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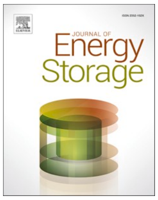

Research papers

Thermal properties of PEG-based form-stable Phase Change Materials (PCMs) incorporated in mortars for energy efficiency of buildings

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ABSTRACT

The purpose of a phase change material (PCM) is to store/release energy during its transition from solid to liquid state, being able to count on a range of melting/crystallization temperatures comparable to environmental temperatures. The inclusion of a PCM in mortars, or in other construction elements, guarantees a reduction in energy consumption for heating and cooling of buildings, provided that the phase transition range of the PCM corresponds to the variation range of the environmental temperatures. This implies that a PCM with a suitable transition range must be identified for each climate zone. Two Poly-Ethylene Glycol (PEG)-based form-stable PCMs have been, then, produced with the intent of include them in mortars applied in buildings located in different climatic zones, i.e. continental and Mediterranean regions. The form-stable PCMs were realized starting from two PEGs possessing different molecular weights, i.e. PEG800 and PEG1000, characterized by different ranges of melting/crystallization temperatures. The PEGs were included in flakes of a porous stone, i.e., Lecce Stone (LS), to produce two form-stable PCMs, namely: LS/PEG800 and LS/PEG800_PEG1000 (50/50 wt%). In the present paper, the thermal performance of the PCM-modified mortars was assessed in a climatic chamber able to simulate the variation of environmental temperatures in the two climatic zones under consideration. The effectiveness of the original PCMs to mitigate indoor temperature fluctuations was, then, assessed: it was found that the mortar formulations containing the mixed PCM (i.e., LS/PEG800_PEG1000 compound) offered the best advantage in reducing cooling and heating needs by 8 % and 13 %, respectively. On the basis of these results, the energy savings for indoor heating/cooling were calculated, with the corresponding reduction in costs: the inclusion of PCM LS/PEG800_PEG1000 in the mortars, especially those based on hydraulic lime, produced a noticeable reduction in the cooling cost, i.e. around 8 % during the summer, and 12 % during the spring and autumn seasons for internal heating of buildings located in the Mediterranean area. The time lag between the maximum and minimum temperatures with respect to the external (which simulates the environmental one) temperature was also evaluated: the cement-based mortar containing the mixed PCM generally performed the best, regardless of the climatic zone taken as a reference.

1. Introduction

The building sector is responsible for almost one-third of the global energy consumption in the world, with almost 15 % of direct CO_2 emissions [1]. Energy demand from buildings continues to rise, driven by an improved access to energy in developing Countries, a growing request for air conditioning in Tropical/Mediterranean regions and heating needs in continental area, a wider use of energy-consuming appliances [1]. Consequently, political decisions push towards solutions aimed at reducing the energy needs of buildings. In addition,

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Abbreviations: C, Cement; HL, Hydraulic Lime; LHTES, Latent heat thermal energy storage; LS, Lecce Stone; NE, Energy saving due to the inclusion of a PCM in a mortar; NE_{0PCM}, Energy need calculated for the mortar not including a PCM; NE_{PCM}, Energy need calculated for the mortar containing a PCM; PCM, Phase Change Material; PEG, Polyethylene-Glycol; SP, Superplasticizer; Tc_{end}, Final temperature of the crystallization process; Tc_{peak}, Peak temperature of crystallization process; Tc_{start}, Initial temperature of the crystallization process; TES, Thermal Energy Storage; Tm_{end}, Final temperature of the melting process; Tm_{peak}, Peak temperature of melting process; Tm_{start}, Initial temperature of the melting process; XPS, Extruded Polystyrene.

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among European objectives is the de-carbonization of buildings which should be carbon neutral by 2050 [2]. The academic research and R&D sectors of companies are facing this challenge by trying to find new technologies and materials able to limit the waste of energy resources and, at the same time, reduce greenhouse gas emissions into the environment.

It is a common opinion that to reduce the energy consumption, mainly employed for the indoor heating and cooling, it is essential to improve the energy efficiency of the buildings. A viable way to achieve this objective is represented by the Thermal Energy Storage (TES) technology which is able to stock the thermal energy, reducing energy consumption bringing environmental benefits [3]. The TES methods, based on the charge, accumulation and discharge of thermal energy, can be classified according to the storage mechanism, i.e.: sensible heat storage, latent heat storage, and thermo-chemical storage. The differences between these methods lie in the material used, the range of temperatures and in other operating parameters [4]. Among others, the latent heat thermal energy storage (LHTES) method is based on the capabilities of a phase change material (PCM). PCMs can, in fact, absorb and release heat during their phase transitions (from the solid to liquid state and from liquid to solid, respectively) as a consequence of the variations in environmental temperatures. When integrated into a building component, a PCM can improve the indoor thermal comfort by reducing peaks and fluctuations in temperature, thus reducing the need for heating/cooling energy [5–7]. Moreover, PCMs are also applied to shift the peak load into off-peak hours, positively affecting the energy efficiency of buildings [8]. The incorporation of a PCM is, therefore, a fast-growing and promising technology able of reducing the environmental impact of buildings.

In recent years, many experimental studies have been carried out to evaluate the thermal performance of materials for buildings containing PCMs. They can be integrated in a wide variety of building components, i.e.: wallboard [9,10], roof and ceiling [11], floor [12,13], external wall [14], windows [15,16], bricks [17,18], mortars and concrete [19–21]. The latter two constitute the most interesting application for two reasons: firstly, the mortar is applied over a very large surface, and this offers the possibility of incorporating a large amount of PCM, taking into account that both the latent heat and storage capacity increase with the amount of the PCM present in the constructive element [22,23]. The second, the final material, i.e., the mortar containing the PCM, can be adapted to a wide variety of shapes and sizes. The latter aspect is particularly important because buildings can last for decades; therefore, if the goal is to make a building energy efficient, it is important to develop technologies that can be used for the thermal retrofit of existing buildings as well as of new ones. In addition, mortar is a constructive element present in all buildings and can be easily replaced: therefore, the inclusion of a PCM in a mortar seems to be the best solution to integrate it into a building with the aim of improving its thermal performance [24].

The methods available for incorporating a PCM into a mortar have been well described in the literature: direct incorporation of a PCM in mortars [25,26]; PCM contained in macro-capsules or micro-capsules [27,28]; form-stable method [22]. The form-stable method, in particular, has proved to be very effective, offering advantages over the others. Direct incorporation is the simplest and most economical method as the PCM is directly incorporated into the construction material during its production. This technique, however, shows some disadvantages, such as: the PCM can affect the hydration products; the adhesion strength between the binder paste and the aggregate can be reduced; the mechanical properties and durability can be adversely affected [29]. In the macro- or micro-encapsulation method, the PCM is enclosed within a shell made of a high-strenght polymer. This widely used procedure offers various advantages, such as: an increased specific heat, due to a larger surface area especially in the case of micro-encapsulated PCMs; very limited volume changes during the phase transitions; good chemical stability of the PCMs; better thermal reliability. The disadvantage presented by this scheme resides in the potential breakage of the microcapsules during the process of inclusion of the PCM in the mortar, in addition to substantially higher costs [30,31]. The form-stable method, on the other hand, offers the possibility of creating in a simple and economical way a composite material consisting of the actual PCM and an inorganic matrix that contains it. Even though the addition of a form-stable PCM can affect to some extent the mechanical properties of the final mortars, solutions can be employed to mitigate this problem [32–34]. The inclusion of a form-stable PCM in mortars, for example in partial replacement of inert aggregates, proved to lead to real benefits in terms of reducing the thermal loads to thermo-regulate buildings [35,36].

The selection of raw materials to prepare a form-stable PCM can be made based on convenient choices, in particular it must be related to the climate in which the building where it is applied is located. To this regard, the phase change temperature of the PCM must be overlapped to the ambient temperatures characteristic of that area. In addition, to create a form-stable PCM it is possible to choose waste materials, coming from other processes, in line with the Circular Economy strategies. Still complying with the principles of sustainability and protection of environment and human health, the components of the PCM should be materials with low environmental impact, non-toxic, non-harmful, possibly inexpensive. In accordance with these requirements, a form-stable PCM was produced consisting of an inert matrix of stone pieces (waste from the extraction and processing of a very porous stone, Lecce Stone) impregnated with a low environmental impact polymer, i.e. Poly-Ethylene Glycol (PEG) [37,38]. PEG is an organic compound with excellent phase change properties, such as adequate enthalpy value, no supercooling and good chemical and thermal stability [39]. Another interesting advantage offered by PEG polymers lies in the fact that it can be synthesized in different molecular weights, each molecular weight corresponding to a different range of melting/crystallization temperatures. In our wide research, the PEG 1000 was first chosen to produce a form-stable PCM, this polymer offering phase change temperatures suitable for climatic regions characterized by mild/warm temperatures, as Mediterranean ones. In [40] it was proved, in fact, that the addition to mortars of a form-stable PCM, based on PEG 1000 included in Lecce Stone granules, reduced thermal loads of cement and hydraulic lime-based mortars if applied in buildings located in warm countries. In order to extend the application of PEG-based PCMs to other climate areas, PEG 800 was proposed [41,42]. This grade of Poly-Ethylene Glycol, in fact, offers melting/crystallization temperatures close to those typical of continental regions. In order to try to broaden the temperature ranges in which PEGs-based PCMs are able to operate, two PCMs based on PEG800 and PEG1000, respectively, were added at 50/50 in weight as aggregate in mortars based on aerial and hydraulic limes, gypsum and cement [42]. After having determined the main characteristics of the mortars containing the PEG-based PCMs in the fresh and hardened states [41,42], the thermal performance of a selection of such mortars, i.e. those based on hydraulic lime and cement, were analyzed, and presented in this work. To this aim, an experimental setup was implemented in a climatic chamber to simulate the hourly variation of the ambient temperatures relating to two climatic zones, one continental and one Mediterranean, analyzing the thermal behavior of mortars containing or not PCMs. A cost estimation was made in order to calculate the economic savings resulting from the introduction of PEG-based PCMs in the mortars applied in buildings located in Mediterranean area, as concrete advantages were observed only for this climatic zone.

2. Motivation and novelty

From an in-depth study of the current literature on PCMs, the materials already tested for their production, the most common applications of PCMs, and keeping in mind the current sustainability requirements, a combination of materials and applications not yet investigated was identified.

The authors focused their attention on the form-stable method, i.e., a method capable of creating a composite PCM in a simple and economical way. According to Wang et al. [43], keeping low the production costs of a PCM often takes a backseat as more emphasis is placed on the type of PCM and the type of inclusion. In the last decade, for example, numerous experimental works have used this technique starting from a matrix which, in order to obtain a suitable porosity, must be subjected to (expensive and lengthy) thermal or chemical treatments [44–46]. On the other hand, if expensive components and production methods are used to produce PCMs, these cannot be fully considered as sustainable cost-effective methods of achieving energy efficiency in buildings. According to what has just been reported, the form-stable method has been proposed in this work.

