced by the phase change of paraffin (i.e., its latent heat). The maximum accumulation point is 12.24 J/g·°C and occurs at 24.27°C (**Table 2** and **Figure 2**).

Materials were tested by following the normative [19–27], which refers to mortars for masonry, attending to the absence of regulated and internationally agreed-upon norms for clay mortars.

Three different dosages were used: 5, 10 and 15 wt% MPCMs per dried weight of mortar. Composite clay mortars were produced by weighting first the desired masses of clay, water and MPCMs and following a mixing protocol according to [23] and the recommendations of Ecoclay. The components were placed together in a tray and mixed firstly for 1 min at an agitation; the stirring was stopped and immediately activated again for other 30 s. Once this time of agitation was achieved, the agitation was stopped per 5 min, in order to reach the proper

Ds (kg/m^3)	LL (%)	LP (%)	IP (%)	Cf (%)
1543	23.8	14.7	9.4	1.52

Table 1. Physical characteristics of the Ecoclay-based-fiber clay mortar: density (Ds), liquid limit (LL), plastic limit (LP), plasticity index (IP), and fiber content (Cf).

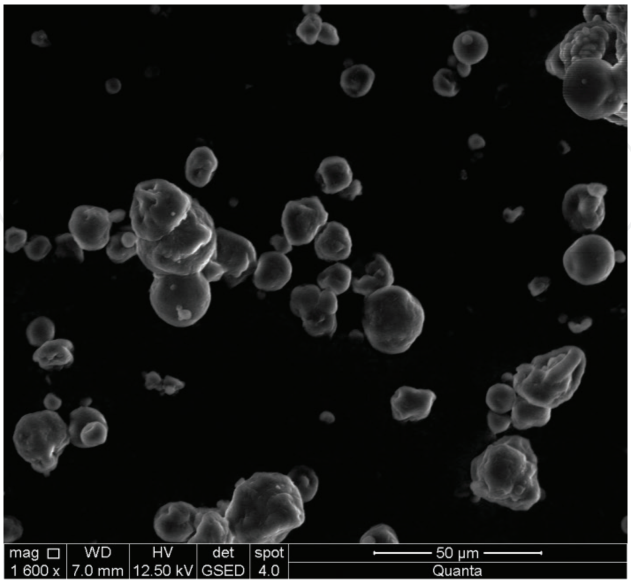

Figure 1. Microcapsules from low-density polyethylene and ethylvinylacetate containing Rubitherm®RT27 by spray drying.

	MCr (°C)	SHc (kJ/kgK)	HSc (kJ/kg)	Ds (kg/m^3)	Dl (kg/m^3)	Hc (W/(mK))	MT (K)
Rubitherm RT27	25–28	2.84	179	880	760	0.2	297.42

Table 2. Physical and thermal characteristics of Rubitherm RT27 (from http://www.rubitherm.com/) for encapsulation using spray-drying: melting/freezing range (MCr), specific heat capacity (SHc), solid density (Ds), liquid density (Dl), heat conductivity (Hc) and maximum operating temperature (MT). DSC was used to determine the SHc of the encapsulated paraffin (2.84 kJ/kg; the HSc was 83.41 kJ/kg for 46% microencapsulated paraffin).

hydration of the mixture. Finally, the mixing procedure was completed after 1 additional minute of agitation.

Test pieces were cured under laboratory conditions (20°C and 60% RH) during 14 days for favoring the chemical reactions in the presence of water, allowing to achieve the proper strength. Further, they were demolded over at least 4 days later (**Figure 3**).

2.1. Physical, mechanical, and thermal characterization

The physical characterization of fresh mortars was performed to determine the consistency using a shaking Table [24], bulk density and occluded air content [25, 26, respectively] and period of workability and open time [27]. Besides, some regulations were adapted to find the density of the test specimens [28], the water vapor absorption [29] and the water vapor permeability [22].

The mechanical study included the flexural strength and compressive strength of the hardened mortar following the [20] and the adhesive strength of plaster mortar and hardened plaster applied to substrates according to the norm [21] and the Shore C hardness following the [28].

