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Enhancing energy efficiency of buildings located in the Mediterranean area using Phase Change Materials (PCMs) integrated into mortar formulations.

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Abstract. Phase Change Materials (PCMs) in building materials can significantly reduce energy consumption in heating and cooling systems. PCMs absorb, store, and release thermal energy by transitioning between solid and liquid states based on external temperatures, helping to regulate indoor temperatures and lower energy use. This study evaluates the thermal performance of various mortar compositions containing PCMs made from hydraulic lime and cement. The PCMs were developed using the "form-stable" method, incorporating a porous matrix of Lecce Stone (LS), known for its high porosity, and sourced from processing waste, supporting sustainability principles. The selected PCMs were Polyethylene Glycol (PEG) with molecular weights of 800 and 1000 g/mol, suitable for Mediterranean climate temperatures. The temperatures that characterize this geographic area were simulated in a climatic chamber to assess the thermal behavior of the mortars containing the PCMs across all four seasons. The results showed that mortars with composite form-stable PCMs effectively mitigated indoor temperature fluctuations, reducing the need for heating and cooling. Additionally, energy savings calculations demonstrated significant reductions in heating and cooling costs, underscoring the potential of the PCMs to enhance building energy efficiency.

1. Introduction

The depletion of fossil fuels and the escalating impacts of climate change necessitate a shift towards sustainable and renewable energy systems. Traditional energy sources, predominantly fossil fuels, are not only finite but also contribute significantly to greenhouse gas emissions, exacerbating global warming and climate instability. Consequently, there is an urgent need to develop and implement technologies that reduce energy consumption and promote environmental sustainability. The building industry represents about one-third of the world's energy usage and roughly 15% of direct CO_2 emissions. The demand for energy in buildings is escalating due to enhanced energy availability in developing nations, the expanding use of air conditioning in tropical and Mediterranean areas, and the growing need for heating. As a result, political measures are being implemented to reduce the energy demands of buildings. Additionally, one of the European Union's goals is to achieve carbon-neutral buildings by 2050

[1]. To address this challenge, academic research and corporate R&D sectors are working to develop new technologies and materials that minimize energy waste and reduce greenhouse gas emissions. One promising approach is the integration of Phase Change Materials (PCMs) into building materials to enhance energy efficiency in heating and cooling systems. PCMs have the unique capability to absorb, store, and release thermal energy by transitioning between solid and liquid states in response to external temperature changes. This ability allows PCMs to regulate indoor temperatures more effectively, reducing the reliance on conventional heating and cooling systems and thereby lowering energy consumption. The result is not only cost savings for building owners but also a significant reduction in overall energy usage, contributing to environmental conservation efforts [2].

In recent years, a variety of experimental research has been conducted to evaluate the thermal properties of building materials incorporating PCMs, as these materials can be embedded into different building components, such as wallboard, roofs, ceilings, floors, external walls, windows, bricks, mortars, and concrete [3]. Among these applications, mortars and concrete are particularly interesting for two reasons: first, mortars cover large surfaces, allowing the incorporation of substantial amounts of PCM, which enhances latent heat and storage capacity; second, mortar containing PCM can be adapted to various shapes and sizes, making it suitable for retrofitting existing buildings and constructing new ones. Mortar is a common component in all constructions and can be easily replaced, making it an ideal medium for integrating PCMs to improve thermal performance. Furthermore, several methods for incorporating PCMs into this component have been described in literature. The most common are: direct incorporation, encapsulation in macro- or micro-capsules, and the form-stable method [2]. This latter has proven to be particularly effective, offering numerous advantages over the others. Using this method, it is possible to create a composite material consisting of a matrix (generally a porous matrix) capable of containing the PCM. In this study, two form-stable PCMs were created using waste Lecce Stone, a porous stone employed as the matrix, impregnated with Poly-Ethylene Glycol (PEG), a polymer known for its outstanding phase change features, such as appropriate enthalpy, absence of supercooling, and both chemical and thermal stability [4]. PEG can be produced in various molecular weights, each associated with distinct melting and crystallization temperature ranges.

