Title:

Developing a PCM-enhanced mortar for thermally active precast walls

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Abstract

This work presents an experimental research on the thermal properties of novel cementitious mortars incorporating microencapsulated Phase Change Materials intended to be used as the innermost layer in a precast radiant building component actively controlled by an integrated hydronic system.

The characterization was developed in two steps: the first one focused on the effects of different fine aggregates and admixtures for a fixed PCM content and the second one on the effect of changing the amount of PCM. Results show that using silica aggregates and antifoaming

admixture outperform the other options, producing mortars with statistically significant higher thermal conductivities, diffusivities and effusivities. Besides, increasing the amount of PCM significantly reduces conductivity and diffusivity, but the effusivity is practically invariant. This suggests that the mortar design has to be defined by predominantly focusing on diffusivity, in order to achieve appropriate heat penetration rates and activation times for an efficient system operation.

Keywords: Phase Change Material, Thermal energy storage, Thermal diffusivity, Thermal effusivity, Cementitious mortar.

1. Introduction

The total final energy demand of the European Union member states was approximately 1084 Mtoe (Million Tonnes of Oil Equivalent) in 2015, according to the latest data published by Eurostat [1]. Building-related sectors such as residential and services were the most energy-intensive demanding sectors producing together a demand of 422 Mtoe corresponding to 39% of the total, with about two-thirds corresponding to the residential sector [1,2]. Despite the increasing interest in promoting energy-efficient buildings and the current energy policies aimed to reduce the energy impact of the construction sector [3–5], the weight of building-related sectors on the European final energy balance has slightly increased from 35% in 1990 to 39% in 2015. Looking at the energy end-uses in buildings, space heating is the most energy consuming one in the residential sector, representing 71% of the total consumption of households, whereas cooling represents almost 10% of the total energy consumption in Southern countries mainly due to a rapid penetration of air conditioning systems [2,6].

In this context, strategies focused on achieving thermal comfort in buildings, while reducing heating and cooling energy demand, such as Thermal Energy Storage (TES) systems and Thermally Activated Building Systems (TABS), have gained interest proving high energy savings potential [7]. Building integration of TES technologies improves the building energy efficiency by reducing peak loads, uncoupling the energy demand from its availability, allowing the integration of renewable energy sources and providing an efficient management of thermal energy [8–10]. TABS consist of hydronic pipes embedded in building elements and actively used to transfer heat and/or cold to building components such as walls, ceiling or floors [10]. The thermal mass activation of building components has a big potential for energy use reduction in buildings mainly due to its low temperature operation (low temperature heating and high temperature cooling, as a result of the large heat exchange surfaces) and the high thermal inertia that enables shaving peak loads and shifting energy consumption to low energy cost periods [11,12]. Furthermore, radiative heat exchange of TABS provides comfort conditions, avoiding typical draught problems of convective systems [13–15].

Thermal characteristics of conventional cement-based mixtures without PCM have been analysed by several authors. Although the values vary considerably depending on the specific composition of the mixtures, typical values are in the range from 1.5 to 3.4 W m^{-1} K^{-1} for thermal conductivity [16–19], from 0.38 to 0.90 mm^{2} s^{-}1for thermal diffusivity [17,19,20] and from 323 to 1800 W·$s^{0.5}$·m^{-2}·K^{-1} for thermal effusivity [18,20].

Available literature on building materials incorporating Phase Change Materials (PCM) is extensive since a wide range of different materials and building products, such as gypsum plaster, gypsum boards, concrete, panels, bricks, membranes and insulating materials, have been considered as matrix materials to include PCM. The main objective of these studies was to improve the thermal behaviour of passive construction systems by increasing the thermal storage capacity of the building envelope [17,21–27].

However, research on the use of latent heat storage materials in active building components is not very extensive, likely because TABS and PCM in most cases have been investigated as individual technologies.

In spite of this, TABS in combination with PCM might result in an improvement of the thermal comfort in buildings and at the same time in a reduction of the HVAC energy consumption, mainly due to (i) the increased energy storage density of latent heat storage systems that contributes to the peak loads shifting, including in the case of lightweight buildings, (ii) the flexible operation of the hydronic pipes that provide active charging and discharging of the PCM depending on the actual heating or cooling needs, and (iii) the possibility to be efficiently coupled with heat pumps and solar-assisted systems, being a low-temperature heating and high-temperature cooling system [28–30].

Regarding the hydronic thermal activation of building components incorporating PCM, a first study was proposed by Koschenz and Lehmann [31]. They designed a ceiling panel incorporating a 5 cm thick layer made of gypsum and microencapsulated PCM (25% by weight) with embedded capillary tubes for the night cooling of lightweight buildings. One of the findings of the development process was the significant thermal conductivity reduction of gypsum after the PCM addition and the need of incorporate aluminium fins to compensate for the decrease of the gypsum thermal conductivity from the expected value of 0.8-1.0 $W \cdot m^{-1\cancel{2}} \cdot K^{-1}$ to 0.2 $W \cdot m^{-1\cancel{2}} \cdot K^{-1}$ caused by PCM addition.

Another study on the thermal mass activation of a concrete slab including PCM by means of embedded hydronic pipes was proposed by Jin and Zhang [32]. The proposed system consists of a radiant floor with two layers of PCM with different melting temperatures to cover both heating and cooling periods. The objective of the paper was to define the optimal melting temperatures of the layers in order to store heat or cold energy in off-peak period and release the energy in peak period. Authors found by numerical analysis that the fluctuations of the floor surface temperature and heat flux were reduced by using PCM, not only for the direct effect of latent heat capacity but also as a consequence of the low thermal conductivity of the PCM layers. Moreover, they found that the optimal melting temperatures were 38°C and 18°C for heating and cooling respectively, and that the energy released by the floor with PCM in peak period was increased by 41% for heating and 38% for cooling in comparison with the radiant floor without PCM.

A similar study on the development of radiant floor panels incorporating granulated PCM and activated by water pipes was presented by Arsuini et al. [33]. Results showed that the integrated PCM layer improved the thermal performance of the floor during summer cooling regimes by storing the internal gains without temperature increase. However, the heating performance was not as good as expected mainly due to the inefficient heat exchange between the water and the environment produced by the increased thermal resistance of the melted granular PCM. In order to lower the contact resistance between the pipes and the PCM, a steel matrix was inserted in the PCM layer providing the necessary ~~conductibility~~ conductivity to bypass the parasitic resistances introduced by the PCM.