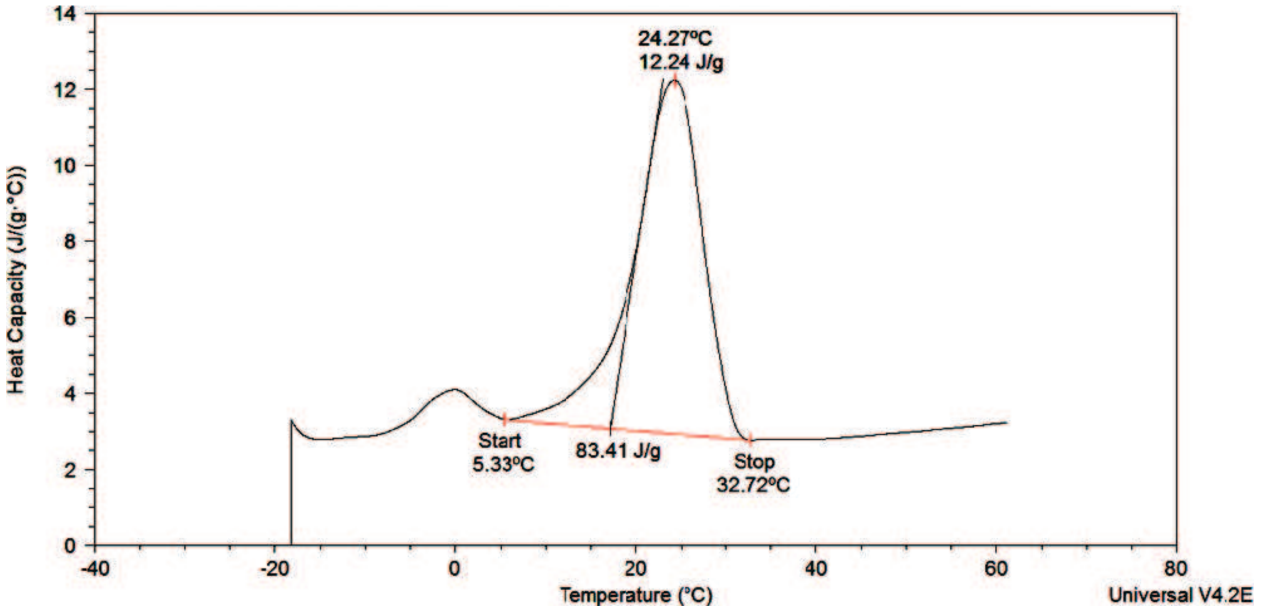

Figure 2. DSC curve of microcapsules of Rubitherm RT27 (from http://www.rubitherm.com/) for encapsulation using spray drying.

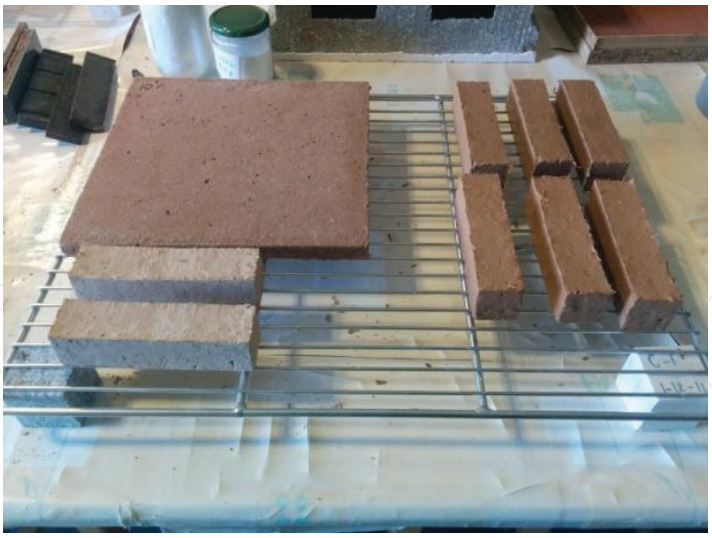

Figure 3. Specimens used for physical, thermal, and mechanical characterization.

Finally, the thermal behavior of the specimens was tested using DSC with a TA Instruments Q100 calorimeter, from which the apparent heat capacity and the enthalpy curves were obtained. The thermal conductivities and the thermal energy storage (TES) capacities were calculated using homemade equipment described and proved in previous works [30, 31].

2.2. Thermal behavior modeling

Experimental results of the resulting construction material were parameterized and modeled using EnergyPlus energy simulation software provided of its graphical interface, DesignBuilder®. This software has been used by [15] to evaluate the energy demand of a reference architectural model containing PCMs. For the proper whole building energy simulation, the program requires the inputs of enthalpy curve of the material, the thermal conductivity and the apparent heat capacity.