This research investigates the incorporation of two Poly-Ethylene Glycols into mortar compositions based on hydraulic lime and cement, aiming to improve the thermal performance of buildings specifically placed in the Mediterranean area. The PEGs chosen for this study had a molecular weight of 800 and 1000 g/mol, which are characterized by thermal properties (i.e., appropriate melting and crystallization peak temperatures) suitable for the typical temperatures of a Mediterranean climate. To study the thermal performance of these mortar compositions containing the selected PCMs, an experimental setup was designed and built using a climatic chamber simulated hourly the temperature variations for Mediterranean climates during the four seasons of the year, comparing mortars with and without PCMs (i.e., those mortars used as references). The experimental results demonstrated that mortars incorporating the composite form-stable PCMs significantly mitigated indoor temperature fluctuations, thereby reducing the need for heating and cooling. Furthermore, the evaluation of the time lag between maximum and minimum temperatures relative to external conditions revealed consistent advantages for the mortars containing PCMs. Energy savings calculations indicated notable reductions in heating and cooling costs, underscoring the potential of PCMs to enhance building energy efficiency.

2. Materials

Previous research developed two new composite materials combined a porous stone with polymer based-PCMs through a vacuum impregnation method, known as form-stable method.

This procedure described by Frigione et. al [5], was applied on a highly porous biocalcarenite from Salento, South Italy, known as Lecce Stone (LS). This latter, obtained as a waste product from stone extraction and production, was first crushed and sieved to achieve a particle size between 1.6 and 2.0 mm and then impregnated with both PEGs with the aim to be used as mortar aggregate. The two selected PCMs were: Poly-Ethylene Glycol with a molecular weight of 800 g/mol (PEG800), supplied by Wuhan Fortuna Chemical Co. (Wuhan, China) and Poly-Ethylene Glycol with a molecular weight of 1000 g/mol (PEG1000), sourced in solid form from Sigma–Aldrich, Germany. The final materials obtained, named "LS/PEG800" and "LS/PEG1000", were created therefore using the same porous stone (LS) but different types of polyethylene glycol (PEG). The PEG was absorbed into the porous stone using the impregnation method, and the quantity of absorbed PEG by the stone granules was determined to be 23% by weight through thermogravimetric analysis, as reported in [5,6]. These composite materials shown a different melting and crystallization temperatures. LS/PEG800 exhibited a melting temperature peak of about 13 °C and a solidification peak of about 9 °C; while LS/PEG1000 demonstrated a melting temperature peak of about 39 °C and a crystallization peak of about 19 °C [5,6].

Initially, the idea of using two PCMs with different thermal characteristics was aimed at broadening the temperature range within which PEG could operate, thereby extending its applicability. This approach was intended to enable its use not only in temperate climatic zones, such as the Mediterranean, but also in colder climates, like those found in continental regions. However, previous research indicated that while PEG800 operates at lower temperatures compared to PEG1000, these temperatures were not sufficiently low to provide advantages in a continental climate [7]. Significant improvements, on the other hand, are observed when applied to a Mediterranean climate. Subsequent studies [8] explored various mortar formulations incorporating aerial lime, hydraulic lime, gypsum, and cement, aiming to determine the optimal mix for mechanical properties. Mortars based on hydraulic lime and cement were identified as the most effective from a mechanical point of view and were further analyzed for testing their thermal performances. The hydraulic lime (HL) used has a density of 2700 kg/m^3 (CIMPOR, Lisbon), and the cement (C), (CEM I 42.5 R), has a density of 3030 kg/m^3 (SECIL, Lisbon). A polyacrylate superplasticizer (SP) (MasterGlenium SKY 627, BASF) with a density of 1050 kg/m^3 was added to reduce water usage in the mixes. To assess the impact of incorporating PCMs on the thermal properties of various mortars, four different compositions were developed. Two compositions included the composite LS/PEG800 (50%wt) and LS/PEG1000 (50%wt), both with a density of 3724 kg/m^3, were carried out and, for comparative analysis, two control formulations, using only LS as the aggregate without PCM, having a density of 2957 kg/m^3, were prepared. The mortar compositions, reported in Table 1, were formulated using a binder's content of 800 kg/m^3, following European Standard EN 998-1.

Table 1. Composition Details of Produced Mortars (kg/m^3)

System	LS amount	PEG 800 amount	PEG 1000 amount	SP	W_s[1]	Water	W/B[2]
HL_LS	682	0	0	20	171	380	0.38
HL_LS/PEG800_ LS/PEG1000	1082	124	124	20	0	320	0.32

C_LS	772	0	0	20	194	390	0.39
C_LS/ PEG800_ LS/PEG1000	1307	150	150	20	0	300	0.30

[1] Ws is the water saturation used to fill the LS aggregates without the PCM.
[2] W/B is the water/binder ratio.