Regarding the thermal properties of self-compacting concrete including different amounts of microencapsulated PCM, a study was performed by Hunger et al. [16]. They found out that increasing the amount of PCM significantly increases the specific heat capacity as expected. However, the thermal mass presents an upper limit, corresponding to 4-5% PCM in weight, due to the decreasing concrete density. Furthermore, they found out that the addition of PCM results in a substantial reduction of thermal conductivity (of about 40% for the concrete with 5% of PCM by mass in comparison with the reference mix) that improves the concrete insulation properties, but makes the PCM thermal activation more difficult. In the same research line, Pomianowski et al. [34] presented an experimental method to determine the specific heat capacity of concrete materials incorporating PCM as a function of the temperature for the melting process. In this work, the authors emphasise that an efficient application of PCM-enhanced concretes in buildings is strongly limited by their low thermal conductivity that hinders the PCM thermal activation, as also indicated in [18].

In light of these results, it seems clear that the thermal properties of PCM-added materials have a fundamental role in the development of efficient TABS solutions. In fact, the very high latent heat storage capacity of the PCM can be unexploited if the thermal activation of the material cannot be reached due to the low thermal conduction in the composite. Likewise, the low thermal conductivity and density of cementitious material including PCM can decrease the building element thermal inertia and thus the performance of TABS [18,31]. In fact, in order to fully exploit the improved thermal storage capacity of the PCM-based material in comparison with the conventional one, it is crucial that the addition of the PCM does not produce a substantial drop in density and thermal conductivity, as has been highlighted by several studies [16,18,31,34]. Bearing in mind these premises, the general objective of this work is the formulation of a PCM-enhanced mortar to be used as the inside layer in precast thermally activated façade components. More specifically, this work presents the experimental research carried out to assess the thermal properties of different cementitious mortars added with microencapsulated PCM in order to point out the optimum solution in terms of mix components for this specific application.

2. Methodology

2.1 General approach

This study analyses five properties of different cementitious mortars containing microencapsulated PCM; density, air content, thermal conductivity, thermal diffusivity, and thermal effusivity have been experimentally studied as the first step in the definition of the optimum formulation of a PCM-added mortar for precast thermally activated building components. In fact, for this application, besides having good workability and proper self-compacting properties, the mortar is required to have specific thermal characteristics to achieve a good compromise between the energy storage capacity and the charging and discharging rates of the element. In particular, in this study three thermal characteristics were analysed:

a) Thermal conductivity λ [$W \cdot m^{-1} \cdot K^{-1}$]

b) Thermal diffusivity α [$m^2 \cdot s^{-1}$]

c) Thermal effusivity e [$W \cdot s^{0.5} \cdot m^{-2} \cdot K^{-1}$]

Thermal conductivity is the property of a material to conduct heat and describes the transport of energy through the mass. In spite of the importance of this fundamental property to represent how well a material conducts heat, it is not adequate to predict the behaviour of a TES system in which the heat transfer process depends on transient heat flows. In fact, the heat flow through building components rarely reaches a steady state, so for an accurate estimation of the thermal behaviour, it is necessary to take into account the heat storage capacity of the element. To this aim, derived properties incorporating the material heat storage capability, such as thermal diffusivity and effusivity, are much more useful dynamic performance indicators from which the behaviour of the system may be deduced.

Thermal diffusivity α is calculated according to Eq. 1:

$$\alpha\ [m^2 s^{-1}] = \frac{\lambda\ [W m^{-1} K^{-1}]}{\rho\ [kg\ m^{-3}]\ c_p [J\ kg^{-1} K^{-1}]} \qquad \text{Eq. 1}$$

Where λ is the ~~defined as the~~ thermal conductivity, ρ ~~divided~~ the ~~by~~ density and c_p the specific heat (i.e. the heat storage capacity of a material per unit volume).

Thermal effusivity e (also called specific admittance, heat penetration coefficient or thermal inertia) is ~~defined~~ calculated according to the Eq. 2 [18,35,36]:

$$e\ [W s^{0.5} m^{-2} K^{-1}] = \sqrt{(\lambda\ [W m^{-1} K^{-1}]\ \rho\ [kg\ m^{-3}]\ c_p [J\ kg^{-1} K^{-1}])} \qquad \text{Eq. 2}$$

~~as the square root of the product of thermal conductivity, density and specific heat [32–34].~~

These two derived properties, despite containing the same variables, describe different characteristics of the materials regarding their thermal behaviour in dynamic conditions. In particular, diffusivity defines how fast the material temperature adapts to the surrounding temperature, whilst effusivity assesses the material ability to exchange thermal energy with its surroundings [20].~~.~~ Briefly, materials with high diffusivity values transmit boundary heat flux fluctuations more quickly than materials with low values do, while materials with high effusivity values will more readily absorb a surface heat flux. For this specific system, consisting of a radiant wall incorporating on the inner side a PCM-added mortar activated by means of water pipes, thermal diffusivity mainly limits the capacity of activating the PCM in deeper layers and consequently the charging times, as long as thermal effusivity would dominate the surface heat flux and the passive heat exchanges with the indoor ambient. Therefore, a good balance between both properties is required in order to achieve a material that can store high amounts of thermal energy under fast heat transfer process, allowing short charging and discharging cycles and thus being adequate to be used in PCM-enhanced thermally activated building elements.

The analysis presented in this study was developed in two phases: in the first step the study focused on the effect of fine aggregates and antifoaming admixture on specific characteristics of the mortar for a constant amount of PCM; in the second one, the effect of the PCM content on the properties of the mortar was assessed.

2.2 Step 1 - Aggregate and antifoaming effects - 2×2 factorial design

The first step the study focused on pointing out the effect of ~~two factors:~~ (i) the fine aggregates and (ii) the antifoaming admixture (AF) on several properties of the mortar, such as density, air entrapped, ~~and~~ thermal ~~properties, i.e.~~ conductivity, diffusivity and effusivity ~~of the mortar~~. To conduct this study, a full factorial experiment with the aforementioned two factors, each one taking two levels (two different fine aggregates, silica and barite 0-4 sands and using or not the AF) was carried out. The advantage of this study is the capability of examining not only the effect of each factor on the response variable, but also the effect of the interaction between the factors on the response variables.