The simulation was performed using the finite difference algorithm (CondFD). This algorithm divides the surfaces of walls, floors and ceilings into a system of nodes and uses the implicit method of finite differences to solve the heat transfer equation numerically [32].

2.2.1. Geometry and boundary conditions

The architectural model for the simulation was generated using SketchUp® and it had a simple geometry for ensuring a homogeneous internal airflow throughout the volume, avoiding the presence of preferential heat flows (**Figure 4**). There were no partitions and the internal air was in constant contact with the envelope of the building. This enclosure allowed the volume of indoor air to interact with the external conditions (without infiltrations or ventilation); in this sense, the enclosure was designed to have a high thermal transmittance without insulation except the bottom plate. The gaps were oriented to the west, south and east to ensure that solar radiation was collected throughout the day. Finally, heating, cooling and lighting systems were not incorporated. With these design criteria, it was possible to establish a volume of controlled air that interacted with the environments in which they were located.

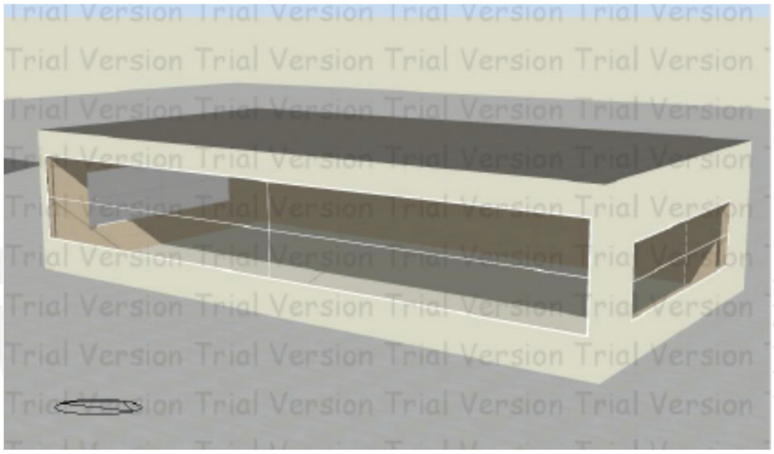

Figure 4. Three-dimensional view of the model building. Total surface area: 112.52 m^2. Latitude: 38.99°. Longitude: −3.9°. Elevation: 629 masl.

The building was located in a central Spanish city (Ciudad Real). This area has a semi-arid continental climate with hot summers (average monthly temperatures above 22°C) and cold winters (average monthly temperatures below 6°C). The annual temperature range can be ranged between 44.3 and −9.4°C, according to the Ciudad Real meteorological observatory. The daily temperature range is also considerable, with ranges of 5–10°C in winter and 15–20°C in summer. The climatic data used in the simulation were obtained from the American Society of Air Conditioning, Refrigeration and Heating (ASHRAE). The hypotheses used with the simulations were developed for summer conditions with simulation periods of 15 days and an integration time step less than 1 min. The selected period was summer, July15–31; each season lasted 408 h.

2.2.2. Construction parameters

The same building was simulated by using two different envelopes of a clay coating containing 15% of thermoregulating microcapsules and other free of PCMs. Results were also compared with those obtained using gypsum as a conventional mortar coating. The thickness of the coating considered was 3 cm, following the manufacturer's recommendations.

3. Results

3.1. Fresh mortar: physical properties

Because this material was applied as a layer of mortar on the inside of the wall, its rheological properties were fundamental. The densities of the samples and the increase in the mixing water required to produce the same runoff of the standard mortar were 1823.34, 1550.07, 1491.19 and 1406.12 kg/m^3 and 0, 9, 18 and 30%, for microcapsules contents of 0, 5, 10 and 15%, respectively. This result indicates that the higher the microcapsule content, the lower the density of the fresh mortar and lower the workability of the mortars.

The open time of the fresh mortar showed that both the standard mortar and the mortars containing different amounts of the MPCMs exceeded the strength determined by the corresponding standard (0.5 N/mm^2) within 6 days of being mixed. On the fourth day, the four samples were very similar in strength, with a significant increase with the presence of microcapsules. On the fifth day, the difference in strength between the different samples increased; the samples containing more of the PCM were stronger. By the sixth day, the trend had reversed, with the standard sample and the sample containing 5% PCM being the strongest.