3. Methods

The thermal performances of the manufactured mortars were evaluated using the designed experimental setup including a climatic chamber setted with a temperature program that mimics the conditions of each season of the year. Figure 1 illustrates the experimental set up employed to carried out this test. This was done to assess the mortars' behavior during summer, spring, autumn, and winter, using climatic data from a weather station in the Salento region, Southern Italy. A small-scale test cell was built for each mortar compositions manufactured, consisting of a 3-cm thick polystyrene insulating material coated internally with a 1 cm mortar layer (Figure1a, b). Each cell was a 200 mm^3, with a thermocouple positioned at its center. These test cells were positioned inside the climatic chamber equipped with thermocouples used as precise temperature controller (Figure 1c). The thermocouples (Type K) were connected to a high-sensitivity data acquisition system (AGILENT 34970A), recording temperatures every minute both in the climatic chamber and inside the test cells via the BenchLinkDataLogger3 software.

This setup has been shown to provide accurate and consistent data on the thermal performance of mortars, as confirmed in previous studies [9–13].

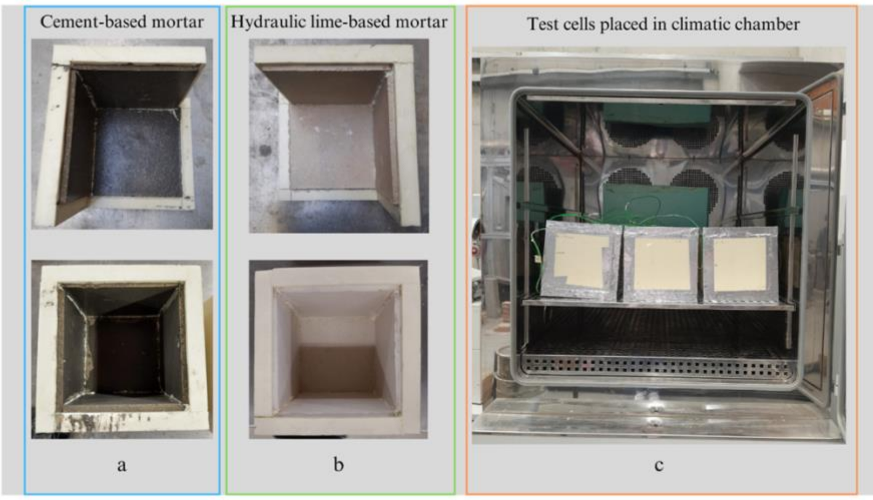

Figure 1. Experimental set up used to assess the thermal behavior of the mortars formulations: (a) cement-based mortar and (b) hydraulic lime-based mortar applied on test cells and inserted in a (c) climatic chamber.

4. Results and Discussion

4.1 Thermal performances

Considering that the incorporation of a PCM is anticipated to enhance the internal temperature regulation of a room where it is utilized, thermal tests were carried out to assess the thermal performance of mortars with PCM inclusion. The tests evaluated the thermal behavior across all seasons, referencing the climate data from the Salento region (South Italy). PEG1000 and PEG800 were chosen as PCMs due to their suitable melting and crystallization temperature range for this application as reported in [6,7]. As reported in [7], other climatic conditions (i.e., Continental climatic zone) were also analyzed but the most significant results were obtained using climatic data typical of the Mediterranean climate zone.

To replicate summer conditions, temperatures were set between 22 °C and 32 °C. For spring, the temperature range was adjusted to 12 °C to 24 °C. Autumn conditions were mirrored with temperatures from 16 °C to 24 °C, and winter was simulated with temperatures ranging from 8 °C to 15 °C. Figure 2 depicts the specific temperatures utilized to simulate typical seasonal conditions in the Salento region. Each season was emulated over three cycles, each lasting 24 hours.

Figures 2 to 5 illustrate the performance of the developed mortars, both hydraulic lime-based and cement-based, with and without the inclusion of novel PCMs, under the simulated climatic conditions of spring, summer, autumn, and winter. Each graph also presents the typical temperature variations for each season, as established in the climate chamber where the test cells were positioned. Figure 2 shows the thermal behavior of the mortars during summer, indicating that temperatures above 25 °C were recorded, while temperatures did not fall below 20 °C, highlighting a potential need for cooling during the summer period.

