

Article

# Lightweight Concrete Containing Phase Change Materials (PCMs): A Numerical Investigation on the Thermal Behaviour of Cladding Panels

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**Abstract:** The use of phase change materials (PCMs) in building elements has gained increasing popularity in recent years because of the potential energy savings that result from the heat stored during variable temperature–time histories. This paper describes the results of non-linear numerical analyses on sandwich panels characterized by different geometry and consisting of an innovative concrete, i.e., lightweight concrete with aggregates containing PCMs. The amount of embedded PCMs has no equal in the literature, and this calls for a detailed assessment of its thermal performance within a typical building element. The heat transfer process inside the panels is modelled via finite elements in order to evaluate the effectiveness of the addition of PCMs with regard to insulation. The results show that adding PCMs may significantly reduce (by up to 20%) the energy required for cooling in the hot season, while the reduction of the energy required for heating in the cold season is lower (up to 10%). Moreover, there is a significant reduction in the instantaneous power required, both for heating and cooling.

**Keywords:** phase change materials (PCMs); lightweight concrete; claddings; non-linear finite element analysis

## 1. Introduction

Buildings use 40% of the total European Union (EU) energy consumption and generate 36% of the Union's CO<sub>2</sub> emissions [1]; moreover, the U.S. Department of Energy (DoE) [2] estimates that the building envelope typically impacts 57% of a building's thermal loads. More than 20% of the energy consumption in the EU is due to dispersion through building envelopes, and similar figures hold for greenhouse gases. Within this context, cladding plays a crucial role for increasing energy saving in buildings, which are responsible for a major contribution to emissions in the EU. An increase in energy savings could contribute positively to the decarbonisation of the European economy: as a matter of fact, the challenging objective of reducing CO<sub>2</sub> emissions by at least 80%, and energy consumption by as much as 50%, must be met by 2050 [3].

Innovative concepts for new building materials were proposed in the *E4iBuildings* project [4,5]. The aim of *E4iBuildings* was to develop and investigate innovative lightweight aggregates for concrete containing embedded phase change materials (PCMs). Concrete containing the aforementioned aggregates may be used to manufacture innovative cladding systems (wall panels and blockwork [6]). The addition of PCMs to concrete brings an increase in the ability of cladding to store thermal energy within building envelopes by reducing and delaying the peak amplitude of heat fluxes, and hence

the energy consumption for heating and cooling. Equally important, this approach helps reduce peak heating and cooling loads at times when infrastructures are vulnerable to overload, a typical occurrence during extreme climatic events. In addition, E4iBuildings aims to find new solutions for reducing the consumption of raw materials, a goal that could be attained using secondary by-products up-cycled from other industrial processes; an example is the refining of biodiesel from waste oils, which generates by-products like *fatty acids* and *polyols* that could be used as PCMs. Keeping in mind the life cycle perspective, these by-products also have a reduced carbon footprint and are available at very competitive prices [7,8]. Inclusion within concrete gives PCMs other useful properties such as high-temperature resistance and improved durability, while avoiding chemical, ultraviolet (UV) and biological degradation. Recycling at the end of life stage is further simplified using biodegradable PCMs [9].

## 2. Lightweight Concrete with Embedded PCMs

### 2.1. Concept and Methodology

During the last decades, building techniques have been oriented towards a reduction in self-weight [10] through the use of building materials characterized by a reduced mass. When structural behaviour under seismic excitations is the issue (e.g., in the Mediterranean area), this is especially favourable, more so than the decrease of the vertical loads. On the other hand, reduced mass is a drawback for the energy efficiency of the building envelope, and more specifically for its capacity to retain heat, because the thermal mass, i.e., the inertia against temperature variations, decreases as the mass decreases. To compensate for the aforementioned reduction, the use of materials with high latent heat retention has been proposed. This allows the reduction of mass thanks to the use of lightweight concrete, and, at the same time, an increase in the thermal performance of building envelopes thanks to the use of PCMs. The energy efficiency of building envelopes can be developed by taking advantage of either their active or their passive behaviour. *Passive* approaches are aimed at improving the thermal performances by employing low conductivity materials [11], while *active* methods obtain similar results by increasing the thermal inertia, using materials with high thermal capacity: thermal energy storage (TES) materials. TES materials are able to profit from latent thermal energy (LTE) or sensible thermal energy (STE). Significant daily temperature variations, combined with a large heat storage capacity per unit volume, might increase the heat retained within the building envelope during the daytime in order to use it when the external temperature decreases [8].