The occluded air content of the mortar increased substantially when the PCM was incorporated. For the standard sample, it was calculated to be 7%, but with the first addition, this value increased to 14%. There was a downward trend as the dosage increased; the 10% sample contained 14% occluded air, and the 15% sample contained 12% occluded air.

3.2. Hardened mortar: physical properties

The results of the retraction calculation increased as the PCM was added (**Table 3**). These values were 3.22% for the standard sample, 4.71% for the 5% sample, 5.47% for the 10% sample and 6.71% for the 15% sample. As with the apparent density of the fresh mortar, the density of the hardened mortar was evidently influenced by the addition of the MPCMs to the clay mortar (**Table 3**). Logically, the density difference between the dry components (1543 kg/m^3 for the clay mortar and 866 kg/m^3 for the PCM) means that adding the PCM to the mixture necessarily displaced the clay mortar, which caused the density to decrease.

The water vapor absorption capacity decreased as the number of microcapsules increased; however, the high hygroscopic capacity of the clay meant that all the samples, regardless of the PCM content, presented better results than other conventional mortars, such as gypsum or mortars of cement and lime (**Figure 5**). The permeability to water vapor followed the same trend as the absorption of water vapor, that is, both decreased as the PCM was added. This is due to the hydrophobic character of the PCM microcapsules. The standard sample had a permeability of 2.28×10^{-11} kg·m/m^2·s·Pa. After the first addition, this value decreased to 1.42×10^{-11} kg·m/m^2·s·Pa. For the samples containing 10 and 15% by weight, the permeabilities were 1.04×10^{-11} and $0.95\cdot \times 10^{-11}$ kg·m/m^2·s·Pa, respectively. These values represent decreases of 37.7, 54.4 and 58.3%.

Mortar	R (%)	Da (kg/m^3)	Wvp (kg·m/m^2·s·Pa)
MS	3.22	1645.86	2.28×10^{-11}
5%	4.71	1447.26	1.42×10^{-11}
10%	5.47	1437.08	1.04×10^{-11}
15%	6.71	1383.00	0.95×10^{-11}

Table 3. Physical characteristics of the clay mortar samples containing microcapsules at 5, 10, and 15% contents: master sample (MS), retraction (R), apparent density (Da), and water vapor permeability (Wvp).

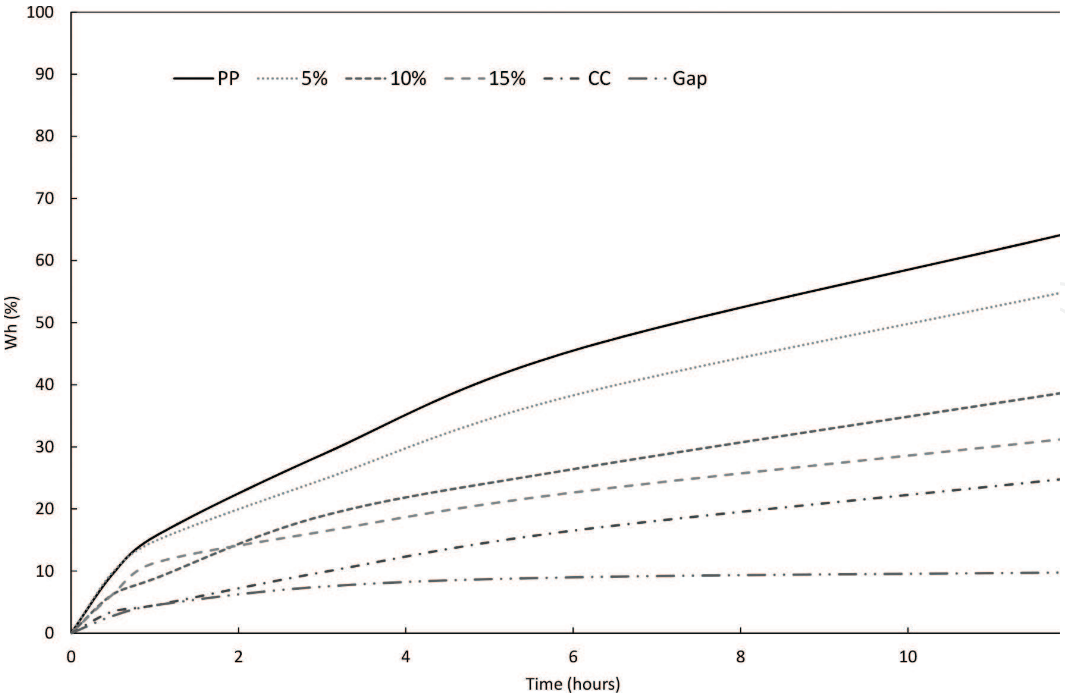

Figure 5. Water vapor absorption curves after a 50–80% increase in the relative humidity for 5, 10, and 15% microcapsule contents, the standard sample (PP), a lime and cement mortar (CC), and gypsum mortars applied by a machine (Gap). The water content (Wh) is shown as a function of time.