The interest of using heavy aggregates in the formulation of mortars with PCM can be explained taking into account that when a portion of the aggregates is replaced by microencapsulated PCM, a significant reduction in density is produced [16,37]. Although the density reduction may not be critical in terms of thermal mass reduction, since it is counterbalanced by the additional latent heat capacity provided by the phase change material [27], on the other hand, it could lead to a significant reduction in thermal effusivity, delaying the thermal activation of the building component. So, heavy aggregates could be a solution to obtain mixtures with acceptable densities when high amounts of PCM are incorporated. Furthermore, the authors have observed in previous pilot tests that the density reduction produced by the PCM addition is not only due to the direct effect of replacing heavier components by lighter ones, but also to the trapped air introduced into the mixture by the PCM [38]. In fact, for higher PCM contents in the mixture, a larger amount of entrapped air was observed, probably due to the coating of the microcapsules that acts as an air-entrainment agent. The consequent increase in porosity leads to lower density and especially lower thermal conductivity, which implies lower thermal diffusivity and effusivity. Therefore, the effectiveness of using an antifoaming admixture in order to reduce the entrapped air was analysed.

It is worth highlighting that in this first part of the study the PCM content was maintained constant for all the mixtures (28% in volume), in order to take into account only the effects produced by the aggregates and the AF admixture.

In order to perform the analysis of the data with a statistical power higher than 80% and a confidence level of 95%, three replications of each aggregate-admixture combination were executed, following a fully randomised sequence for both mixing process and test performing. Next, a two-way Analysis of Variance (ANOVA) statistical test was carried out in order to investigate the effects of the independent variables and the interaction between them on the dependent variable [39]. In short, this analysis was performed to establish if the aggregate, the admixture and the interaction between them significantly affect the density, the air entrapped, and finally the thermal performance of the mortars.

2.3 Step 2 - PCM content effect – regression

In the second step, the effect of the PCM content on the properties of the mortar was assessed. With this aim, the best performing mixture in terms of thermal properties found out in the first phase of the research was taken as the reference dosage for defining other mixtures with different PCM content. Starting from the mortar with 28% PCM in volume selected from Step 1, four mixes with a PCM content ranging between 20% and 32% in volume were defined, reducing the content of fine aggregates accordingly. For all the mixtures, all the others components, i.e. cement, water, superplasticizer and antifoaming admixture, were kept constant in order to account for the PCM effect only. It has to be emphasized that a wider range of mixtures in terms of PCM content could not be analysed because the PCM content was limited by the workability of the mixtures. In fact, for PCM contents higher than 32% the mixture exhibited a very high viscosity, in accordance with the direct relationship between the PCM content and the viscosity of the mixture observed by other authors [16,37,40]. On the contrary, for a PCM content lower than 19% in volume the mixture was too fluid causing the segregation of the aggregates. This aspect can be explained considering that the reference composition of the mortar containing 28% PCM had already been optimized in terms of workability for using the compound in the fabrication of precast elements, and then if cement and water amounts are kept constant whereas PCM dosage is reduced, the viscosity of the mix also decreases. In other words, to analyse mixtures with a lower content of PCM, a reformulation of the mortar would have been necessary, but in this case a comparative analysis would not have made sense, being the mixtures completely different.

Regarding the analysis of the data, four samples of each mixture were prepared for a total of 16 samples, obtaining a statistical power higher than 80% at a confidence level of 95%. Both sample preparation and testing were performed following a randomised sequence to minimise the influence of systematic errors. Next, to determine if the differences among the mean values were significant, and thus if the PCM content affects the thermal performance of the mortar, a one-way ANOVA was carried out [41]. The goal of this analysis is to investigate if the between-sample variance is much larger when compared to the within-sample variance, in other words, if the variations of the response variables (i.e. density, air content and thermal properties) are largely caused by the PCM quantity, rather than chance variation.

3. Materials and equipment

3.1 Mortar mix preparation

3.1.1 Mortar mix preparation for step 1

The cementitious mortars analysed in this study consists of cement CEM I 52.5 R, silica or barite 0-4 sand as fine aggregates, superplasticizer agent, antifoaming admixture and microencapsulated PCM Micronal DS 5038X, commercially available from BASF. The general properties of the PCM are shown in Table 1.

Table 1. Properties of the PCM used in the research (manufacturer data)

Material	Product type	Melting point [°C]	Total storage capacity [$kJ\ kg^{-1}$]	Latent heat capacity [$kJ\ kg^{-1}$]	Apparent density [$kg\ m^{-3}$]
BASF Micronal® DS 5038X	Powder	26	145	110	250-350

To prepare the specimens, the following assumptions have been made:

- The liquid phase (consisting of water, superplasticizer and AF admixtures) to cement ratio was kept constant for all the mixtures. For the formulations without AF, water content was increased by the same quantity of the AF used in the mixtures with AF.

– The fine aggregate-to-cement ratio at ~~in volume (~~2.4~~)~~ as well as the PCM content by volume at ~~(~~28%~~)~~, were kept constant for all the mixtures, in order to point out the effect of fine aggregates and AF only. This means that the theoretical volume is constant for all the mixtures, but the total mass varies depending on the fine aggregate used, being the densities of silica and barite sand substantially different.

As regards the superplasticizer (SP) content, it was established performing a set of preliminary tests using the Marsh funnel and varying its content from 0.6% to 1.3% with a fixed liquid to cement ratio. In this way, the SP saturation point was determined and used in further experimentations. All the formulations analysed in the first phase of the study are shown in Table 2.

Table 2. Mix compositions in the first phase of the study

	I [Silica w/o AF]		II [Silica w/ AF]		III [Barite w/o AF]		IV [Barite w/ AF]	
	Mass [kg]	Vol [dm^3]	Mass [kg]	Vol [dm^3]	Mass [kg]	Vol [dm^3]	Mass [kg]	Vol [dm^3]
Total water	0.600	0.600	0.597	0.597	0.600	0.600	0.597	0.597
Cement	0.600	0.190	0.600	0.190	0.600	0.190	0.600	0.190
Superplasticizer	0.008	0.007	0.008	0.007	0.008	0.007	0.008	0.007
0/4 Silica sand	1.200	0.448	1.200	0.448	-	-	-	-
0/4 Barite sand	-	-	-	-	2.015	0.448	2.015	0.448
PCM	0.482	0.482	0.482	0.482	0.482	0.482	0.482	0.482
Antifoaming	0.000	0.000	0.003	0.003	0.000	0.000	0.003	0.003
Theo. vol. [dm^3]		1.728		1.728		1.728		1.728
Total mass [kg]		2.890		2.890		3.705		3.705
Theo. density [$kg\ dm^{-3}$]		1.673		1.672		2.144		2.144
Water-to-cement ratio		1.0		1.0		1.0		1.0
Agg. to cem. ratio in vol.		2.4		2.4		2.4		2.4
SP/Cem [wt.%]		1.3		1.3		1.3		1.3
AF/Tot [vol.%]		0.0		0.2		0.0		0.2
PCM/Tot [wt.%]		17		17		13		13
PCM/Tot [vol.%]		28		28		28		28

Regarding the mixing procedure, it started with the dry mixing of cement, fine aggregate and PCM for 30 seconds to obtain a homogeneous mixture. Next, the superplasticizer was dissolved into the water and gradually added to the mixture during mixing for 60 seconds. At this point the AF admixture was incorporated and mixing continued for another two minutes to ensure a proper amalgamation of all the components. For the mixtures without AF, the same procedure was followed with the difference that the mixing continued for 3 minutes without interruptions after the first 30 seconds of dry mixing.