The first novelty that distinguishes this study from those previously published by other authors concerns the inert support: a natural stone was chosen, available locally (i.e., a 0 km material with respect to the University of Salento), obtained from the waste of its processing, ready to be impregnated without the need for further (chemical, thermal) treatments. While in most of the previously published works the PCM composite is obtained through a direct impregnation process, which can lead to an undesirable leaching phenomenon (i.e., the polymer phase can leak from the support during its phase change) [42,44,45], in the present research the impregnation of the stone granules was performed under vacuum: this procedure guarantees a better and more complete impregnation and most likely limits the leaching phenomenon.

To the best of our knowledge, no researcher had previously proposed the exploitation of waste materials to produce PCMs. The reuse of (locally sourced) waste materials represents a very advantageous choice from an economic and environmental point of view, it complies with the principles of the Circular Economy as it allows the exploitation of a material that should be disposed, with a consequent reduction of the costs for its disposal. Furthermore, the success of our choice opens up the possibility of exploiting various inert porous supports obtained as waste from other local processes/productions, with multiple beneficial effects for the environment.

The use of PEG as a sustainable, environment friendly polymer to produce form-stable PCMs is not an absolute novelty [47–50]. On the other hand, the creation of a mixed PCM composed of PEGs of different molecular weights, in order to broaden the PCM service temperature range and make it suitable for different climates, to the best of our knowledge has not yet been proposed by any other author.

Most of the studies reporting the capability of PCMs as thermal efficiency devices refer to applications in buildings located in temperate climates. According to Liu et al. [51], 64 % of the works published so far on PCMs refer to applications in temperate climates, 13 % of the studies analyzes the thermal properties of PCMs applied in buildings located in cold areas and only 2 % refer to hot/tropical climates. For this reason, the present work aims to focus its attention on continental/cold (Czech Republic) and Mediterranean/hot (Southern Italy) climates, comparing advantages and limitations of using the same PCM, characterized by a wide range of phase change temperatures, in both climatic conditions. Furthermore, the review of the current literature demonstrates that published studies often analyze the behavior of a PCM in relation to the climate of only one season of the year, whereas it has been strongly recommended to conduct experiments on an annual basis, as reported in [52].

Finally, the analysis of the current literature allows to highlight another gap: there are only few studies reporting a detailed analysis on the energy and economic savings obtainable with the use of PCMs in mortars, in relation to the expected external climate. The present study, therefore, has the further objective of deepening the knowledge on these applicative aspects.

3. Materials and methods

3.1. Preparation of the PEG-based form-stable Phase Change Materials

Two form-stable phase change materials were produced starting from the components reported in Table 1.

Lecce Stone (LS) is a natural stone mainly composed of calcium carbonate ($CaCO_3$). It can be easily found in quarries located in the province of Lecce (Apulia, South Italy). It is well-known for its workability and its high degree of porosity. As previously found [37], Lecce Stone displays an open porosity of about 30 %, with average pore radius around 0.054 μm. Its high open porosity makes this stone an ideal matrix to contain a phase change material using the form-stable method. The Lecce Stone is used both as a construction material and to create decorative elements: during its processing, large quantities of waste stones are produced, posing problems for their disposal. Therefore, the stone can be collected and recovered from the quarry (in the form of flakes), obtaining small granules to be used as aggregates in mortar formulations. In the present work, waste Lecce Stone was collected, ground and, then, sieved to obtain grains of a proper granulometry, i.e. in the range 1.6–2.0 mm. A part of these granules was used as it is, to make the reference mortars not containing any PCM, while another part was subjected to the impregnation process with PEG.

The polymers employed to produce the form-stable PCMs were Poly-ethylene Glycol 800 (PEG800) and Poly-ethylene Glycol 1000 (PEG1000). The main characteristics of both PEGs are summarized in Table 1. Basically, the different molecular weights are responsible for the different ranges of melting/crystallization temperatures, reported for each of the two PEGs in [37,41], respectively. Through a simple and economical impregnation process, conducted under vacuum at mild temperatures [37,41], each of the two PEGs was included in LS granules, obtaining two form-stable composite materials, namely LS/PEG800 and LS/PEG1000, respectively. Previous experiments have shown that the maximum obtainable amount of PEG absorbed in LS granules was 23 % by weight, regardless of the grade of PEG [41]. In addition, the leakage of the polymer from the stone granules was evaluated, even at temperatures well above the melting point of each PEG: it was found that the form-stable composite PCMs were thermally stable since the inert support (i.e. Lecce Stone) was able to retain each of the two absorbed PEGs [41]. The thermal properties of both PEG-based PCMs have been previously evaluated [37,41], they are summarized in Table 2. From the observation of the calorimetric data reported in Table 2, the selection of the two polymers is clear: PEG 1000 is suitable for producing a PCM for warmer climates, while a PCM based on PEG 800 would be appropriate for colder weathers.

Table 1
Materials used to produce the form-stable PCMs, with main features and properties.

Materials	Poly-Ethylene Glycol 800 (PEG800)	Poly-Ethylene Glycol 1000 (PEG1000)	Lecce Stone (LS)
Main Features	Semi-crystalline thermoplastic polymers. Low toxic, low flammable. The thermal properties (ranges of melting/crystallization temperatures, melting/crystallization peak temperatures, enthalpies) depend on the molecular weight of each PEG		Highly porous stone used as a matrix, available as waste material
Density (kg/m^3)	1200		2957
Molecular weight (amu)	800	1000	–
Supplier	Wuhan Fortuna Chemical Co. (Wuhan, China)	Sigma—Aldrich Company (Darmstadt, Germany)	L'essenza della Pietra, Taviano (Lecce), Italy

Table 2
Thermal properties of form-stable PEG-based PCMs [37,41].

Form-stable PCM	Thermal Properties					
	Melting			Crystallization		
	Tm_{start} (°C)	Tm_{peak}(°C)	Tm_{end}(°C)	Tc_{start} (°C)	Tc_{peak}(°C)	Tc_{end}(°C)
LS/PEG800	−5.3 ± 0.6	12.7 ± 1.4	25.4 ± 2.2	12.4 ± 0.8	9.3 ± 0.9	−8.2 ± 0.4
LS/PEG1000	31.7 ± 1.2	39.3 ± 0.7	47.7 ± 2.4	23.5 ± 0.7	19.4 ± 0.9	9.3 ± 0.5

Tm_{start}, Tm_{end} are the initial and final temperatures, respectively, of the melting process of the PCMs under study; Tc_{start}, Tc_{end} are the initial and final temperatures, respectively, of the crystallization process of the PCMs under study; Tm_{peak} and Tc_{peak} are the peak temperatures of melting and crystallization processes, respectively.

3.2. Preparation of the mortar formulations

The two form stable composite PCMs, i.e. LS/PEG800 and LS/PEG1000, were added as aggregates in mortar formulations based on hydraulic lime and cement. For comparison purposes, reference mortars, based on the same binders and containing un-impregnated Lecce Stone granules only, were manufactured. In a previous phase of the research [42], the form-stable PCMs based on PEG800 or PEG800/PEG1000 50/50 wt. were added to several mortar formulations based on different binders (i.e., aerial lime, hydraulic lime, gypsum, cement), measuring their mechanical properties. From the obtained results, it was possible to identify the best performing mortars, i.e. those based on hydraulic lime and cement. This choice was found to be also in agreement with another previous study [40], in which the thermal properties of mortars based on hydraulic lime and cement and containing a form-stable PCM based on PEG1000 were evaluated in a climatic chamber, able to reproduce the temperatures typical of a Mediterranean region. Once it was demonstrated that the inclusion of a PEG1000-based PCM in those mortars was able to reduce the thermal load of buildings located in warm-temperate climates, in this work we used PEG800 to produce a PCM that was active in a range of temperature shifted to lower values, i.e. possibly characteristic of colder climates, and a mix (50:50 in weight) of PEG800/PEG1000 to manufacture a form-stable PCM active in a wider interval of temperatures.

The components of the produced mortars are reported in Table 3, with their main characteristics.

For each binder, three different mortar formulations were realized: a reference containing Lecce Stone as aggregates; a mortar containing LS/PEG800 as aggregate; and a formulation containing 50%wt. of LS/PEG800 and 50%wt. of LS/PEG1000. Table 4 summarized the composition of each mortar analyzed in the present study; they were all manufactured according to the European Standard EN 998–1 [53]. Each mortar was produced using 1000 kg/m^3 of binder. The "water saturation" is the water used to saturate the LS aggregates in order to avoid them to absorb the water required for the production of the mortars not containing any PCM. When a LS/PEG composite PCM is added to mortars, no additional water was required: in this case, in fact, the pores of the stone were almost completely saturated by PEG 800 or PEG 1000 polymers.

3.3. Analysis of thermal properties of mortars

The main objective of this work was the study of the thermal properties of the developed mortars containing the two PCMs. To pursue this goal, a small-scale box was created that simulated a room exposed to external environmental conditions, reproduced inside a climatic chamber, as previously experienced [40]. With such a device, reported in other researches [54–59], it is possible to analyze the thermal properties of mortars containing a PCM, in particular their response in terms of a drop of the thermal load following changes in the external temperature. The temperature program in the climate chamber (Fitoclima 1000 EC45, Aralab Company, Rio de Mouro, Portugal) is able to simulate the four seasons of the year (i.e. summer, spring, fall and winter) for a specific climatic region. Two different thermal programs were employed in the present study: one referred to the typical temperatures of a continental region, the other referred to a characteristic climate of the Mediterranean area. In the first case, the temperatures recorded during 2020 by the weather station in Prague (Czech Republic) were taken into account; the temperatures recorded in the same year (i.e., 2020) by the meteorological station of Lecce (Italy) were used to set the second program. For each season, the temperature program was repeated for 5 days. On the other hand, the measurements of the first and last days were excluded from the data analysis to avoid that the temperature recording was affected by errors during the temperature change.

The small-scale boxes, whose internal walls had been covered with the mortars reported in Table 4, were placed inside the climatic chamber (as illustrated in Fig. 1a). The cubic boxes were realized in insulating material (Extruded Polystyrene, XPS), with a 20 cm side and a 3 cm thickness (Fig. 1b). The thickness of the layers of each mortar, placed on all internal sides of the box, was 1 cm (Fig. 1c). Inside each box, a type K thermocouple was inserted, making sure it was positioned exactly in the center of the box (Fig. 1d). Any thermocouple was, then, connected to a data acquisition system (AGILENT 34970A, Santa Clara, CA, United States) which measured every 30 s the temperature inside the box and outside it, that is, inside the climatic chamber (Fig. 1e). The recorded temperatures were, finally, analyzed by a proper data analysis software (Bench Link Data Logger 3, downloaded for free from Keysight, Santa Rosa, CA, United States).