3.3. Hardened mortar: Mechanical properties

The results of the mechanical compression and bending tests are shown in **Table 4**. The mechanical strength of the mortars decreased in all cases with respect to the standard sample but it tended to be recovered with the amount of microcapsules. The reductions in compression and flexion for the sample containing 5% of MPCMs respect to the standard sample were 53 and 45%, respectively, indicating that this material meets the minimum requirements to plaster. With respect to the compressive strength, the decrease in strength was 50% for the 10% sample and 46% for the 15% sample. The decrease in the flexural strength was similarly attenuated, by 33% for the 10% sample and by 24% for the 15% sample, with respect to the standard sample.

Mortar	CS (N/mm^2)	FS (N/mm^2)	AS (N/mm^2)	USC (units)
MS	1.76	0.69	0.10	61
5%	0.82	0.38	0.11	38
10%	0.88	0.46	0.10	32
15%	0.95	0.52	0.12	24

Table 4. Mechanical characteristics of the clay mortar samples containing microcapsules at 5, 10, and 15% contents: master sample (MS), compressive strength (CS), flexural strength (FS), adhesion strength (AS) and Shore C hardness (USC).

In the same way, the adhesion test results showed that the perpendicular tensile strength was stable regardless of the amount of the PCM added, even with respect to the standard sample. As for the Shore C surface hardness, a significant decrease in the hardness occurred as the PCM content increased.

3.4. Hardened mortar: Thermal properties

The total latent heat (Ql) and the influence of the melting temperature range of the PCM on the thermal behavior of the mortars were determined by using DSC. **Figure 6** shows the apparent heat capacity (**Figure 6a**) and the enthalpy (**Figure 6b**) of the mortars as a function of the temperature. The apparent heat capacity of the standard sample was completely linear, whereas all the mortars containing MPCMs present a peak that increases with the MPCM content and in the same melting temperature range of the pure PCM. These results indicated that the higher the thermoregulating material used to produce the mortar, the higher the TES capacity of the developed composite.

From this information, the enthalpy curves were determined (**Figure 6b**). Excluding the temperature range in which latent heat accumulates, DSC showed that a certain amount of energy was required to increase the sample’s temperature; we call this the specific heat (Cp). The average specific heat (Cpm) of the standard sample (clay mortar) was 1.0 J/g, which is similar to results obtained for crude earth, whereas that of paraffin is approximately 3.5 J/g. This is why an increase in the Cpm of more than 0.3 J/g is seen as the amount of the PCM is increased. The catalog of construction elements in the Spanish Technical Building Code [33] (i.e., CAT-ECv6.3 MARCH10.doc) lists a heat capacity of 1 J/g°C for several types of mortars, which is in agreement with the data obtained in this study. In the same way, Ql increased as the MPCM content of the mortar increased. For the 5% sample in the influence temperature range of the PCM, it was 2.8 J/g; it was 5.5 J/g for the 10% sample and 10.5 J/g for the 15% sample.

The thermal conductivity remained stable across the different samples; no trend was observed as a function of the amount of the PCM incorporated. Its average value was 0.3 W/m°C (**Table 5**). The TES parameter (kWh/m^3), which evaluates the storage capacity per unit volume, progressively increased with the amount of the PCM incorporated. With the first incorporation of 5% PCM by weight with respect to the standard mortar, an increase of 9% was seen; however, for the higher dosages, the TES capacity increased significantly, by 42% for the 10% PCM sample and by 65% for the 15% sample (**Table 5**).

3.5. Simulation results

The results of the simulations performed for summer conditions are shown in **Figure 7**. It can be seen that the clay mortar with added MPCMs attenuated the temperature peaks in comparison with the reference material building without PCM.