3.1.2 Mortar mix preparation for step 2

To formulate the specimens for the second stage of the study, the following assumptions were made:

- Constant amounts of water, SP and AF admixtures as well as of cement.
- Increasing aggregate-to-cement ratio in volume from 2.0 for mixture A (32% PCM in volume) to 3.1 for mixture D (19% PCM in volume).
- Decreasing PCM content from 32% in volume (mixture A) to 19% in volume (mixture D).

Also in this case, the theoretical volume is constant for all samples, but the total mass varies due to the different densities of silica sand and PCM. Mortars analysed in the second phase of the research are shown in Table 3.

Table 3. Mixture compositions in the second phase of the study

	A (32 vol.% PCM)		B (28 vol.% PCM)		C (24 vol.% PCM)		D (19 vol.% PCM)	
	Mass [kg]	Vol [dm^3]	Mass [kg]	Vol [dm^3]	Mass [kg]	Vol [dm^3]	Mass [kg]	Vol [dm^3]
Total water	0.597	0.597	0.597	0.597	0.597	0.597	0.597	0.597
Cement	0.600	0.190	0.600	0.190	0.600	0.190	0.600	0.190
Superplasticizer	0.008	0.007	0.008	0.007	0.008	0.007	0.008	0.007
0/4 Silica sand	1.023	0.382	1.200	0.448	1.390	0.519	1.594	0.595
PCM	0.548	0.548	0.482	0.482	0.411	0.411	0.335	0.335
Antifoaming	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Theo. vol. [dm^3]		1.728		1.728		1.728		1.728
Total mass [kg]		2.779		2.890		3.009		3.137
Theo. density [kg dm^{-3}]		1.608		1.672		1.741		1.815

Water-to-cement ratio		1.0		1.0		1.0		1.0
Agg. to cem. ratio in vol.		2.0		2.4		2.7		3.1
SP/Cem [wt.%]		1.3		1.3		1.3		1.3
AF/Tot [vol.%]		0.2		0.2		0.2		0.2
PCM/Tot [wt.%]		20		17		14		11
PCM/Tot [vol.%]		32		28		24		20

3.2 Analysis

3.2.1 Workability

Considering that workability of the paste is a fundamental property that constrains the feasibility of using the compound in the fabrication of precast elements, other mixtures that did not meet the required rheological characteristics were discarded from the study in a previous step. Further characterizations were only performed for the usable mixtures reported in Table 2 and Table 3. To assess the mortar composition influence on workability, the mini-slump flow test as an indirect measure of the yield stress and fluidity was conducted.

3.2.2 Density

To calculate the density of mortars, the volume and mass of specimens casted in plastic cups were measured. Volume was measured by completely filling the cup with water and checking the total filling by positioning a piece of planar transparent glass on the top of the plastic cup. In this way, it was ensured that no air bubbles remained inside the cup and so the specimen volume was determined by weighing the water mass, after taring the scale with the empty cup and the piece of glass. In the unit conversion from kilogrammes to cubic meters a water density of 1000 kg m^{-3} was assumed. To measure the mass of the water, as well as the mass of mortars and slurries specimens, a scale Mettler Toledo SB32001 DeltaRange was used.

3.2.3 Air content

To calculate the air content of the mortars, the gravimetric method described in the ASTM C138 standard was used [42]. First, the fresh densities of the mixtures were calculated following the same method described in the previous section. Next, the theoretical density was calculated by dividing the total mass by the theoretical volume of the mixtures (see Table 2 and Table 3). With these data, the air content was calculated following Eq. 31.

$$AC\ [\%] = \frac{\rho_{\mathrm{theo}}\ [kg/dm^3] - \rho_{\mathrm{fr}}\ [kg/dm^3]}{\rho_{\mathrm{theo}}\ [kg/dm^3]} \cdot 100 \qquad \text{Eq. 31}$$

being AC the air content, ρ_{theo} the theoretical density, and ρ_{fr}, the fresh density.

3.2.4 Mechanical strength

Despite the mortars investigated will not be used for structural purposes, the flexural and compressive strength of the samples have been measured according to Standard EN 1015-11 [43], with the aim of assessing the order of magnitude of these properties and the applicability of the mortars for practical uses.

3.3 Thermal properties

To assess the thermal properties of the samples, a Decagon Devices KD2 PRO instrument equipped with two different probes (TR-1 and SH-1) was used [44]. This apparatus uses transient line heat source methods to measure thermal properties, as described in the following sections. A critical issue for accurate measurements by means of this method is to ensure a good thermal contact between the sensor and the material, in order to minimise the thermal contact resistance. With this aim, pilot holes were bored in fresh mixes by using pilot pins having exactly the same diameter as the measuring needles. Pilot pins were firstly coated with a thin film of release-agents and then were installed in the centre of fresh mortar samples as shown in Figure 1. Once hardened, pins were removed, sensors were coated with thermal grease, inserted into the cast hole and readings started to be taken. During the measurement, the temperature of the samples was kept as constant as possible and 15 minutes between each measurement were allowed for temperatures to equilibrate. The measurement time was set to 10 minutes for most accurate results according to the manufacturer instructions, minimising errors caused by the large diameter needle and the contact resistance between the sensor and the sample.

3.3.1 Thermal conductivity

To assess the thermal conductivity of the samples, the Decagon Devices KD2 PRO was equipped with the single needle TR-1 sensor [44]. This probe consists of a needle with a heater and a temperature sensor inside. A constant current passes through the heater and the system monitors the temperature of the sensor over time by using a high-resolution temperature sensor. Specific algorithms are applied to analyse measurements made during heating and cooling intervals and to compute thermal conductivity [44]. According to the manufacturer specifications, the accuracy of the single needle TR-1 sensor (2.4 mm diameter x 10 cm long) in the conductivity range from 0.2 to 4.0 $Wm^{-1}K^{-1}$ is ±10%.