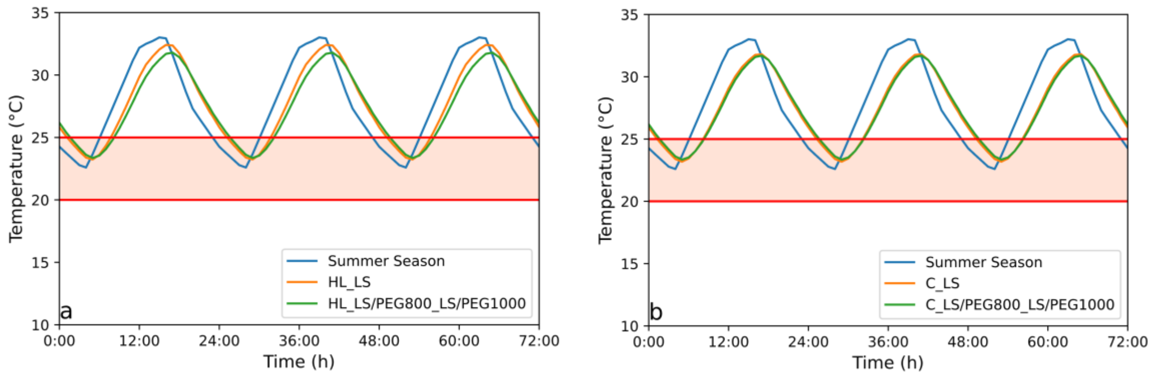

Figure 2. Thermal performance of the manufacture mortars in summer: (a) hydraulic lime-based mortar and (b) cement-based mortar. The red bar on the graphs represents the thermal comfort zone between 20 and 25°C.

As shown in Figure 2, during the heating phase with temperatures exceeding 25 °C, mortars incorporating PCMs demonstrated slower heating and achieved lower peak temperatures. This effect was especially noticeable in the hydraulic lime-based mortar. In Figure 2a, during the highest summer temperatures, the peak internal temperature was approximately 2 °C lower than the external temperature. However, within the indoor thermal comfort range (20–25 °C), the cells exhibited similar temperature values. The heat storage and release effect became evident only when temperatures fell outside the thermal comfort range. For the cement-based mortar, the thermal behavior closely mirrored that of the reference mortar, showing no significant benefit from the inclusion of PCMs.

Figure 3 illustrates the thermal performance of the mortars in spring. In this scenario, cooling is not necessary as the maximum temperature stays below 25 °C. However, heating is required since temperatures drop below 20 °C, falling outside the comfort range.

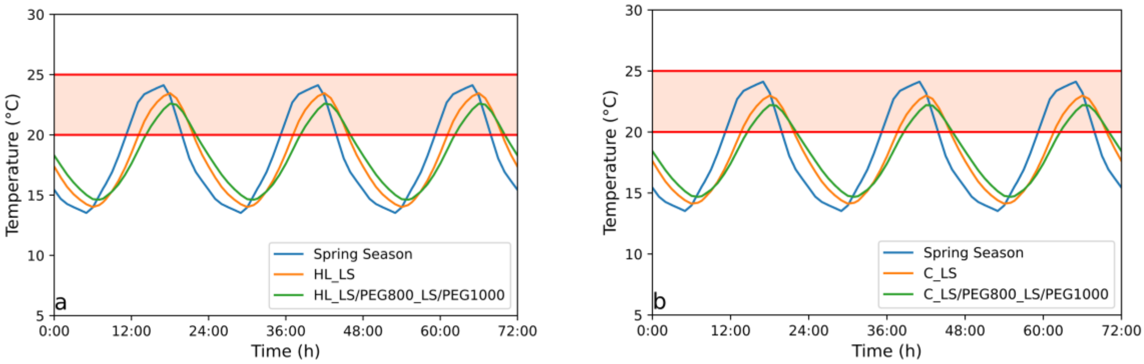

Figure 3. Thermal performance of manufacture mortars in spring: (a) hydraulic lime-based mortar and (b) cement-based mortar. The red bar on the graphs represents the thermal comfort zone between 20 and 25°C.

During the spring season, typical temperatures in Mediterranean regions range from 13 ° to 24 °C. As shown in Figure 3, heating is required during the coldest hours to maintain a comfortable temperature range. Both mortar compositions with incorporated PCMs effectively raise the minimum temperatures recorded inside the test-scale box, irrespective of the mortar type. Additionally, the inclusion of PCMs in both mortars leads to a reduction of approximately 2 °C in the maximum temperatures, while still remaining within the comfortable temperature range.