4. Results and discussion

By adding a PCM in a mortar it is possible to modify its thermal behavior due to the ability of the PCM to change phase according to the external temperature. It can therefore be deduced that the appropriate PCM must be chosen on the basis of the expected external temperatures, that is, the climatic conditions typical of a geographical area [51].

Table 3
Materials used to produce the mortars, with main features and properties.

Materials	Hydraulic Lime (HL)	Cement, CEM I 42.5 R (C)	Superplasticizer, Master Glenium SKY 627 (SP)
Density (kg/m^3)	2700	3030	1050
Main Features	Mainly used to produce plasters and mortars, able to harden even in extreme conditions (i.e. underwater). They are typically used in applications with not excessive loads and as plasters for conservation and restoration.	Widely used in construction for high mechanical resistance. It can be employed for repairing of damaged concrete, for rendering and floor leveling. It is widely used to produce precast products.	Polyacrylate added to each mortar in order to reduce the amount of water required for the mixing. It confers good workability and adequate mechanical properties to the mortars.
Supplier	CIMPOR Company (Lisbon, Portugal)	SECIL Company (Lisbon, Portugal)	BASF (Porto, Portugal)

Table 4
Mortar compositions (amounts reported as kg/m^3).

System	Binder/Content	Aggregates			SP	Water Saturation	Water	Water/Binder
		LS	PEG800 content	PEG1000 content				
HL_LS	HL/1000	682	0	0	20	171	380	0.38
HL_LS/PEG800		1082	249	0	20	0	320	0.32
HL_LS/PEG800_PEG1000		1082	124	124	20	0	320	0.32
C_LS	C/1000	772	0	0	20	194	390	0.39
C_LS/PEG800		1307	301	0	20	0	300	0.30
C_LS/PEG800_PEG1000		1307	150	150	20	0	300	0.30

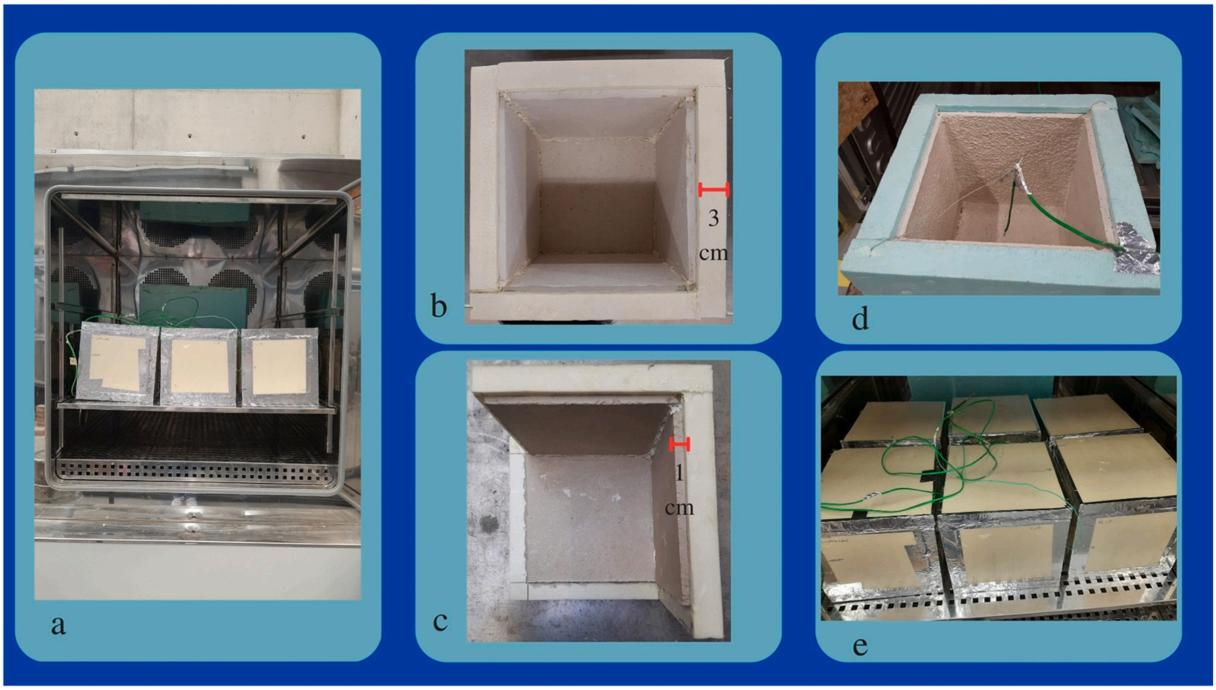

Fig. 1. Experimental equipment employed for studying thermal properties of mortars. a) small-scale boxes inside the climatic chamber; b) box realized in XPS; c) application of a 1 cm-thick mortar layer inside a small-scale box; d) a small-scale box with a thermocouple in the center; e) image of six small-scale boxes inside the climatic chamber, each of them connected with the data acquisition system.

Bearing in mind these considerations, in this study Poly-ethylene Glycol 800 and Poly-ethylene Glycol 1000 were selected as polymeric components of two PCMs included in different mortars. Previous investigations have demonstrated the validity of these selections. In Table 5, the initial and final temperatures measured in calorimetric tests during melting and crystallization on the mortars based on hydraulic lime and cement are reported as a function of the PCM added [42]. In fact, the melting/crystallization processes can only be attributed to the PEG component/components in each PCM. According to the data reported in Table 5, the mortars containing the PEG800-based PCM, i.e. LS/PEG800, display a melting process that starts just below 0 °C and ends at around 21–25 °C; the crystallization process of the same mortars takes place between 15 and 19 °C and just below 0 °C. This PCM could be, therefore, reasonably proposed to produce mortars applied in buildings located in continental areas, characterized by lower temperatures. When a mix of both PCMs (i.e. LS/PEG800/LS/PEG1000 50/50 % wt.) is added to the same mortars, larger melting/crystallization peaks are recorded, shifted to high temperatures: the melting process from 3 to 7 °C to around 40 °C; the crystallization one between 25 °C and about 0 °C. This last PCM composite could be, therefore, proposed for buildings located in different climates or where large temperature variations are expected, for example from day to night.

Table 5
Initial, final and peak temperatures recorded in melting (heating stage) and crystallization (cooling stage) processes on the mortars based on hydraulic lime and cement containing a PEG-based PCM (data from [42]).

	System	T_{start} (°C)	T_{end} (°C)
Heating stage	HL_LS/PEG800	−2.3 ± 0.8	21.2 ± 0.5
	C_LS/PEG800	−2.0 ± 0.8	25.8 ± 1.8
Cooling stage	HL_LS/PEG800	14.6 ± 1.4	−3.3 ± 0.6
	C_LS/PEG800	19.1 ± 0.6	−0.4 ± 0.2
Heating stage	HL_LS/PEG800_LS/PEG1000	6.9 ± 3.1	38.4 ± 0.8
	C_LS/PEG800_LS/PEG1000	3.5 ± 1.8	42.3 ± 0.4
Cooling stage	HL_LS/PEG800_LS/PEG1000	25.1 ± 0.7	−1.4 ± 2.2
	C_LS/PEG800_LS/PEG1000	25.9 ± 0.5	0.3 ± 0.2

Starting from these calorimetric data, the thermal performance of mortars based on hydraulic lime and cement, containing or not one of the PEG-based PCMs, were analyzed in a climatic chamber, to establish their ability to reduce indoor temperature fluctuations due to external thermal variations related to two climatic zones. Fig. 2 shows the characteristic temperatures registered in each season in two geographical areas taken as reference, i.e. a continental region (a) and a Mediterranean area (b), respectively. Referring to the continental regions, the average temperatures range from 0 °C in winter to a maximum of 20 °C in summer. On the other hand, in the Mediterranean area, the average temperatures range from around 7 °C in winter to about 33 °C in summer. The aim of this research was, therefore, to ensure that the internal

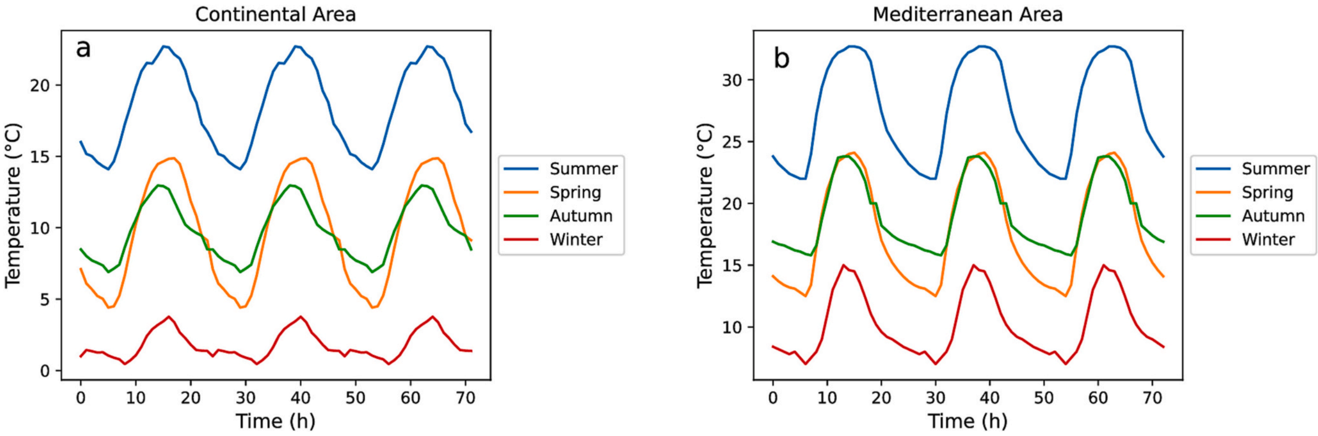

Fig. 2. Characteristic temperatures registered in the four seasons in: a) continental area; and b) Mediterranean regions.

temperature of a home, in which mortars containing the proper PCM are applied, remains within the comfort temperature range, reported to be between 20° and 25 °C [60], regardless of the climatic zone in which the building is located.