Figure 1. Mortar samples curing with the pilot pins inserted inside (left) and thermal conductivity measurement on hardened samples with the Decagon Devices KD2 PRO (right).

3.3.2 Thermal diffusivity

To measure the thermal diffusivity of the mortars, Decagon Devices KD2 PRO instrument was equipped with the dual needle SH-1 probe. The operation of this sensor is similar to the single needle, but in this case the heater and temperature sensors are placed in separate needles. Heat is applied to the heated needle for a set heating time and the temperature is measured in the monitoring needle 6 mm distant during the heating and the following cooling period. Readings are then processed taking into account the ambient temperature registered at the beginning of the test and the heat per unit length provided by the heating needle. Different equations are applied during the heating and cooling periods to fit three constants and compute the thermal diffusivity [44]. According to the manufacturer specifications, the accuracy of the dual needle SH-1 sensor (1.3 mm diameter x 3 cm long, 6 mm spacing) in measuring diffusivity of materials with conductivity higher than 0.1 $W \cdot m^{-1} \cdot K^{-1}$ is ±10%.

Another output data of the measurements performed using SH-1 sensor is the volumetric heat capacity, that was also measured in order to calculate the thermal effusivity as explained in the following section. The accuracy of the probe in the determination of the volumetric heat capacity of materials with conductivity higher than 0.1 $W \cdot m^{-1} \cdot K^{-1}$ is ±10%.

3.3.3 Thermal effusivity

Thermal effusivity was calculated as the square root of the product of thermal conductivity and volumetric heat capacity. Thermal conductivity was assessed using probe TR-1 as explained in Section 3.3.1 and volumetric heat capacity was measured using probe SH-1. Volumetric heat capacity was also used to calculate the specific heat capacity, as the ratio between volumetric heat capacity and density.

4. Results

4.1 Step 1 - Aggregate and antifoaming effects - 2×2 factorial design

4.1.1 Density

A relevant aspect to be considered is how the fine aggregates and AF agent affect the density of the mixture, being density an important parameter for the thermal properties of the material. Table 4(a) shows the density values of the different mixtures, with three replications for each aggregate-AF combination. It can be seen that the higher values are obtained with barite aggregates and AF admixture (1.93-1.94 kg dm^{-3}), whereas when using silica without AF the density ranges between 1.31 kg dm^{-3} and 1.34 kg dm^{-3}. For both aggregates, using AF agent produces an increase in the density of the mixture.

Table 4. Density values of the samples analysed (a) and summary output from the two-way ANOVA (b). It consists of the Sum of Squares (SS), the Degree of Freedom (DF), the Mean Squares (MS), the F-value (F), the associated p-value and the F critical.

Density [kg dm^{-3}] (a)	
	Fine aggregates

Two-way ANOVA (b)						
Source of variation	SS	DF	MS	F	p-value	F crit.

	Silica	Barite
W/ Antifoaming	1.55	1.93
	1.53	1.93
	1.54	1.94
W/O Antifoaming	1.34	1.81
	1.31	1.80
	1.31	1.82

Antifoaming	0.088	1	0.088	838.8	2.19E-09	5.32
Aggregates	0.584	1	0.584	5568.1	1.16E-12	5.32
Interaction	0.006	1	0.006	58.7	5.95E-05	5.32
Within	0.001	8	0.000			
Total	0.679	11				

Two-way ANOVA statistical test reported in Table 4(b) allows concluding that the AF, the aggregates and the interaction between them significantly affect the density of the mortars. In fact, all the p-values are lower than the significance level (0.05), so the null hypotheses is rejected (there are not statistically significant differences in density) and it is concluded with 95% confidence that the use of AF, different aggregates, and interaction between them produces mortars statistically different in density.

4.1.2 Air content

Air content of the mixtures is shown in Table 5(a). It can be clearly noticed the effect of the AF admixture, that provides a substantial reduction in the air content of the mixtures. In fact, the air content is reduced from about 20% to 6% and from 15% to 9% when silica or barite aggregates are respectively used. In this sense, it can be observed that using common silica aggregates in the formulation of a mortar with PCM without AF admixtures produces very high air contents (about 20%), with all the limitations that this implies in terms of high porosity and low conductivity as it will be discussed in the next section. When barite is used, the same amount of PCM produces lower air contents (about 14%), however the effectiveness of the AF seems to be higher when silica aggregates are used in comparison with mixes based on barite.

Table 5. Air content values of the samples analysed (a) and summary output from the two-way ANOVA (b)

Air content [%] (a)		
	Fine aggregates	
	Silica	Barite
W/ Antifoaming	5.8	8.7

Two-way ANOVA (b)						
Source of variation	SS	DF	MS	F	p-value	F crit.
Antifoaming	268.8	1	268.8	786.20	2.83E-09	5.32
Aggregates	6.1	1	6.1	17.71	2.93E-03	5.32

	6.8	8.6
	6.6	8.4
W/O Antifoaming	18.5	14.3
	19.9	15.1
	20.1	14.0

Interaction	38.9	1	38.9	113.71	5.24E-06	5.32
Within	2.7	8	0.3			
Total	316.5	11				

Two-way ANOVA shows that also in this case AF, aggregates, and interaction between them produce mortars with statistically significant differences in the air content, being the p-values lower than 0.05 in all the cases.

4.1.3 Thermal conductivity

Higher thermal conductivity values are obtained using silica aggregates with AF admixture as shown in Table 6(a). In general, it can be observed that the use of silica aggregates seems to be more favourable in maximizing this parameter, probably because this type of aggregate itself has higher thermal conductivity than the barite. In fact, thermal conductivity values for silica-based mortars with high air content (about 20%, without AF) are still higher than those of barite based mixtures with lower air content (about 8%, with AF).

From a statistical point of view (Table 6(b)), the two independent variables (aggregates, AF) produce a statistically significant difference in the thermal conductivity, being the p-values of the main factors AF and aggregates lower than 0.05 in both cases. However, in this case the interaction term has a p-value higher than the significance level (p-value=0.32 > 0.05=α), so the null hypothesis cannot be rejected, hence there are no significant differences in the interaction between aggregates and AF agent. This means that the effect of the AF admixture on the thermal conductivity is the same for both using silica and barite aggregates (and vice versa).

Table 6. Thermal conductivity values of the samples analysed (a) and summary output from the two-way ANOVA (b)

Thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$] (a)	
	Fine aggregates

Two-way ANOVA (b)						
Source of variation	SS	DF	MS	F	p-value	F crit.