HVAC equipment simulation system has been used to evaluate architectural design strategies in the initial stages of projects, to optimize the environmental and energy-related aspects

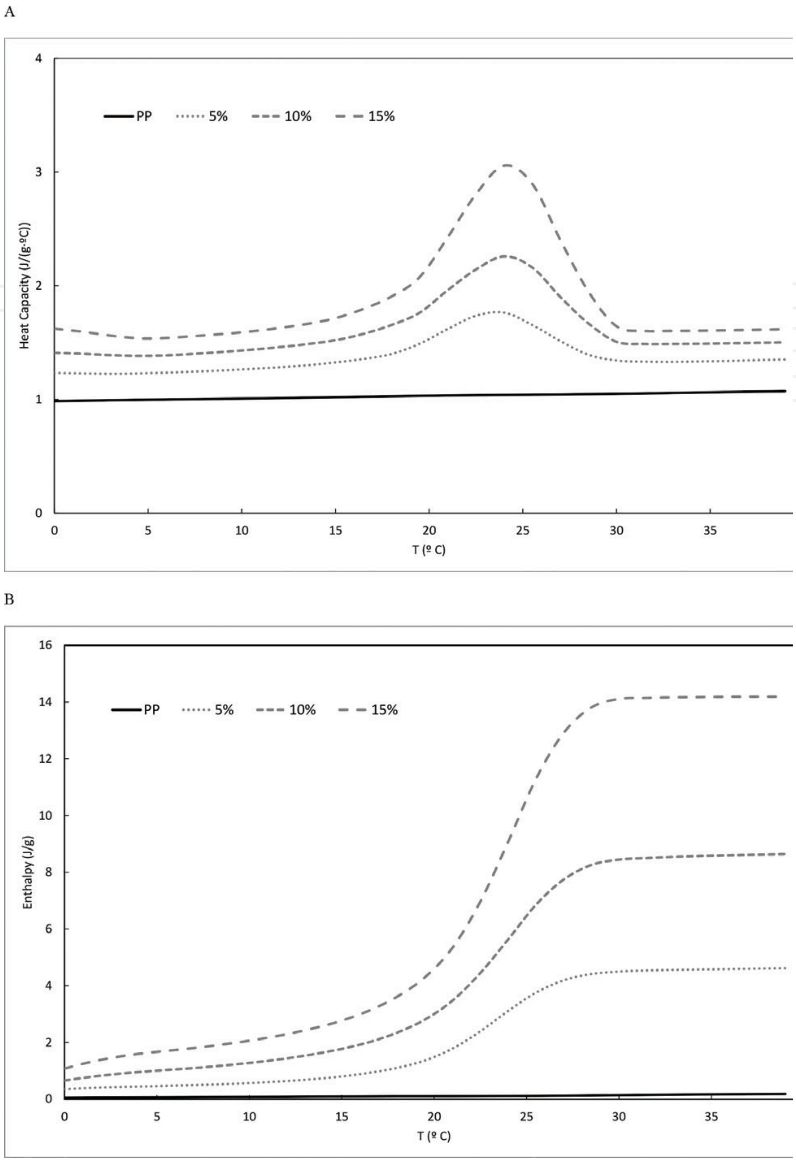

Figure 6. Apparent heat capacity (A) and enthalpy (B) of the mortars containing 0, 5, 10, and 15% of MPCMs.

of buildings and to check the performance of HVAC equipment before modeling the system in detail.

To this end, the model constantly regulates the interior temperature of the building by means of a cooling system when it exceeds the set temperature range. In our case, this range corresponded to conditions for thermal comfort, that is, a maximum of 24°C and a minimum of 21°C. The attenuation and reduction of the temperature peaks by the incorporated PCM meant that less energy was needed to reach the established comfortable conditions (**Table 6**). Under summer conditions (for a study period of 408 h), the simulations show an energy savings between 2 and 4% in the building with the coating containing 15% PCM by weight in comparison with the building with the coating of Ecoclay based-fiber mortar. Relative to gypsum plaster, a savings of almost 10% was produced by adding the PCM to the clay mortar.