4.1. Continental area

In Figs. 3 to 6, the graphs of the temperatures collected inside the small-scale boxes (Fig. 1a) during the thermal tests carried out in a climatic chamber, simulating the external climatic conditions in each season, are presented. In Fig. 3a and b, the thermal behavior of the box internally lined by hydraulic lime-based and cement-based mortars, respectively, with and without the form-stable PCMs, i.e. LS/PEG800 and LS/PEG800_LS/PEG1000, is illustrated. The curves recorded for the mortars containing no PCM aided to identify the effect of each PCM on the mortar thermal behavior. The trend of the temperatures recorded in continental countries in summer season is also reported. A horizontal band representing the comfort temperature range is also shown.

The lowest temperature registered in these countries in summer is 14 °C and the highest 23 °C. This observation suggests that both PCMs should be able to activate their phase transition, absorbing and releasing thermal energy, in the mortars based on the two different binders. A certain decrease in maximum temperatures and an increase in minimum temperatures was recorded in the small-scale boxes when a PCM was added to mortars, suggesting a beneficial effect of both PCMs on the indoor temperature in the coldest period of the day. During the hottest hours, on the other hand, the indoor temperatures remain within the comfort temperature range, there is no need for cooling. Finally, negligible differences are measured between the two different binders and the different form-stable PCMs.

Fig. 4 illustrates the thermal behavior measured in the small-scale boxes, simulating external temperatures characteristic of spring season, where the hydraulic lime-based mortars, Fig. 4a, and the cement-based mortars, Fig. 4b, were applied. The greatest outdoor temperature recorded during this season is 15 °C, the coldest 5 °C: the indoor environment must be, therefore, substantially heated to ensure thermal comfort. As it is observed in the graphs reported in Fig. 4, the mortars containing both PCMs experienced a certain increase in the minimum temperatures. The maximum temperatures, on the other hand, decreased, proving that the PCMs were not able to provide the desired thermal effects in this season. Only small differences in temperatures were recorded for mortars with or without the PCMs.

Similar considerations can be drawn from the observation of the temperature data relating to autumn, reported in Fig. 5a and b for lime-based and cement-based mortars, respectively.

The maximum/minimum temperatures recorded in this season are 13 °C and 7 °C, respectively. The lowest temperatures measured in the small-scale boxes increased, the maximum ones declined. Furthermore, the PCMs contained in the mortars did not appear to have contributed effectively to the thermal behavior of the mortars, as the temperatures measured for mortars containing or not the PCMs did not substantially differ.

Finally, Fig. 6 shows the temperature graphs relative to winter season. Winter is the coldest season, with a maximum temperature of 4 °C and a minimum of 0 °C. At these low temperatures, it was observed a substantial increase in minimum temperatures with respect to the external temperatures but also a decrease in maximum ones. In this case, moreover, a different thermal behavior was observed for the mortars

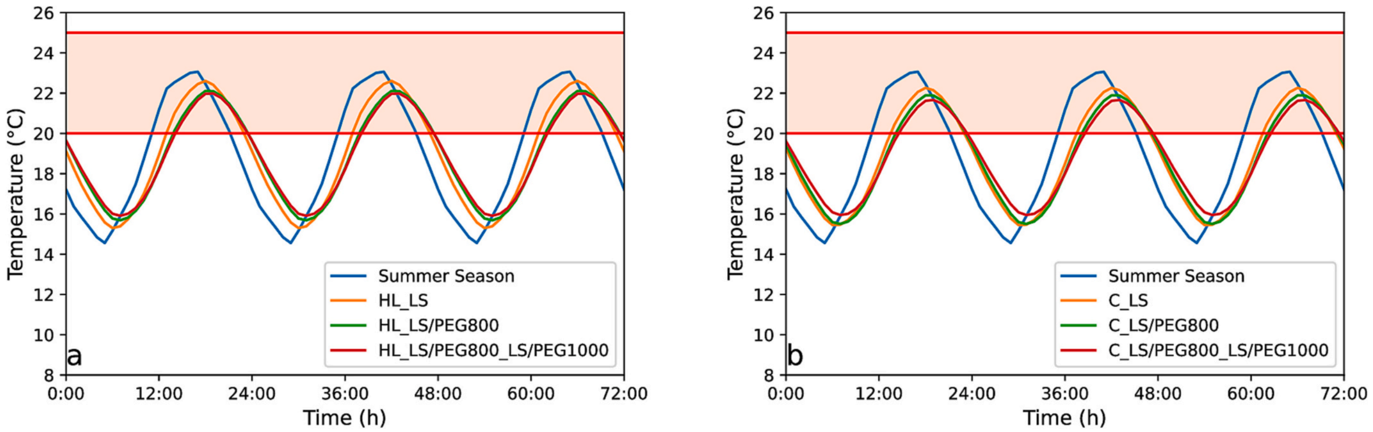

Fig. 3. Temperatures registered in small-scale boxes simulating the summer in continental regions for: a) hydraulic lime-based mortars and b) cement-based mortars.

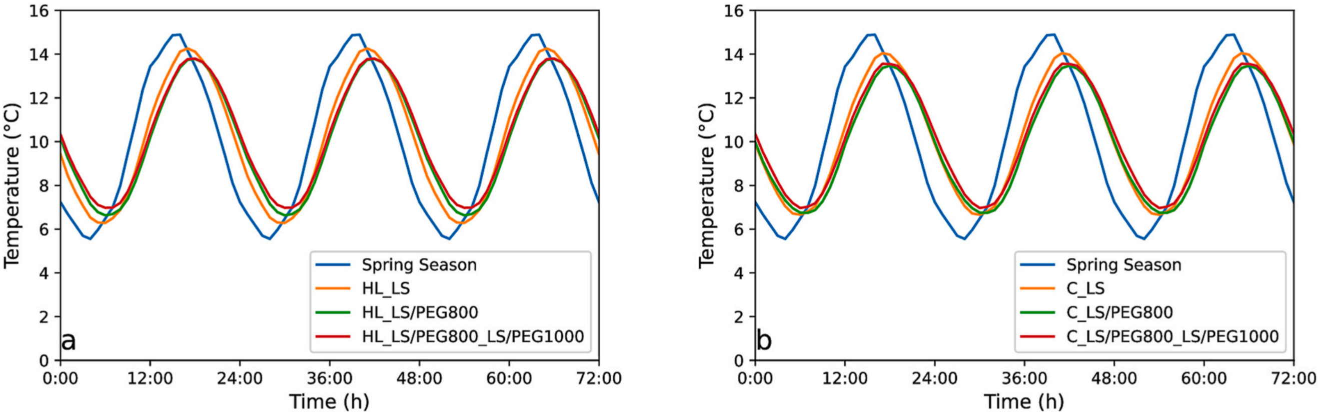

Fig. 4. Temperatures registered in small-scale boxes simulating the spring in continental regions for: a) hydraulic lime-based mortars and b) cement-based mortars.

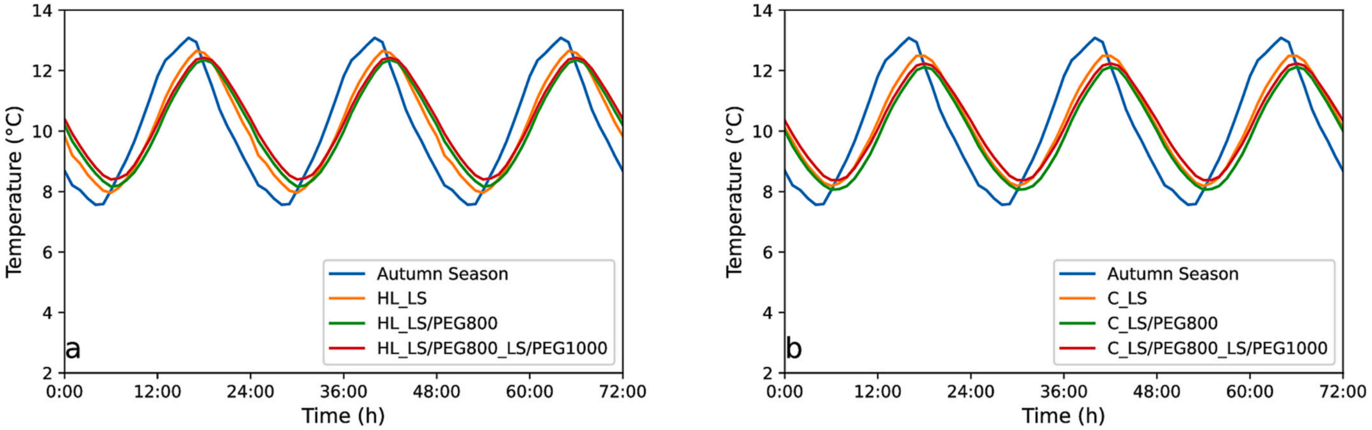

Fig. 5. Temperatures registered in small-scale boxes simulating the autumn in continental regions for: a) hydraulic lime-based mortars and b) cement-based mortars.

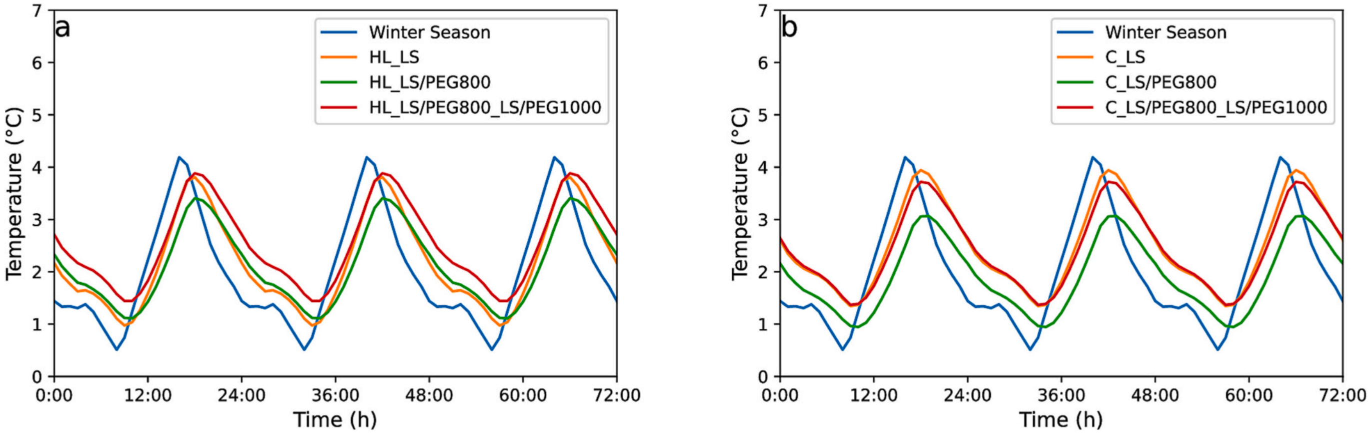

Fig. 6. Temperatures registered in small-scale boxes simulating the winter in continental regions for: a) hydraulic lime-based mortars and b) cement-based mortars.

containing the different composite PCMs: LS/PEG800_LS/PEG1000 composite provided a better thermal behavior to the mortars in which it was included.