	Silica	Barite
W/ Antifoaming	1.09	0.79
	1.03	0.83
	1.08	0.77
W/O Antifoaming	0.88	0.65
	0.92	0.67
	0.78	0.62

Antifoaming	0.095	1	0.095	49.68	1.07E-04	5.32
Aggregates	0.170	1	0.170	89.45	1.28E-05	5.32
Interaction	0.002	1	0.002	1.14	3.18E-01	5.32
Within	0.015	8	0.002			
Total	0.282	11				

4.1.4 Thermal diffusivity

Thermal diffusivity values range between 0.20 to 0.23 $mm^2\ s^{-1}$ for the mortar with silica aggregates and AF, and between 0.14 and 0.15 $mm^2 s^{-1}$ for the mortar with barite without AF agent, as shown in Table 7(a). This means that the first one allows a 30% faster heat penetration than the second one, reducing the time required to activate the element. Two-way ANOVA shows that the independent variables cause a statistically significant difference in the thermal diffusivity; however the interaction term has a p-value higher than the significance level (p-value=0.80 > 0.05=α), meaning that the effect of the admixture on the thermal conductivity is the same for both types of fine aggregates (Table 7(b)).

Table 7. Thermal diffusivity values of the samples analysed (a) and summary output from the two-way ANOVA (b)

Thermal diffusivity [$mm^2 \cdot s^{-1}$] (a)		
	Fine aggregates	
	Silica	Barite
W/ Antifoaming	0.23	0.19
	0.22	0.19
	0.20	0.17
W/O Antifoaming	0.21	0.14
	0.17	0.15
	0.15	0.14

Two-way ANOVA (b)						
Source of variation	SS	DF	MS	F	p-value	F crit.
Antifoaming	0.005	1	0.005	15.46	4.34E-03	5.32
Aggregates	0.004	1	0.004	11.64	9.20E-03	5.32
Interaction	0.000	1	0.000	0.07	8.01E-01	5.32
Within	0.003	8	0.000			
Total	0.011	11				

4.1.5 Thermal effusivity

Also in terms of thermal effusivity, the better performance mortar is obtained using silica aggregates with AF admixture as shown in Table 8(a). In particular, this combination in average outperforms the other solutions by 25% (barite w/o AF), 19% (barite w/ AF), and 11% (silica w/o AF). This result can be explained taking into account that thermal effusivity combines thermal conductivity with density and specific heat capacity. Mixtures based on silica have relatively high thermal conductivity and low density, whereas mixtures based on barite present low conductivity and high density, as shown in Table 4 and Table 6. If the mixtures w/ AF are analysed, first, the product of the average conductivity by the average density is almost constant being 1639 $W \cdot kg \cdot m^{-4} \cdot K$ for silica aggregates and 1547 $W \cdot kg \cdot m^{-4} \cdot K$ for barite aggregates. However, the specific heat capacity of the mortar is considerably much higher when silica instead of barite is used, with average values of 3194 $J \cdot kg^{-1} \cdot K^{-1}$ for the first one and 2235 $J \cdot kg^{-1} \cdot K^{-1}$ for the second one. The same occurs with mixes w/o AF: the product of conductivity by density is constant, with values of 1138 $W \cdot kg \cdot m^{-4} \cdot K$ and 1174 $W \cdot kg \cdot m^{-4} \cdot K$ for silica and barite, respectively, but the specific heat capacity is about 3671 $J \cdot kg^{-1} \cdot K^{-1}$ for silica and only 2528 $J \cdot kg^{-1} \cdot K^{-1}$ for mortar with barite. The overall result is that mortars based on silica outperform the others option in terms of thermal effusivity, regardless the use of AF admixture.

Table 8. Thermal effusivity values of the samples analysed (a) and summary output from the two-way ANOVA (b)

Thermal effusivity [$W \cdot s^{0.5} \cdot m^{-2} \cdot K^{-1}$] (a)		
	Fine aggregates	
	Silica	Barite
W/ Antifoaming	2289	1824
	2172	1903
	2400	1850
W/O Antifoaming	1904	1755
	2203	1766
	2008	1647

Two-way ANOVA (b)						
Source of variation	SS	DF	MS	F	p-value	F crit.
Antifoaming	1.1E+05	1	1.1E+05	10.58	1.1E-02	5.32
Aggregates	4.1E+05	1	4.1E+05	39.35	2.4E-04	5.32
Interaction	9.4E+03	1	9.4E+03	0.89	3.7E-01	5.32
Within	8.4E+04	8	1.1E+04			
Total	6.2E+05	11				

A two-way ANOVA examined the effect of antifoaming and aggregates on thermal effusivity, showing at 95% confidence that both AF and aggregates result in statistically significant difference, with the p- values of the main factors lower than 0.05. The interaction, however, does not have a statistically significant effect on the effusivity, meaning that the effect of the aggregates on this parameter is the same for either using or not the AF admixture (and vice versa).

4.2 Step 2 - PCM content effect – One-way ANOVA

4.2.1 Density

As stated in the methodology section, the second step of the study focused on the effects produced by different amounts of PCM on the properties of the mortars. The first parameter analysed was the density of the mortars in the hardened state, as it can be seen in Table 9(a). As expected, for increasing PCM contents density decreases, ranging between 1.72 and 1.75 kg dm^{-3} for mixtures with 20% PCM and 1.44-1.46 kg dm^{-3} for mortars with 32% PCM. In order to establish whether there is a statistically significant difference between the group means, a one-way ANOVA analysis was conducted as shown in Table 9(b). The significance value (i.e. the p-value = 1.8E-13) is below 0.05 and therefore it can be concluded that there is a statistically significant difference in the mean density between the different mortars. However, ANOVA does not provide any information about pairwise differences between groups but only demonstrates that there are statistically significant differences between the groups as a whole. So, a Tukey-Kramer multiple comparisons post-hoc test was performed to show which mortars differed from each other in terms of density [45]. The output of Tukey-Kramer test revealed that density is statistically significantly between all the mixtures (Table 10).

Table 9. Density values of the samples analysed (a) and summary output from the one-way ANOVA (b).

Density [kg·dm^{-3}] (a)			
PCM	PCM	PCM	PCM

One-way ANOVA (b)						
Source of Variation	SS	DF	MS	F	p-value	F crit.

20%	24%	28%	32%
1.75	1.65	1.55	1.45
1.72	1.64	1.56	1.44
1.72	1.64	1.55	1.46
1.73	1.66	1.55	1.45

Between Groups	0.175	3	5.84E-02	633.8	1.78E-13	3.49
Within Groups	0.001	12	9.22E-05			
Total	0.176	15				

Table 10. Tukey–Kramer statistical test applied to find mixtures that have significantly different densities from each other.