Figure 4 illustrates the thermal performance during autumn. In this scenario, slight heating is required as the minimum temperatures dip below 20 °C.

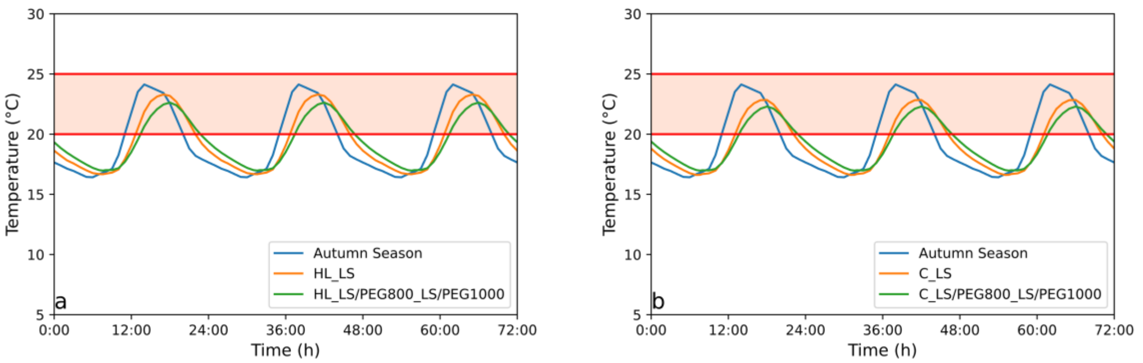

Figure 4. Thermal performance of manufacture mortars in autumn: (a) hydraulic lime-based mortar and (b) cement-based mortar. The red bar on the graphs represents the thermal comfort zone between 20 and 25°C.

Figure 4 clearly shows that the minimum temperatures fall below 20 °C, outside the comfort zone, indicating a potential need for heating systems that could increase energy consumption in buildings. The results in Figure 4 demonstrate that both mortar compositions with PCMs effectively lower the maximum recorded temperatures while maintaining the indoor temperature within the comfort range. However, the addition of PCMs does not show significant benefits at the lower temperatures. Overall, no substantial differences were observed regarding the type of binder used in the mortars.

Figure 5 depicts the thermal behavior during winter. In this season, typical temperatures in the area range from 7 °C to 15 °C, which are considerably below comfort levels. At these temperatures, the PCMs were unable to elevate indoor temperatures to the comfort range, although they did increase the minimum temperatures recorded in the mortars. The inclusion of PCMs had only a limited impact on the thermal performance of both mortars, particularly in hydraulic lime-based mortars.

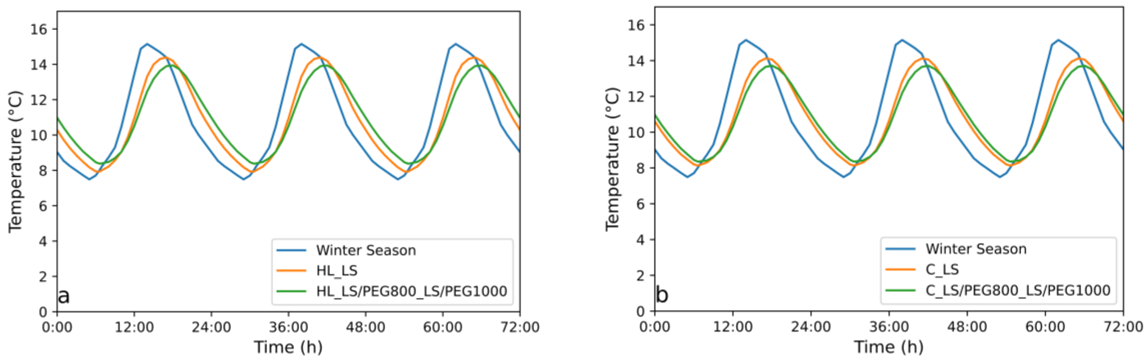

Figure 5. Thermal performance of manufacture mortars in winter: (a) hydraulic lime-based mortar and (b) cement-based mortar.