Although the results just reported on the thermal behavior of mortars containing PCMs in relation to a continental climate were not entirely satisfactory, a time lag in the temperature curves was generally observed, irrespective to the season. The time lag data, measured for maximum and minimum temperatures with respect to the external temperature, are reported in Table 6 for the reference mortars and for those containing the experimental PEG-based PCMs.

To obtain a real advantage in terms of a shift in the peak thermal load, the delay of the peak temperatures (minimum and maximum) must be in the order of magnitude of an hour. From the data presented in Table 6, it was concluded that all the mortars containing a PEG-based PCM exhibited greater time lags than the respective reference mortars (i.e. those without any PCM), confirming the beneficial contribution of the produced PCMs. Generally speaking, the greatest time lags were recorded for the cement-based mortars. This is due to the lower porosity of these mortars. Referring to the kind of PCM, that based on both PEGs, i.e. LS/PEG800_LS/PEG1000, offered the greatest advantages during

Table 6
Time lag between the maximum and minimum temperatures recorded for reference mortars and for those containing the PCMs with respect to the external (set) temperatures relative to continental regions. (In bold, the best performing mortars, in terms of greater time lag values, in each season).

	Summer		Spring		Autumn		Winter	
	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}
HL/LS	110	115	115	105	115	100	130	85
HL_LS/PEG800	150	155	155	150	160	140	180	130
HL_LS/PEG800_LS/PEG1000	160	160	155	145	160	140	170	120
C/LS	130	130	135	125	140	120	155	105
C_LS/PEG800	155	155	**165**	**155**	**165**	145	**190**	**140**
C_LS/PEG800_LS/PEG1000	**170**	**170**	**165**	**155**	**165**	**150**	180	125

summer; in winter, the PCM containing the PEG produced with PEG 800 appeared to be more favorable; finally, the data recorded in spring and autumn revealed that both PCMs led to the same time lags. These observations must be related to the melting/crystallization temperatures ranges of the two systems: during summer the best advantages are achieved using a PEG with a melting/crystallization temperatures ranges shifted towards greater values (i.e. PEG 1000, in addition to PEG 800); in winter, on the other hand, the PEG exhibiting lower phase change temperatures, i.e. PEG 800, leads to the greatest time lags.

To obtain further useful information on the thermal performance of the mortars containing the different PCMs, their thermal gradient was calculated, being the latter the difference in temperature between the mortar containing a PCM and its reference mortar (without any PCM). In Fig. 7, the thermal gradient curves for each mortar in each season, are reported.

The thermal gradient provides a measure of the heat storage capacity of the PCM contained in a mortar relative to its reference mortar. Therefore, a high thermal gradient corresponds to a large storage capacity of a PCM, and in turn to a better thermal performance. From the evaluation of the thermal gradients reported in Fig. 7, it is possible to conclude that the mortars based on hydraulic lime offered a better thermal performance, this characteristic being assessed through a greater difference in temperatures with the reference mortar not containing any PCM. This result can be partly attributed to a greater porosity offered by these mortars.

4.2. Mediterranean area

The thermal performance of the hydraulic lime-based and cement-based mortars containing the developed PCMs were, then, investigated in relation to the characteristic temperatures of the Mediterranean area. In Figs. 8-11, the graphs relative to the temperatures, relative to the four seasons, registered in the small-scale boxes during the thermal tests performed in the climatic chamber on mortars containing or not the PCMs, are shown. In the same graphs, the curves relative to the temperatures recorded in each season in Mediterranean countries in summer season are shown; the horizontal band representing the comfort

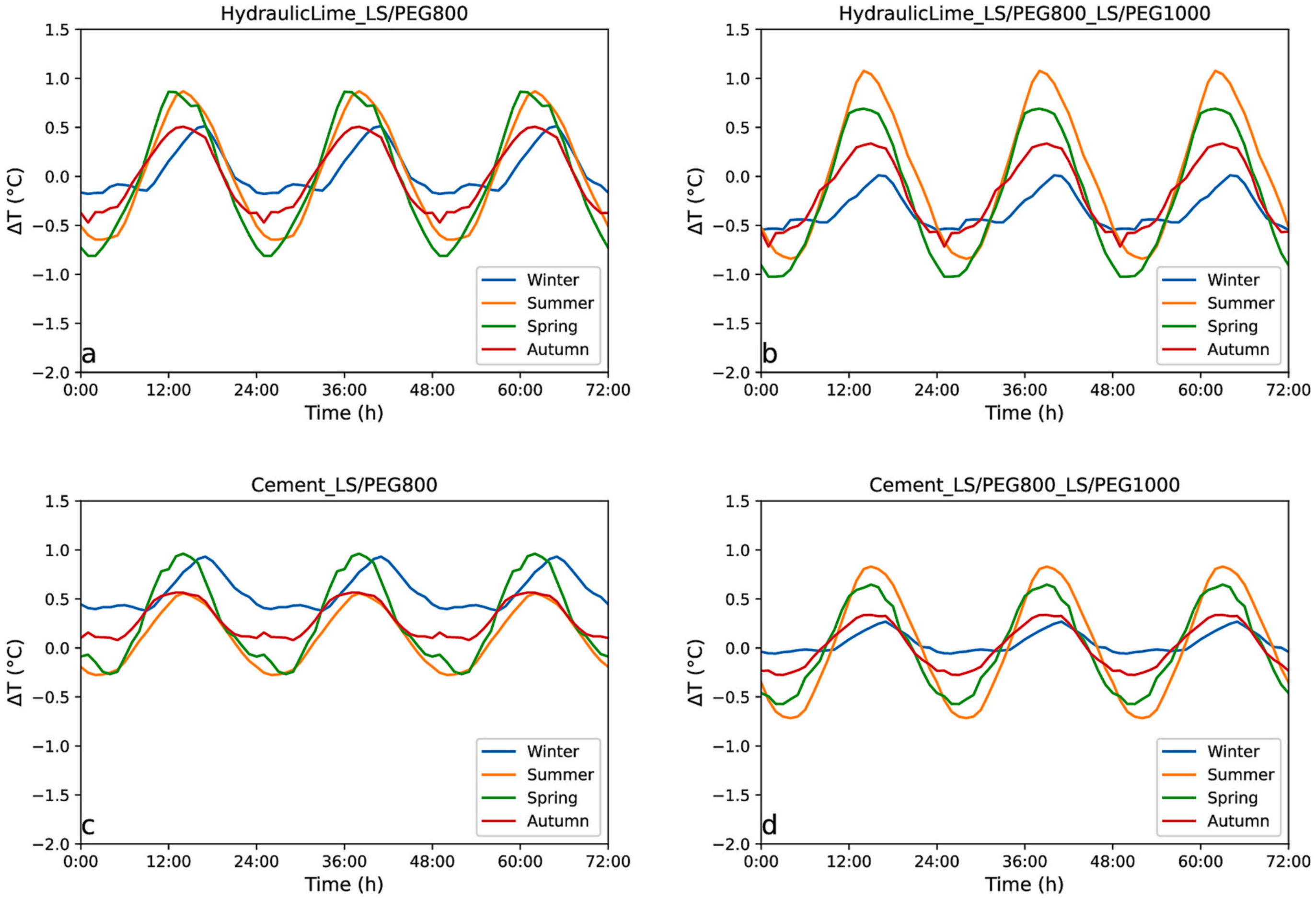
HydraulicLime_LS/PEG800
HydraulicLime_LS/PEG800_LS/PEG1000
Cement_LS/PEG800
Cement_LS/PEG800_LS/PEG1000

Fig. 7. Thermal gradient between reference (no PCM) and PCM-based mortars for each season in continental regions relative to: a) hydraulic lime-based mortar containing LS/PEG800; b) hydraulic lime-based mortar containing LS/PEG800_LS/PEG1000; c) cement-based mortar containing LS/PEG800; and d) cement-based mortar containing LS/PEG800_LS/PEG1000.

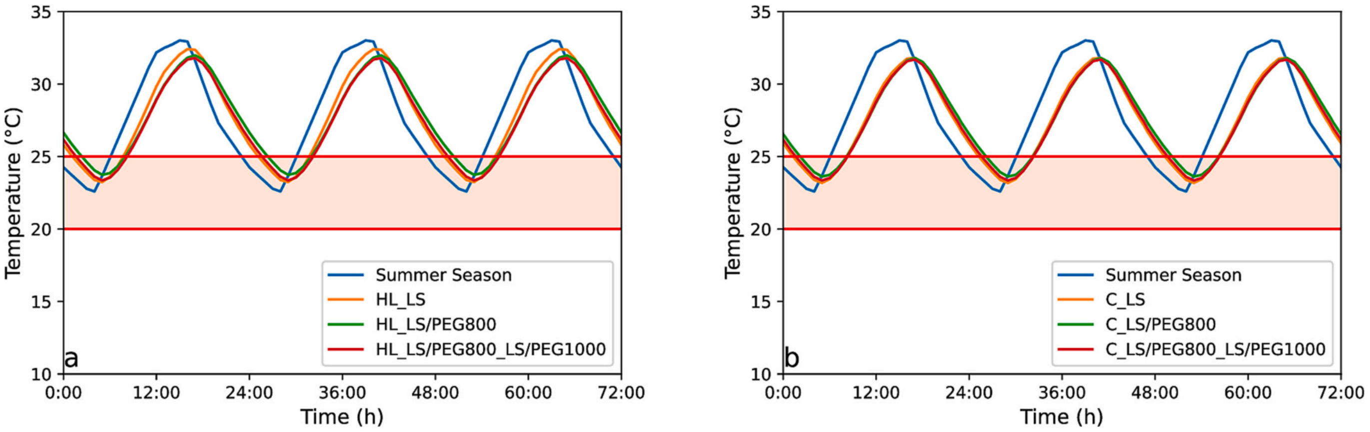

Fig. 8. Temperatures registered in small-scale boxes simulating the summer in Mediterranean regions for: a) hydraulic lime-based mortars and b) cement-based mortars.