Tukey-Kramer Multiple Comparisons			
Comparison	Absolute difference	Critical range	Result
20% to 24%	0.082	0.020	Different
20% to 28%	0.180	0.020	Different
20% to 32%	0.279	0.020	Different
24% to 28%	0.097	0.020	Different
24% to 32%	0.197	0.020	Different
28% to 32%	0.100	0.020	Different

4.2.2 Air content

Table 11(a) shows the air-content values of the mortars. As it can be seen, the air content increases when higher amounts of PCM are added into the mix. In fact, mortars with 20% PCM have values in the range of 2%-3%, whereas in the case of 32% PCM the air content raises up to 8%-9%, despite the same quantity of AF admixture has been used for all the mixtures. Also for this parameter, the ANOVA analysis shows that the probability that the differences of the mean air content values are due to chance is less than the statistical significance at 0.05 (p-value = 1.4E-07), so the null hypothesis that all the mixes have the same air content can be rejected and the alternative hypothesis that they have not (Table 11(b)) can be accepted. A Tukey-Kramer post hoc test revealed that the air content was statistically significantly different between all the mortars with the exception of mortars D (20% PCM) and C (24% PCM), being in this case the absolute difference lower than the critical range (Table 12).

Table 11. Air content values of the samples analysed (a) and summary output from the one-way ANOVA (b).

Air content [%] (a)			
PCM 20%	PCM 24%	PCM 28%	PCM 32%
1.6	3.3	5.6	8.1
3.5	4.2	5.3	9.0
3.3	4.1	5.8	7.9
3.3	3.2	6.1	8.2

One-way ANOVA (b)						
Source of Variation	SS	DF	MS	F	p-value	F crit.
Between Groups	69.18	3	23.06	62.31	1.38E-07	3.49
Within Groups	4.44	12	0.37			
Total	73.62	15				

Table 12. Tukey–Kramer statistical test used to find mixtures that have significantly different air contents from each other.

Tukey-Kramer Multiple Comparisons			
Comparison	Absolute difference	Critical range	Result
20% to 24%	0.791	1.278	Not Different
20% to 28%	2.791	1.278	Different
20% to 32%	5.383	1.278	Different
24% to 28%	1.999	1.278	Different
24% to 32%	4.591	1.278	Different
28% to 32%	2.592	1.278	Different

4.2.3 Mechanical strength

The flexural strength of the mortars ranges between 3.4 MPa and 4.2 MPa decreasing as the PCM content increases. Compressive strength follows the same pattern ranging from 11.5 MPa to 13.6 MPa. These values are in accordance with no structural mortars, suggesting that the PCM-added mortars are suitable for practical uses.

~~4.2.3~~4.2.4 Thermal conductivity

Since density decreases and air-content increases for increasing amounts of PCM, it is expected that the thermal conductivity will also decrease. Table 13(a) shows that effectively there is an inverse relationship between PCM content and conductivity, being the conductivity for mortars with 20% PCM in the range of 1.17-1.27 $W{\cdot}m^{-1}{\cdot}K^{-1}$ and for mixtures with 32% PCM between 0.93 W·m^{-1}·K^{-1} and 1.11 W·m^{-1}·K^{-1}. ANOVA shows that the within-sample variance is lower than the between-sample variance (Table 13(b)), meaning that the thermal conductivity variation among mortars is largely caused by actual different thermal behaviours, rather than chance variation (p-value =0.016 < 0.05 = α).

However, it is worth mentioning that in this case, even though the p-value is still lower than the level of significance, it is not as low as in the previous cases. This result is highlighted by the Tukey-Kramer post hoc test that shows that the thermal conductivity is statistically significantly different only between mortar D (20% PCM) and A (32% PCM), and between mortar C (24% PCM) and A (32% PCM), as shown in Table 14. This means that according to the experiment performed and equipment used in the characterization, using 32% PCM in the mortar mixture provides statistically different thermal conductivities with respect to using 20% or 24% PCM, while all the other combinations of mixtures statistically have the same conductivity.

Table 13. Thermal conductivity at 20°C (a) and summary output from the one-way ANOVA (b).

Thermal conductivity at 20°C [W·m^{-1}·K^{-1}] (a)			
PCM 20%	PCM 24%	PCM 28%	PCM 32%
1.20	1.14	1.20	1.02
1.27	1.21	1.01	1.01
1.17	1.20	0.96	1.11
1.24	1.26	1.23	0.93

One-way ANOVA (b)						
Source of Variation	SS	DF	MS	F	p-value	F crit.
Between Groups	0.107	3	0.036	5.12	0.016	3.49
Within Groups	0.084	12	0.007			
Total	0.191	15				

Table 14. Tukey–Kramer statistical test used to find mixtures with significantly different thermal conductivity values.

Tukey-Kramer Multiple Comparisons			
Comparison	Absolute difference	Critical range	Result
20% to 24%	0.015	0.175	Not Different
20% to 28%	0.119	0.175	Not Different
20% to 32%	0.201	0.175	Different
24% to 28%	0.105	0.175	Not Different
24% to 32%	0.187	0.175	Different

28% to 32%	0.082	0.175	Not Different

~~4.2.4~~4.2.5 Thermal diffusivity

Thermal diffusivity decreases for increasing PCM contents, as shown in Table 16(a). Values range between 0.243 and 0.292 $mm^2 \cdot s^{-1}$ for mortars with 20% PCM and between 0.158 to 0.198 $mm^2 \cdot s^{-1}$ for mortars with 32% PCM. Taking into account that for increasing amounts of PCM both the average thermal conductivity and the average density of the mortars decrease linearly and approximately with the same slope, it can therefore be concluded that the ratio between thermal conductivity and density is almost constant. Thus, the decreasing thermal diffusivity means that, as expected, the thermal capacity of the mixture increases with the PCM content. ANOVA shows that the differences between the mortars in terms of thermal diffusivity are in general statistically significant (p-value =0.002, Table 16(b)), and the Tukey–Kramer test points out that introducing 32% PCM in the mortar causes a statistically different thermal diffusivity from mixes incorporating 20% or 24% PCM.

Table 15. Thermal diffusivity at 20°C values (a) and summary output from the one-way ANOVA (b).