In all tests, except those conducted during the winter season, it was detected that when the temperature inside the box cell reached the 20 °C to 25 °C range, a minor phase change in the PCM occurred. This caused the thermal behavior of the PCM-based mortars to deviate from the set temperature program. Additionally, the temperature variations in the mortar compositions containing PCMs were consistently narrower compared to those without PCMs, demonstrating the effective performance of both LS/PEG composites as phase change materials in various mortars. Furthermore, during the tests, a time lag between the maximum and minimum temperatures for the PCM-containing mortars relative to the external temperatures was recorded. This time lag indicates a shift to off-peak periods for electricity consumption for cooling and heating, leading to potential economic savings. According to the data in Table 2, mortars with PEG-based PCMs generally exhibited a greater time lag compared to those without PCM during both cooling and heating phases. Notably, cement-based mortars showed the highest time lag values.

Table 2. Time lag, for both the reference mortars and those containing PCMs, between the peak and lowest temperatures recorded, compared to the external climatic conditions typical of Mediterranean regions.

	Lag Time (min)							
	Summer		Spring		Autumn		Winter	
Mortar Formulations	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_LS/PEG1000	140	125	170	140	165	115	160	130
C/LS	140	115	140	110	135	85	135	110
C_LS/PEG800_LS/PEG1000	145	125	180	150	175	125	165	135

Finally, Figure 6 presents the thermal gradient between each PCM-based mortar and its corresponding reference mortar (i.e., without PCMs) across different seasons. As the temperature cycle progresses, the thermal gradient initially increases due to the cyclic heat storage process and then decreases until the test-cells reach the same temperature (ΔT = 0). According to Figure 6, hydraulic lime-based mortars demonstrate better thermal regulation, with a greater temperature difference observed within all tested seasons. In contrast, cement-based mortars exhibit a smaller thermal gradient, indicating lower thermal performance.

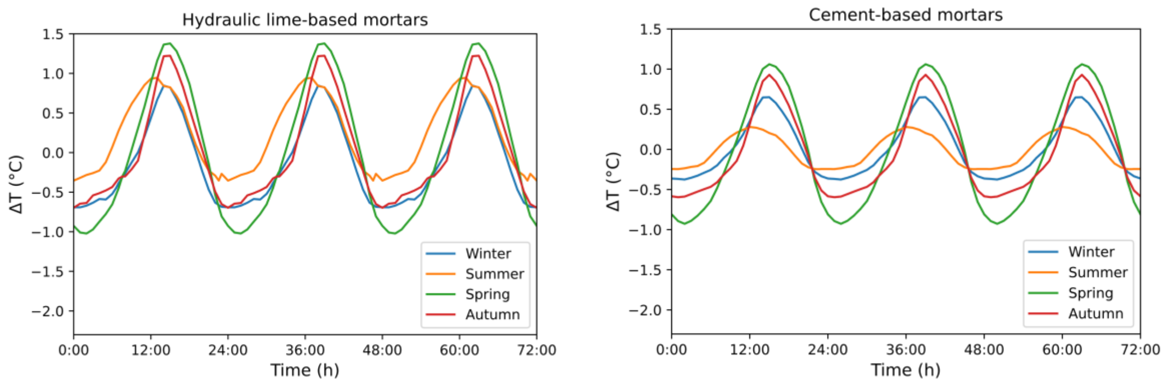

Figure 6. Thermal gradient between test cells covered with reference mortars and those covered with PCM-based mortars relative to: (a) hydraulic lime-based mortar and (b) cement-based mortar.

4.2 Assessment of cooling/heating needs

To quantify the energy savings achieved with the novel PCMs, the temperature curves (Figures 2–5) were analyzed to determine the reduction in energy consumption during the cooling and heating cycles. The energy required to maintain the cell's temperature within the comfort range over a 24-hour period was calculated for each season. This enabled the estimation of the cooling and heating demands (referred to as energy needs, NE) necessary to keep the interior temperature of a building within the 20 °C to 25 °C comfort range. Table 3 outlines the cooling and heating requirements for the various mortar types across different seasons (i.e., Summer, Spring, Autumn).

Table 3. Daily requirements for cooling and heating.