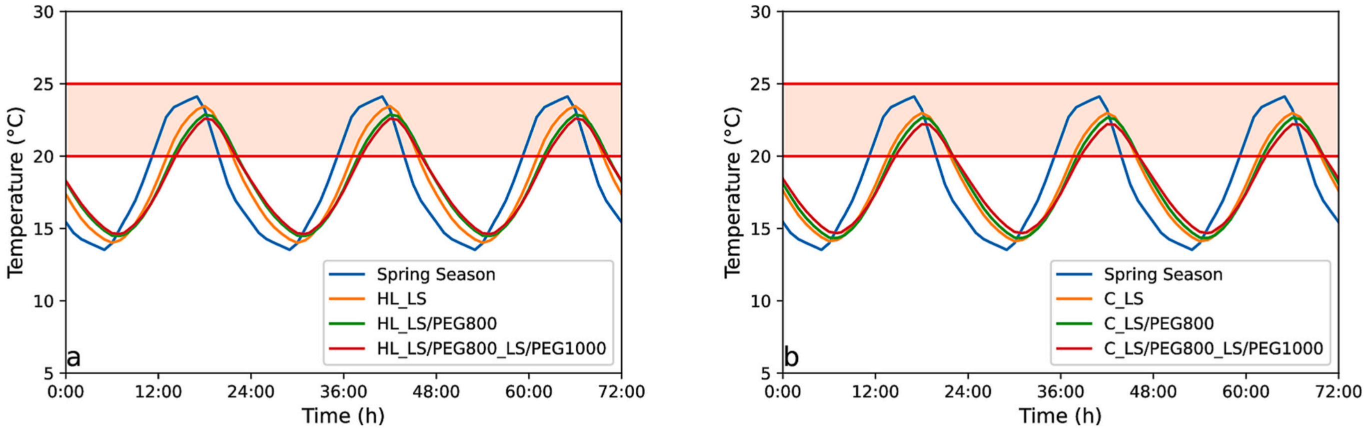

Fig. 9. Temperatures registered in small-scale boxes simulating the spring in Mediterranean regions for: a) hydraulic lime-based mortars and b) cement-based mortars.

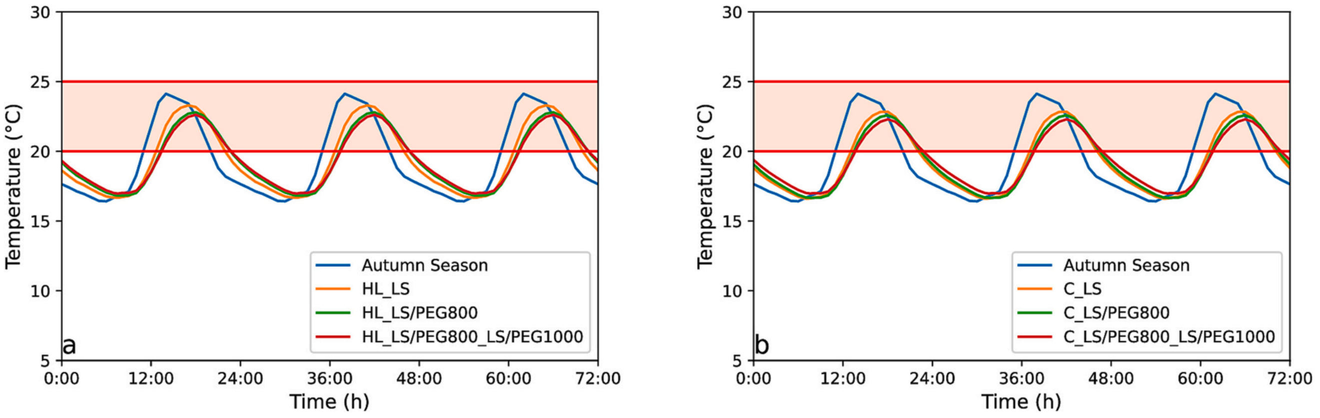

Fig. 10. Temperatures registered in small-scale boxes simulating the autumn in Mediterranean regions for: a) hydraulic lime-based mortars and b) cement-based mortars.

temperature range is also displayed.

Starting from summer (Fig. 8), the maximum outdoor temperature recorded in Mediterranean regions is 33 °C and the minimum is 22 °C, this implies that an indoor environment must be cooled to bring the temperature back into the thermal comfort range. Referring to the cement-based mortars containing the PCMs (Fig. 8b), their thermal behavior was found to be close to that displayed by the corresponding reference mortar, without any substantial advantage due to the addition of a PCM. In all the cement-based mortars analyzed, however, a reduction in the maximum temperatures recorded in the hottest hours is observed. On the other hand, a beneficial effect was offered by hydraulic lime-based mortars containing both PCMs in correspondence of the greatest temperatures recorded during summer, as observable in Fig. 8a, the maximum measured temperature being around 2 °C lower than the

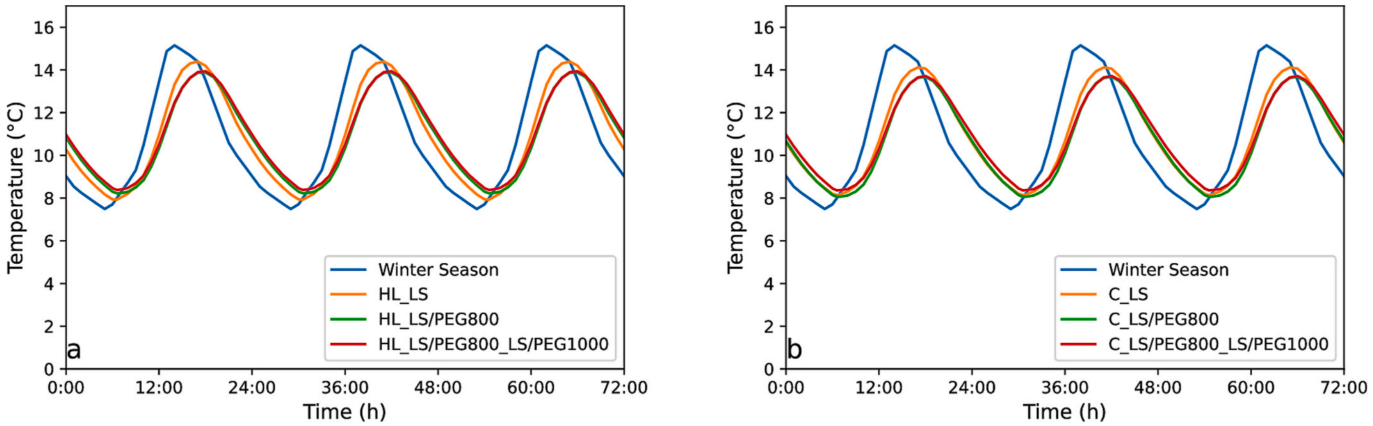

Fig. 11. Temperatures registered in small-scale boxes simulating the winter in Mediterranean regions for: a) hydraulic lime-based mortars and b) cement-based mortars.

external temperature.

Referring to the spring season, the typical temperatures of Mediterranean regions are in the range 13°-24 °C. Consequently, as can be seen in Fig. 9, the need for heating is necessary during this season in the coldest hours to remain in the comfort temperature range. To this regard, both PCMs are able to increase the lowest temperatures recorded inside the small-scale box, irrespective to the type of mortars. At the same time, the incorporation of a PCM in both mortars led to a decrease of around 2 °C in maximum temperatures, the latter still remaining in the comfort temperature range.

Fig. 10 reports the thermal performance of the different mortars in autumn, having as reference the outdoor temperature typically recorded in a Mediterranean climate, i.e. a maximum temperature of 24 °C and a minimum temperature of 16 °C. From the analysis of the results reported in Fig. 10, it can be concluded that both PCMs are able to reduce the maximum recorded temperatures, leaving, however, the indoor temperature within the comfort range. There are no obvious advantages at the lowest temperatures when adding a PCM to the mortars. Generally speaking, no significant differences were observed in relation to the binder used in the mortars.

Finally, in Fig. 11, the thermal behavior of the produced mortars when exposed to a winter climate in Mediterranean regions, is shown. In this season, the typical temperatures recorded in this area are in the range 7°-15 °C, therefore they are far from the comfort conditions. At these temperatures, both PCMs are unable to bring the indoor temperatures into the comfort range, even though the minimum temperatures recorded in the mortars were increased. The presence of a PCM had a limited effect on the thermal behavior of both mortars.

From the results just presented, it can be concluded that both PCMs have brought some advantages to the thermal behavior of hydraulic lime-based and cement-based mortars to which they have been added essentially in the hottest periods of the year, advantages in terms of lower energy needs for cooling the indoor environments of buildings located in Mediterranean regions. The authors arrived at similar results in a previous study carried out in a climatic chamber, setting the temperatures equal to those characteristics of Mediterranean climates, on mortars based on the same binders (hydraulic lime and cement) in which a PCM based only on PEG 1000, i.e. LS/PEG1000, was incorporated [40]. The addition of this PCM to mortars led, in fact, to a reduction of the indoor cooling needs during the hottest season (summer) and of the indoor heating requirements in spring and autumn. In addition, the greatest thermal performance was offered by the mortar based on hydraulic lime and containing the PEG-based PCM, especially in spring and autumn seasons.

To complete the analysis of the results obtained in the climatic chamber simulating a Mediterranean climate, Table 7 compares the time lag, for maximum and minimum temperatures with respect to the external temperature, measured in the different mortars containing or not a PCM. As already underlined, the time lag is representative of the shift to off-peak periods for the consumption of electricity used for cooling/heating needs, with potential economic savings. From the data reported in Table 7, a time lag greater than that measured for mortars not containing any PCM was generally observed in the mortars containing a PEG-based PCM, in both cooling and heating stages. Also in this case, the largest time lag values were generally displayed by the mortars based on cement. As for the type of PEG used to produce the PCMs, it seems that the one offering the greatest advantages in terms of time lag was LS/PEG800_LS/PEG1000, except for the summer. This observation appears to be in contradiction with the melting/crystallization temperatures of the two PEGs and, therefore, it deserves more in-depth analysis.

Table 7
Time lag between the maximum and minimum temperatures recorded for reference mortars and for those containing the PCMs with respect to the external (set) temperatures relative to Mediterranean regions. (In bold, the best performing mortars, in terms of greater time lag values, in each season).

Mortar Formulation	Lag Time (minutes)							
	Summer		Spring		Autumn		Winter	
	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}
HL/LS	110	95	120	90	115	70	110	90
HL_LS/PEG800	**155**	**135**	165	130	160	105	155	130
HL_LS/PEG800_LS/PEG1000	140	125	170	140	165	115	160	130
C/LS	140	115	140	110	135	85	135	110
C_LS/PEG800	**155**	**135**	165	135	160	110	160	130
C_LS/PEG800_LS/PEG1000	145	125	**180**	**150**	**175**	**125**	**165**	**135**

Finally, in Fig. 12, the thermal gradient calculated between each PCM-based mortar and its reference mortar, i.e. without any PCM, in the different seasons reproducing a Mediterranean climate, was reported. Also in this case, the best thermal behavior, i.e. greatest thermal gradients, was offered by the hydraulic lime- mortars containing one of the PEG-based PCMs; as already reported, this behavior can be attributed, at least partly, to a greater porosity characterizing such mortars.