Mortar	Ti (°C)	Tf (°C)	Tma (°C)	Map (J/g°C)	Qlt (J/g)	Cpm (J/g°C)	TES (kWh/m^3)
MS	—	—	—	—		1.01	5.22
5%	15.63	31.26	23.57	1.77	2.87	1.28	5.71
10%	14.03	30.55	24.35	2.26	5.53	1.48	7.45
15%	11.10	30.65	24.39	3.07	10.59	1.53	8.62

Table 5. Summary of the results obtained using DSC and the equipment prepared for the thermal characterization of the samples of clay mortar containing microcapsules at 5, 10, and 15% contents: master sample (MS), initial accumulation temperature (Ti), final accumulation temperature (Tf), maximum accumulation temperature (Tma), maximum accumulation point (Map), total latent heat (Qlt), average specific heat (Cpm) and thermal energy storage (TES).

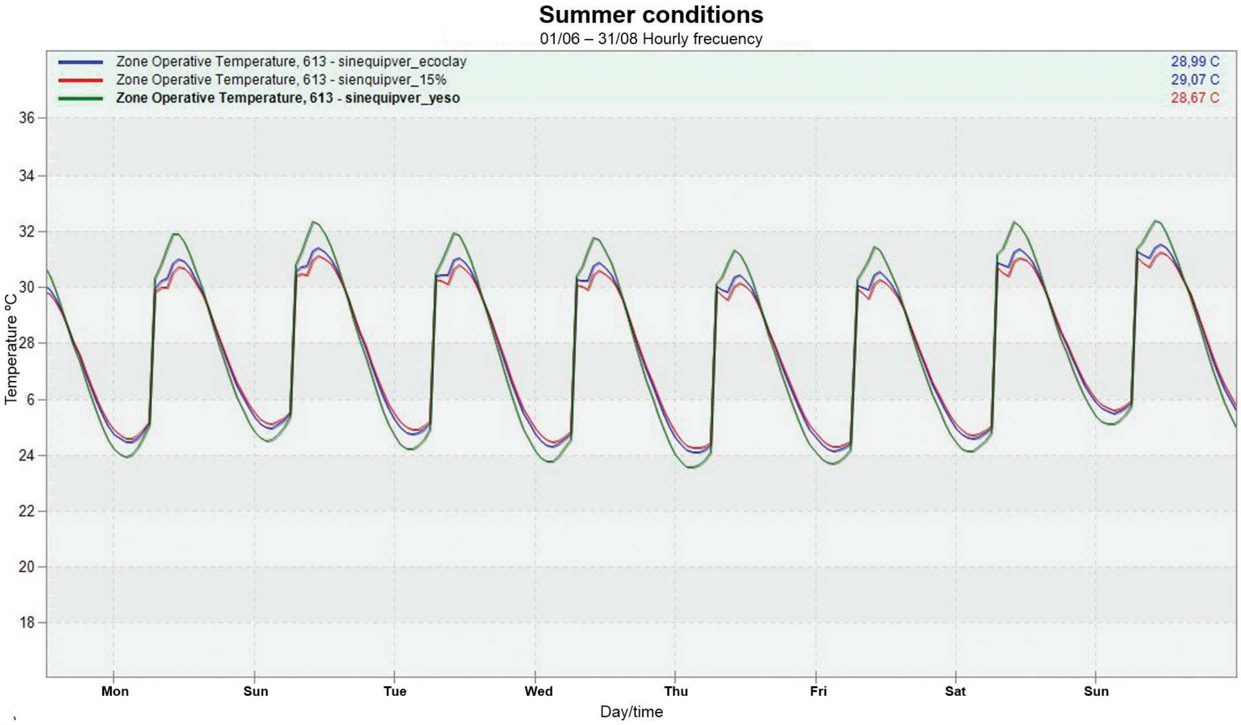

Figure 7. Simulated building temperatures for different types of plaster: clay mortar with a 15% of MPCMs, the standard sample (ecoclay) and a gypsum (Yeso). Summer conditions (July 15–31).

Mortar	TE_{site} (kWh)	TE_{source} (kWh)	$ETBA_{site}$ (kWh/m^2)	$ETBA_{source}$ (kWh/m^2)
B. $MS_{heating}$	593.58	626.63	5.28	5.57
B.$15\%_{heating}$	584.73	617.28	5.20	5.49
B. $Gap_{heating}$	646.01	681.97	5.72	6.04

Table 6. Summary of results obtained by simulating the energy demand using the HVAC (heating/ventilation/air conditioning) option for the different plaster types: clay mortar with a 15% microcapsule content, the master sample (MS), and gypsum mortars applied by a machine (Gap). Summer conditions (July 15–31); 15-day simulation periods, and a step size of less than a minute. Total simulation time: 408 h. Total energy at the site (TE_{site}), total energy from the source (TE_{source}), energy for the total building area at the site ($ETBA_{site}$), and energy per total building area at the source ($ETBA_{source}$).