	Cooling needs (J/m³)	Heating needs (J/m³)	
System	Summer	Spring	Autumn
HL_LS	458081	415848	248181
HL_LS/PEG800_LS/PEG1000	419443	364253	216499
C_LS	423318	406983	247899
C_ LS/PEG800_LS/PEG1000	413803	357031	215564

Table 3 shows that incorporating PEG-based PCMs into both hydraulic lime-based and cement-based mortars reduced cooling demands in the summer and heating demands in the spring and autumn. However, during the winter season, as depicted in Figure 5, the temperatures within the small-scale box did not reach comfort levels, irrespective of the mortar type used. Consequently, it was not feasible to conduct the same numerical analyses for the winter season.

Using the data from Table 3, the energy savings from utilizing mortars with PEG-based PCMs compared to reference mortars (i.e., without PCMs) were calculated, following equation 1:

$$\Delta NE = NE_{0PCM} - NE_{PCMs} \quad (1)$$

Where NE represents the energy savings resulting from incorporating PCMs into the mortar (J/m^3); NE_{0PCM} is the energy requirement calculated for the mortar without PCMs (J/m^3); and NE_{PCMs} is the energy requirement calculated for the mortar with PCMs (J/m^3). The findings are shown in Figure 7.

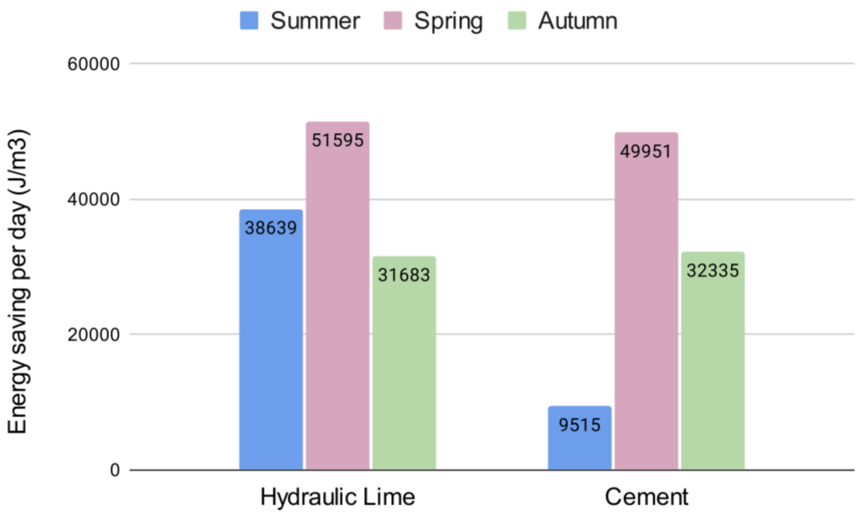

Figure 7. Energy savings in a day in different seasons (i.e., Summer, Spring, Autumn).

Figure 7 illustrates the daily energy savings (in J/m^3) achieved by using mortars containing PCMs during the summer, spring, and autumn seasons, comparing the performance of both types of mortar compositions. In the summer, the hydraulic lime-based mortar demonstrates the highest energy savings, significantly outperforming the cement-based mortar.

During the spring and autumn seasons the findings are, instead, comparable. Overall, Figure 7 indicates that hydraulic lime-based mortars provide the greatest energy savings in the summer for cooling needs, while hydraulic lime-based mortars perform better in the spring and autumn periods for heating needs.

Based on these records, a cost evaluation was conducted to estimate the potential economic benefits of using cement or hydraulic lime-based mortars doped with PCMs.

4.3 Cost analysis

Enhancing energy efficiency in buildings provides several benefits, including a reduced environmental impact by decreasing the reliance on fossil fuels and consequently lowering CO_2 emissions, while still ensuring thermal comfort for residents. On a national scale, reducing energy consumption also lessens dependence on foreign fuel supplies. Most importantly, energy-efficient buildings result in economic savings by lowering heating and cooling expenses.

This section provides an assessment of the costs (expressed in €/m^3) associated with the fossil fuels required to maintain a certain thermal comfort in buildings situated in Mediterranean areas, where mortars with and without PCMs were utilized, depending on the season. The cost computation for cooling and heating needs, indicated as NE, was derived from the data presented in Table 3. The seasonal effective cost (indicated as EC) can be calculated using the following equation (2):