5. Calculation of cooling/heating needs

In order to quantify the energy savings obtained by incorporating one of the two PCMs in the two mortars, the reduction of indoor energy consumption during the heating and cooling processes was calculated.

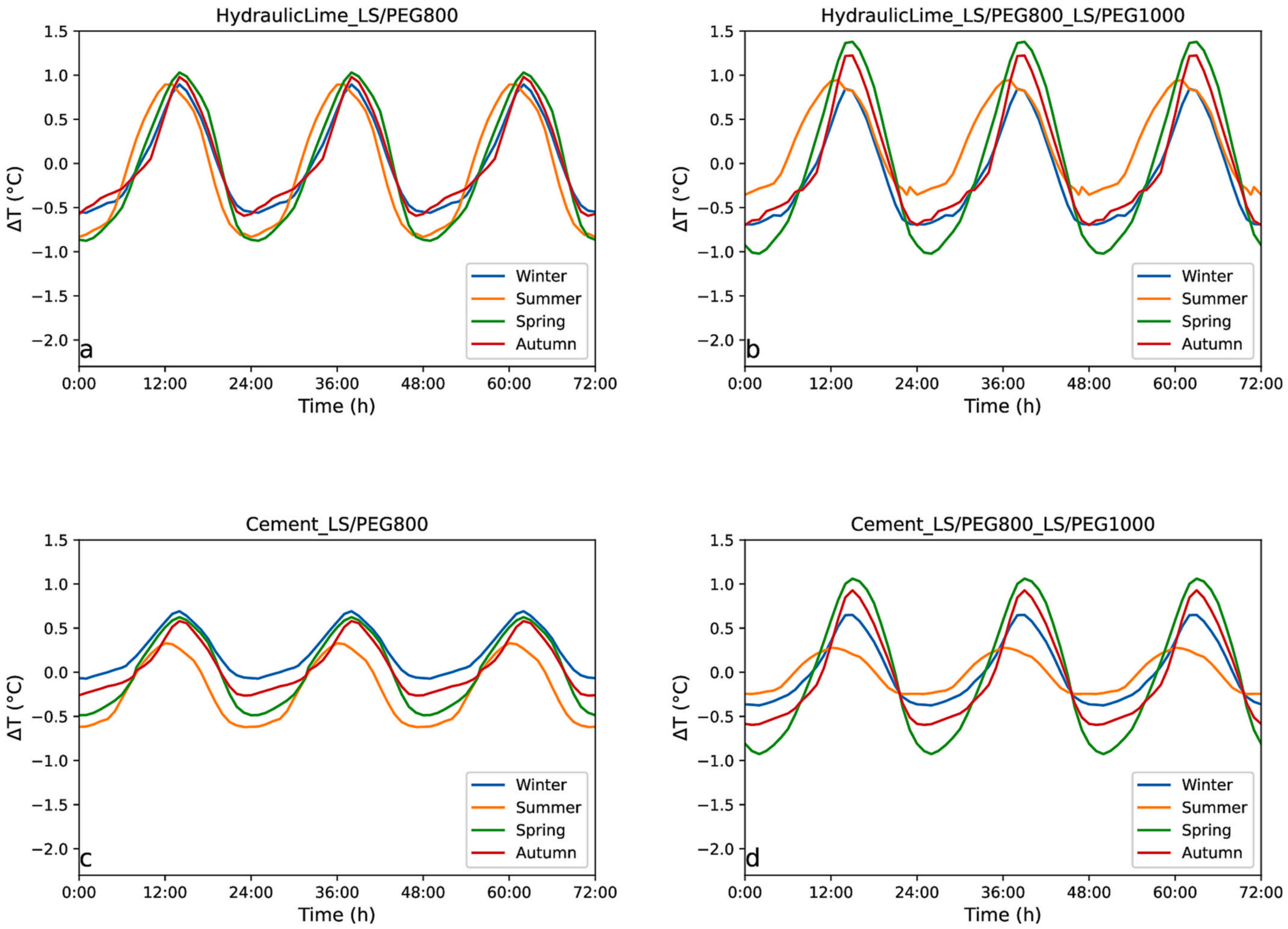

Fig. 12. Thermal gradient between reference (no PCM) and PCM-based mortars for each season in Mediterranean regions relative to: a) hydraulic lime-based mortar containing LS/PEG800; b) hydraulic lime-based mortar containing LS/PEG800_LS/PEG1000; c) cement-based mortar containing LS/PEG800; and d) cement-based mortar containing LS/PEG800_LS/PEG1000.

Referring to the continental regions, only during summer (Fig. 3) the inclusion of a PEG-based PCM in the mortars brought a real advantage in terms of energy saving, with an increase of the lowest temperature registered during this season; the maximum indoor temperatures registered in summer, on the other hand, is already within the comfort temperature range, with no need for cooling. Therefore, it would be inappropriate to use the PEG-based PCMs produced in this study in mortars applied in buildings located in areas with a continental climate since, apart from the summer season, these do not lead to substantial advantages in the rest of the year.

From the analysis performed in Mediterranean regions, as can be observed in Figures from 8 to 10 (relative to summer, spring, autumn, respectively), the application of mortars containing the PEG-based PCMs resulted in a decrease of the maximum temperature recorded in summer, the lowest temperatures being within the comfort temperature range, and an increase of the lowest temperature registered during spring and autumn, since the greatest temperatures were already in the comfort range. Accordingly, the energy needed in a day to keep the temperature inside the small-scale box within the thermal comfort range (i.e. between 20° and 25 °C) was calculated for each season. In particular, the cooling needs required in summer, i.e. the peak area relative to temperatures greater than 25 °C, were calculated; the heating needs, i.e. the peak area below 20 °C, on the other hand, were calculated for spring and autumn seasons. The results for these calculations are reported for each mortar in Table 8.

Table 8
Cooling and heating needs required in the different seasons in a day, Mediterranean regions.

	Cooling Needs (J/m^3)	Heating Needs (J/m^3)	
Mortar Formulation	Summer	Spring	Autumn
HL_LS	458,081	415,848	248,181
HL_LS/PEG800	425,156	383,061	230,778
HL_LS/PEG800_LS/PEG1000	419,443	364,253	216,499
C_LS	423,318	406,983	247,899
C_LS/PEG800	415,375	391,549	243,669
C_LS/PEG800_LS/PEG1000	413,803	357,031	215,564

According to the results reported in Table 8, the incorporation of both PEG-based PCMs in hydraulic lime-based and cement-based mortars produced a certain decrease in cooling needs in summer season and in heating needs in spring and autumn. The PCM providing the greatest advantage in terms of energy saving was LS/PEG800_LS/PEG1000, irrespective to the type of binder and the season analyzed. This PCM, being composed of two PEGs characterized by different melting/crystallization ranges of temperatures (see Table 5), is able to perform adequately in both the hot (summer) and the mild seasons, i.e. in spring and autumn, of a Mediterranean climate.

Referring to a winter climate characteristic of Mediterranean regions (Fig. 11), the addition of a PEG-based PCM in both mortars brought benefits only in terms of energy saved for heating, the minimum temperatures having increased compared to those measured for the reference mortars (i.e. without any PCM). As already underlined, the temperatures recorded in the small-scale box during this season were far from the comfort conditions, irrespective to the mortar applied. However, for completeness of analysis, Table 9 reports the heat needed each day to maintain the indoor temperatures inside the comfort temperature range, as a function of the mortar formulation.

Starting from the data reported in Tables 8 and 9, the energy savings obtained using mortars containing PEG-based PCMs compared to reference mortars, i.e. not containing any PCMs, were calculated. The results are reported in Table 10. The energy savings were determined as the difference of the energy required for cooling or heating the small-scale box in which the mortars, with and without any PCM, where applied, according to Eq. (1):

$$\Delta \mathrm{NE} = \mathrm{NE}_{0\mathrm{PCM}} - \mathrm{NE}_{\mathrm{PCM}} \tag{1}$$

where: ΔNE is the energy saving due to the inclusion of a PCM in the mortar (J/m^3); NE_{0PCM} is the energy need calculated for the mortar not including a PCM (J/m^3); NE_{PCM} is the energy need calculated for the mortar containing a PCM (J/m^3).

As expected, the introduction of a PEG-based PCM in both mortars allowed to reduce the cooling needs in summer and the heating needs in both spring and autumn. On the other hand, the heating needs calculated for the coldest season (i.e., in winter) were generally greater than those required if the reference mortars, i.e., without any PCM, were analyzed. Taking into account the type of PCM, LS/PEG800_LS/PEG1000 composite appeared to offer the best energy saving value, in particular when included in hydraulic lime-based mortar.

Starting from these data, a cost analysis was performed in order to calculate the potential economic advantages due to the inclusion of the two PCMs in cement and hydraulic lime-based mortars, respectively.

6. Cost analysis

The improvement of energy efficiency in a building offers numerous advantages, in terms of lower impact on the environment (reducing the use of fossil fuels, and in turn the greenhouse gas emissions), while still guaranteeing thermal comfort to the inhabitants. The reduction of energy consumption at the national level also means less dependence on the supply of fuels from abroad. But above all, the energy efficiency of buildings allows economic savings through the reduction of heating and cooling costs.

In this section, an estimation of the costs (expressed in €/m^3) of the fossil fuel needed to guarantee the thermal comfort in buildings located in Mediterranean regions, where the mortars (with and without the PCMs, for comparison purposes) where applied, is reported in relation to the season. Only the data recorded for a Mediterranean climate were taken into consideration since, as illustrated in the previous section, only in this case the advantage in using mortars containing a PEG-based PCM occurred in three out of four seasons. In a continental climate, on the other hand, mortars containing a PCM offered a real advantage in terms of energy savings only in summer.

Table 9
Heating needs required in winter in a day, Mediterranean regions.

	Heating Needs (J/m^3)
Mortar Formulation	Winter
HL_LS	1,002,146
HL_LS/PEG800	1,003,040
HL_LS/PEG800_LS/PEG1000	989,294
C_LS	999,085
C_LS/PEG800	1,024,557
C_LS/PEG800_LS/PEG1000	1,001,486

Table 10
Energy savings in a day in different seasons, calculated for mortars containing a PEG-based PCM composite with respect to the reference mortars, Mediterranean regions.