4. Summary and conclusions

Despite the absence of regulated and agreed-upon rules for the characterization of clay-based mortars, it has been possible to propose a test methodology capable of establishing the technical feasibility of this construction material. Considering the nature of materials derived from crude earth and the descriptions in [19–27], the standard series used for mixing, molding and curing of clay mortars allows the comparative analysis of the results of different dosages.

The results of the fresh mortar tests have been used to evaluate the influence of incorporating a PCM on mixing and workability. One of the conclusions drawn is that the addition of a PCM requires the amount of mixing water to be increased to reach the established runoff values. These data show how the addition of a PCM supposes a decrease in the mortar's workability. Regarding the air content occluded in the mortar, it is observed that the microcapsules are deposited between the clay sheets, which increases the distance between them and increases the number of voids.

In the hardened state, the specimens show that the effects of retraction start to be considerable when the amount of the PCM reaches 10%. However, the response to this increase in retraction should be not to increase the amount of the PCM but to increase the amount of mixing water. This aspect should be analyzed using different clay mortar granulometries to improve workability by adding a PCM, thereby avoiding the increase in the amount of mixing water.

Clay-based products tend to perform well in terms of absorption capacity and water vapor permeability. The water vapor absorption capacity decreases as the number of microcapsules increases; however, the high hygroscopic capacity of clay means that all the samples, regardless of the amount of the PCM added, present better results than other conventional mortars, such as gypsum or cement and lime mortars. The permeability to water vapor follows the same trend as the absorption of water vapor, that is, it decreases as a PCM is added. This is due to the hydrophobic character of PCM microcapsules.

The results of the flexion-compression tests show a decrease in strength in both cases; this is more significant in compression (53.5% with respect to the standard dosage) than in flexion (45%) for the sample containing 5% PCM. The decrease in strength experienced with the first addition of the PCM is justified by the loss of density of the material due to the incorporation of the PCM and the increase in occluded air that it generates in the mortar, as previously mentioned. This argument might explain the increase in resistance between the samples containing 5, 10 and 15% PCM. The voids generated by the first addition of microcapsules are supplemented by increasing numbers of microcapsules as the content increases. This decreases the number of pores, which results in a stronger material. These types of mortars are not designed to withstand mechanical stresses but do maintain their compressive strength within the acceptable range indicated by the regulations [1].

The results of the adhesion test show that the perpendicular tensile strength is stable regardless of the dosage used, even with respect to the standard dosage. As for the Shore C surface hardness, a significant decrease occurs as the PCM dosage increases. This is due to the increase in the amount of occluded air and because increasing the dosage increases the probability that the measurement is performed on an agglomeration of microcapsules.

Using DSC and thermal characterization tests, it was possible to verify that incorporating paraffin microcapsules into the clay mortar is effective. The latent heat increases as the PCM content increases, as expected when the addition is performed correctly. It is 2.87 J/g for the 5% sample in the influence temperature range of the PCM, 5.53 J/g for the 10% sample and 10.59 J/g for the 15% sample.

Currently, building simulation software is a fundamental tool for designing buildings with almost zero-energy consumption. In this study, three identical architectural models were simulated. The reference building had inner coatings of clay-based mortar, mortar with 15% added material and a conventional gypsum mortar. These buildings were subjected to the same exposure and radiation conditions, which allowed the result to be compared to evaluate the effect of incorporating the PCM.

Simulations were performed under summer conditions. The results showed that the incorporation of PCM microcapsules into the clay mortar resulted in a decrease of up to 0.5 kWh/m^2 (in the simulation period), that is, 10% in the energy required for cooling compared to gypsum mortar. In environmental terms, assuming an emission factor of 0.385 kg of CO_2 eq/kWh [34], it would mean a savings of about 25 kg of CO_2 equivalent in 15 days. Finally, we affirm that clay mortar allows the incorporation of a PCM without reducing other characteristics that prevent such use. The use of such mortar is more advantageous in summer in climates such as the one at the center of the Iberian Peninsula. This solution will be of great interest for projects involving rehabilitation and improvement in terms of energy efficiency when it is difficult to work on the whole envelope and for small-scale interventions involving interior conditioning.

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