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

where K is derived from the average energy cost in Italy. Notably, the energy cost data was provided by ARERA, the Italian Regulatory Authority for Energy, Networks, and Environment, which estimated the energy cost in June 2024 to be 0.12209 € for the single-rate tariff. However, the same calculation can be repeated using the energy cost from a different country. In Equation (3), K can be calculated from the following relationship:

$$K = C_{vol} * C_E * C_€ * t \tag{3}$$

Here, C_{vol} denotes the volumetric conversion factor, which is the ratio between 1 m^3 and the volume of the experimental box cell (i.e., 20x20x20 cm^3). CE is the conversion factor from J to kWh, and $C_€$ represents the reference energy cost, set at 0.12209 €/kWh. The variable t corresponds to the period considered, which is 90 days (one quarter). Utilizing these factors, the costs required to meet the heating and cooling demands for each season (summer, spring, autumn) in a building located in a Mediterranean region are illustrated in Figure 8. Based on these results, the percentage savings in energy costs can be calculated by comparing mortars with PCMs to those without PCMs.

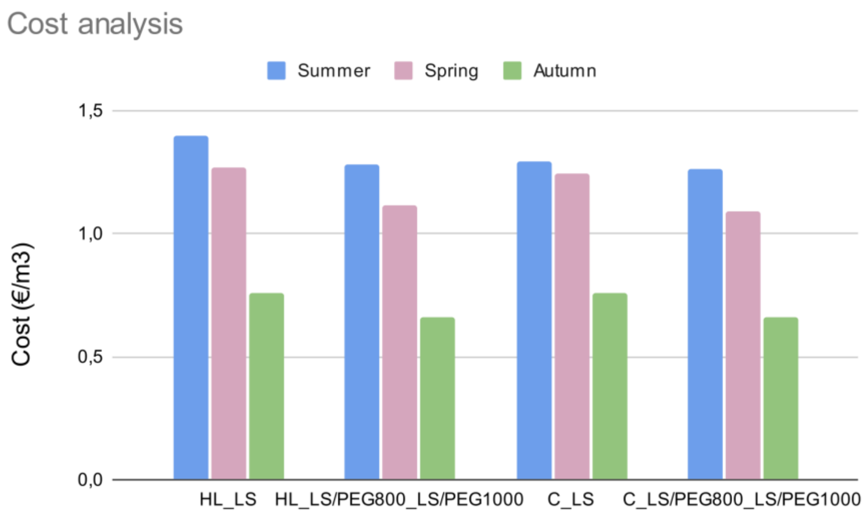

Figure 8. Cost related to energy consumption during summer, spring, and autumn, for both hydraulic lime- and cement-based mortars, with and without PCMs.

According to figure 8, the economic advantage obtained for the summer season for the hydraulic lime-based mortar containing the PCMs was around 8% if compared to the mortar not including a PCM; while for cement-based mortars containing a PEG-based PCMs, a minimal benefit, of about 2%, was reached compared to the reference mortar. In spring and autumn seasons, similar results from the cost analysis were obtained. The economic gain was higher in these seasons, within 12-13%, using those mortars manufactured with PCMs, regardless of the type of binders.

5. Conclusion

In this research, the thermal performance of different types of mortar compositions, one based on cement and the other on hydraulic lime, containing two form-stable phase change materials

(PCMs) were evaluated. The proposed PCMs were centered on Poly-Ethylene Glycol polymers (i.e., PEG800 and PEG1000), which are characterized by different molecular grade and therefore distinct melting/crystallization temperature ranges. The selected PCMs were then integrated into Lecce stone (LS) granules. Due to its porosity, the LS was able to accommodate the PEG through an impregnation process. The final PCMs carried out were composite materials, known as LS/PEG800 and LS/PEG1000, which were used combined together (to the extent of 50/50 wt.%) as aggregates in the manufactured mortar compositions aimed for buildings situated in Mediterranean areas. The thermal performance of the mortars, both with and without the developed PCMs, was tested in a small-scale test box within an environmental chamber capable of simulating typical climatic conditions of the Mediterranean areas. This experimental study led to the following main findings:

- Adding a PEG-based PCMs generally resulted in a greater time lag compared to reference mortars without any PCM, with the largest time lag values observed in cement-based mortars. This is advantageous as this lag implies a shift to off-peak times for energy utilization for cooling and heating needs.
- Regarding the thermal gradient, which reflects the heat storage capacity of the PCMs within a mortar, hydraulic lime-based mortars exhibited the highest thermal gradient values.
- Greater benefits from including a PCMs in mortars were recorded particularly during the warm (summer) and mild (spring and autumn) seasons.
- The LS/PEG800_LS/PEG1000 included in mortars provides high energy savings and consequently reduced the energy costs.

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