	Cooling Needs (J /m^3)	Heating Needs (J /m^3)		
Mortar Formulation	Summer	Spring	Autumn	Winter
HL_LS/PEG800	32,925	32,786	17,404	−894
HL_LS/PEG800_LS/PEG1000	38,639	51,595	31,683	12,852
C_LS/PEG800	7943	15,434	4230	−25,472
C_LS/PEG800_LS/PEG1000	9515	49,951	32,335	−2401

The cost calculation for the cooling/heating needs, these latter indicated as NE, was performed based on the data reported in Tables 8 and 9. The seasonal effective cost (indicated as EC) can be calculated according to the following equation:

$$EC = K*NE \tag{2}$$

where K is based on the average Italian energy cost (referring to June 2022). However, the same calculation can be repeated taking as a reference the cost of energy in a different Country. In Eq. (3), K can be calculated from the following relationship:

$$K = C_{Vol}*C_E*C_{€}*t \tag{3}$$

where, C_{Vol} is the volumetric conversion factor, i.e., the ratio between 1 m^3 and the volume of the experimental test cell (20x20x20 cm^3); C_E is the conversion factor from J to kWh; $C_€$ is the cost of energy taken as a reference (in the case under consideration equal to 0.23 €/kWh); t is the time considered on a quarterly basis (i.e. 90 days). It was, therefore, possible to calculate the savings in energy costs (in percentage) by comparing the mortars containing a PCM to those without any PCM.

The costs required to satisfy the heating and cooling needs in each season in a building located in Italy, in which one of the mortars studied in this study is applied, are reported in Figs. 13 to 16.

Fig. 13 presents the costs for the energy used for indoor cooling in summer. Compared to the mortar not including a PCM, the economic advantage obtained for the hydraulic lime-based mortar was around 8 %, regardless of the PCM. For both cement-based mortars containing a PEG-based PCM, a minimal gain, of about 2 %, was achieved compared to mortar without a PCM.

Similar results from the cost analysis were obtained in spring and autumn seasons (Figs. 14 and 15, respectively). The cost for energy was reduced by about 7 % applying either hydraulic lime or cement-based

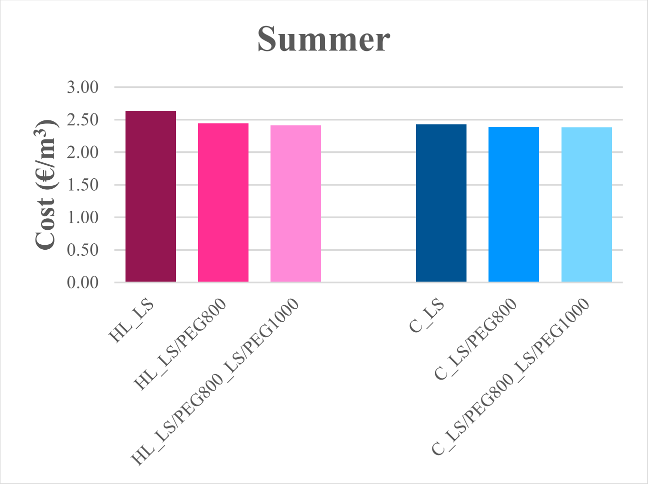

Fig. 13. Cost related to energy consumption during summer for hydraulic lime- and cement-based mortars, with and without a PEG-based PCM.

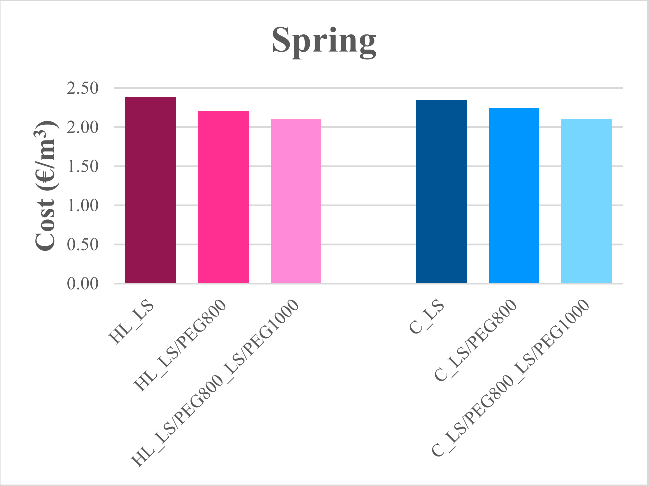

Fig. 14. Cost related to energy consumption during spring for hydraulic lime- and cement-based mortars, with and without a PEG-based PCM.

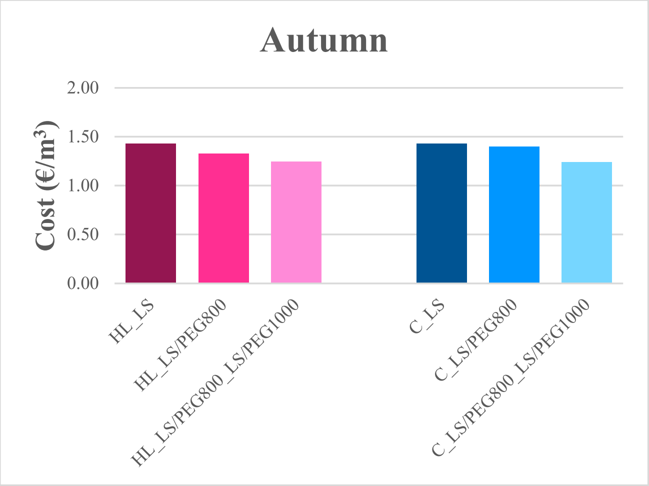

Fig. 15. Cost related to energy consumption during autumn for hydraulic lime- and cement-based mortars, with and without a PEG-based PCM.

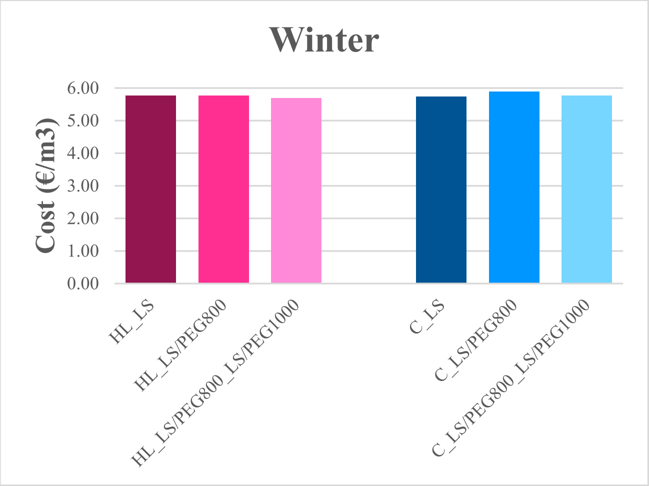

Fig. 16. Cost related to energy consumption during winter for hydraulic lime- and cement-based mortars, with and without a PEG-based PCM.

mortars containing LS/PEG800 PCM, with respect to the reference mortars. The economic gain was even doubled, reaching 14 %, when the same mortars were manufactures including the PCM based on LS/PEG800_LS/PEG1000.

As already observed in the previous sections, the inclusion of a PEG-based PCM in both mortars led to minimal advantages during winter, or it resulted even unfavorable, if compared to reference mortars. This is evident by analyzing the data shown in Fig. 16. The cost required to heat an indoor environment in this season, in fact, was increased in the case of cement-based mortars, by 2.5 % for C_LS/PEG800 and 0.2 % for C_LS/PEG800_LS/PEG1000 mortars, respectively, if compared to the same mortar without any PCM. Limited advantages were still measured for the mortar based on hydraulic lime: the energy cost was reduced by about 0.1 % when including LS/PEG800 PCM in this mortar and by 1.3 % when adding the LS/PEG800_LS/PEG1000 composite PCM.

As general conclusion, the mortars containing the form-stable LS/PEG800_LS/PEG1000 PCM have the highest energy saving potential in a construction located in the Mediterranean area, offering the greatest reductions in energy costs to maintain the comfort indoor temperature, especially when added to mortars based on hydraulic lime.

7. Conclusions

In this work, the thermal behavior of two kind of mortars, namely based on cement and on hydraulic lime, upon the addition of two form-stable phase change materials was evaluated. The PCMs proposed in the study were based on Poly-Ethylene Glycol polymers (i.e., PEG800 and PEG1000) with different molecular weights, characterized, consequently by different ranges of melting/crystallization temperatures. The aim of the project was, in fact, to include the PCMs in the mortars applied in buildings located in different climatic area, i.e. continental and Mediterranean regions. The final PCMs, fabricated employing as inert support pieces of a waste stone (Lecce stone), were: LS/PEG800 and LS/PEG800_LS/PEG1000 (50/50%wt.). The thermal behavior of the mortars, with or without the produced PCMs, was investigated in a small-scale test cell placed in an environmental chamber, this latter able to simulate the typical temperatures of the two climatic regions. To the best of the authors' knowledge, no previous study has proposed an inert porous support obtained as waste from local processes/productions (i.e., available at low cost at km 0) as matrix to produce a form-stable PCM, in accordance with the principles of the Circular Economy. The creation of a mixed PCM, i.e., composed of PEGs of different molecular weights in order to broaden the service temperature range and, consequently, make the PCM suitable for different climates, is a further aspect of novelty of the present work. In addition, the research aimed to analyze benefits and limitations of using this PCM, characterized by a wide range of phase change temperatures, in different climatic conditions, representative of continental/cold and Mediterranean/hot zones.

The wide experimental study allowed to draw the following conclusions:

- a time lag greater than that measured for reference mortars, i.e., those not containing any PCM, was generally achieved with the addition of a PEG-based PCM. The largest time lag values being displayed by the cement-based mortars: this is a great advantage as the measured time lag indicates the shift to off-peak periods for energy consumption for cooling/heating needs;
- with regard to the thermal gradient, representative of the heat storage capacity of the PCM included in a mortar, the mortars based on hydraulic lime offered the greatest thermal gradient values, irrespective to the kind of PCM and the climatic condition analyzed: this behavior was partly attributed to the great porosity of hydraulic lime mortars;
- greater benefits deriving from the inclusion of a PCM in mortars were recorded for the Mediterranean climate, in particular in the warm (summer) and mild (spring and autumn) seasons;

- the LS/PEG800_LS/PEG1000 composite was the form-stable PCM that provided maximum energy savings, and consequently energy costs, regardless of the type of mortar;
- energy savings of 8 % in the summer period and around 12 % in spring and autumn seasons were recorded if the LS/PEG800_-PEG1000 PCM is added hydraulic lime mortars;
- the presence of both PEG polymers in the mixed PCM, therefore, brings greater advantages in terms of reduction of energy requirements and costs, confirming the initial hypotheses of the authors of this study.

CRediT authorship contribution statement

Antonella Sarcinella: Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **José Luís Barroso de Aguiar:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing. **Carlos Jesus:** Formal analysis, Investigation. **Mariaenrica Frigione:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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