Thermal diffusivity at 20°C [$mm^2 \cdot s^{-1}$] (a)			
PCM 20%	PCM 24%	PCM 28%	PCM 32%
0.292	0.242	0.247	0.198
0.273	0.263	0.206	0.198
0.276	0.243	0.179	0.195
0.243	0.274	0.262	0.158

One-way ANOVA (b)						
Source of Variation	SS	DF	MS	F	p-value	F crit.
Between Groups	0.017	3	5.50E-03	8.85	0.002	3.49
Within Groups	0.007	12	6.22E-04			
Total	0.024	15				

Table 16. Tukey–Kramer statistical test performed to find mixtures with significantly different thermal diffusivity values.

Tukey-Kramer Multiple Comparisons			
Comparison	Absolute difference	Critical range	Result
20% to 24%	0.016	0.052	Not Different
20% to 28%	0.048	0.052	Not Different
20% to 32%	0.084	0.052	Different
24% to 28%	0.032	0.052	Not Different

24% to 32%	0.068	0.052	Different
28% to 32%	0.036	0.052	Not Different

4.2.54.2.6 Thermal effusivity

Thermal effusivity ranges between 2200 and 2500 $W{\cdot}s^{0.5}{\cdot}m^{-2}{\cdot}K^{-1}$ and it does not vary substantially with the PCM content (Table 18). For this parameter, the ANOVA analysis shows that the p-value is higher than the significance level, so there is no statistically significant evidence to conclude that there is a difference in the thermal effusivity for the mortars considered. In fact, the thermal effusivity is practically constant for all mortars, with an average value of 2347 $W{\cdot}s^{0.5}{\cdot}m^{-2}{\cdot}K^{-1}$ and a very low standard deviation of 23 $W{\cdot}s^{0.5}{\cdot}m^{-2}{\cdot}K^{-1}$.

This result can be explained taking into account that the thermal effusivity is defined as the root square of the product between density, conductivity, and specific heat. In this case, for increasing amounts of PCM, the reduction in density and conductivity is compensated by the increase in the specific heat of the mixture.

Table 17. Thermal effusivity at 20°C values (a) and summary output from the one-way ANOVA (b).

Thermal effusivity at 20°C [$W{\cdot}s^{0.5}{\cdot}m^{-2}{\cdot}K^{-1}$] (a)			
PCM 20%	PCM 24%	PCM 28%	PCM 32%
2214	2316	2413	2287
2424	2361	2219	2262
2221	2430	2258	2512
2512	2402	2392	2335

One-way ANOVA (b)						
Source of Variation	SS	DF	MS	F	p-value	F crit.
Between Groups	6648	3	2216	0.190	0.901	3.49
Within Groups	140086	12	11674			
Total	146734	15				

5. Conclusions

The presented study describes the experimental campaign performed to characterise the thermal properties of novel mortars incorporating microencapsulated PCM designed to be used as the internal layer in thermally active precast walls. For this specific application, the layer is activated by a water pipe in order to store and/or exchange heat with the indoor environment and the HVAC system depending on the operating conditions. Therefore, the PCM-added mortar is required to have a good balance between thermal diffusivity, that measures how quickly the heat can penetrate the material under unsteady conditions (and consequently the heat penetration depth at a given time) and thermal effusivity, that describes the rate of thermal energy transfer on the material surface and thus the material ability to exchange thermal energy with its surroundings.

The characterization has been developed in two steps: in the first one, a full factorial experiment focused on the effects of using different fine aggregates (silica and barite) and antifoaming admixture on the characteristics of the mortars, keeping the PCM content constant. In the second step, the effect of the PCM amount introduced in the mixtures (from 20% to 32% in the total volume of the mixture) was assessed, reducing proportionally the fine aggregates and keeping constant all the others components (i.e. cement, water, superplasticizer, and antifoaming admixture).

Results show that the combination consisting in using silica fine aggregate and an antifoaming admixture outperform the other options in terms of thermal properties, producing mortars with statistically significant higher values of conductivity, diffusivity and effusivity. The use of heavy aggregates like barite produces a significant increase in the mortar density (of about 25% and 37% in the case of using or not the antifoaming admixture, respectively); however this potential advantage does not result in better thermal properties, since the decrease in conductivity produced by this aggregate exceeds the increase in density, in comparison with silica-based mortars.

Increasing amounts of microencapsulated PCM produce a statistically significant density reduction not only due to the direct effect of replacing heavier mix component by lighter one, but also because the trapped air increases when increasing amounts of PCM are introduced. This makes that density falls from about 1.7 kg dm^{-3} for mortars with 20% PCM (3% trapped air) to about 1.4 kg dm^{-3} for mortars with 32% PCM (8% trapped air). Concerning thermal properties, conductivity and diffusivity decreases when increasing PCM content. In particular, moving from 20% to 32% PCM reduces the thermal conductivity from 1.2 $W{\cdot}m^{-1}{\cdot}K^{-1}$ to 1.0 $W{\cdot}m^{-1}{\cdot}K^{-1}$ (17% reduction) and the diffusivity from 0.27 $mm^{2}{\cdot}s^{-1}$ to 0.19 $mm^{2}{\cdot}s^{-1}$ (31% reduction), meaning that the heat will penetrate 30% faster in the 20% PCM mortar in comparison with the mortar incorporating 32% PCM. Other than that, differences between mortars with similar PCM content are not very clear without performing a detailed statistical analysis. In this case, one-way ANOVA and Tukey-Kramer post hoc test have led to the conclusion that both thermal conductivity and diffusivity are statistically significantly different only between the mortar with the higher PCM content (32%) and mortars with 24% and 20% PCM. For all the other combinations, the results obtained do not allow to conclude that the differences are statistically significant. Finally, the study of the thermal effusivity has revealed that for increasing amounts of PCM, density and conductivity reduction is counterbalanced by the increase of the specific heat capacity, concluding that effusivity is practically invariant to the PCM content, with an average value of about 2300 $W{\cdot}s^{0.5}{\cdot}m^{-2}{\cdot}K^{-1}$ and a coefficient of variation lower than 1%. This result implies that when increasing the amount of PCM the energy storage potential is enhanced, but the thermal inertia presents an upper limit, due to the relevant decrease of both thermal conductivity and density. Moreover, a constant effusivity means that the internal surface of the wall in contact with the indoor air will allow the same heat flux for all the mortars. This suggests that the choice of the most suitable material for this application has to be done by predominantly focusing on diffusivity, in order to define the most appropriate heat penetration rates and activation times for an efficient operation of the precast radiant system.

Therefore, further experimental studies on small and full-scale models should be conducted in order to assess the charging and discharging rates and the energy storage potential of the latent heat storage system under dynamic operating conditions. Moreover, the same methodology could be applied to different finishing mortar mixtures without PCM including aggregates with different properties.

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