The *latent* heat of most building materials is in the range of several tens to several hundreds of *joules per gram*: better heat accumulation—compared with *specific* heat—is thus obtained in common temperature ranges. The harvesting of thermal energy can be further improved by adding materials with higher latent heat, such as phase change materials (PCMs). For this purpose the E4iBuildings project, initiated by the Joint Research Centre of the European Commission (EC-JRC), is attempting to embed much larger amounts of PCMs in lightweight concrete: up to ten times more with respect to the products readily available on the market. In relation to current state-of-the-art practice, the notable differences are the change of scale in the use of PCMs: from *micro*-encapsulation ( $\mu\text{e}$ ) to *macro*-encapsulation, also known as shape stabilisation (*ss*).

Lightweight concrete with enhanced thermal inertia greatly improves the thermal behaviour of the envelope, thus allowing a better performance during the hot season, which has been to date a critical challenge for traditional lightweight insulation. This integrated approach leads to a great reduction in the energy used for cooling and, particularly in temperate climates, it might obviate the need for active air conditioning (AC) systems in many cases [12,13]. Conversely, in colder areas, using PCMs in lightweight concrete—alongside an additional insulation layer—enhances thermal properties by combining a lower thermal conductivity with an improved thermal inertia.

Finally, lightweight concrete with intermediate mechanical/structural properties is a suitable material for manufacturing moderately-stressed structural elements, such as cladding panels (Figure 1).

In addition, the embedding of PCMs combines the better insulation capacities, compared to traditional concrete, of lightweight concrete, with the enhancement of the thermal inertia provided by PCMs.



**Figure 1.** Typical multilayer cladding panel (courtesy of Dr. B. Dal Lago).

## 2.2. PCMs in Cladding

Among the candidate phase change materials for building applications, organic compounds such as lower temperature PCMs are the most promising, because of their chemical stability, non-corrosive behaviour, reproducible melting and crystallisation behaviour even after a high number of thermal cycles [3,14]. Organic materials are furthermore classified as paraffins and non-paraffins. Moreover, they can usually be mixed to obtain the target phase transition temperature (PTt). The *cost* and the *TES-density* are two key parameters for pushing forward a massive adoption of PCMs as energy-efficient building material [15,16].

Paraffins are inexpensive raw materials with a reasonable TES density: from 120 to 240 kJ/kg. Paraffins are available in a wide range of melting temperatures, from approximately 20 °C up to about 70 °C. Within this range they are chemically inert, having a low vapour pressure in the molten phase, and do not undergo segregation, maintaining their performance even after many thermal cycles. They have a low thermal conductivity (of about 0.2 W/m·K), high fire loads and a large change in volume during phase transition. This latter feature partially limits their application; moreover, the derivation of paraffins from crude oil makes their price sensitive to the seasonal and geopolitical scenarios [17]. Finally, although their environmental impact is positive in terms of use conditions, during the initial and disposal phases their burdens are not optimal.

Fatty acids (FAs) and polyols both have a high potential as substitutes of paraffins in the future, competing with existing materials in the field of energy-efficiency in buildings. FAs, which form the basis of bio-based PCMs, can be extracted from animal fat such as beef tallow and lard, or from vegetable oils from plants like palms, coconuts, and soybeans. They are a renewable and green alternative to paraffinic PCMs. Since they are hydrogenated hydrocarbons with a saturated electronic configuration, they are chemically stable and can last for decades. In addition, FAs offer similar or even improved performances in comparison to paraffins, such as better fire resistance and lower carbon impact. They are also fully biodegradable. Like paraffins, their melting temperatures can

be adjusted by selecting a suitable combination of eutectic binary admixtures [18,19]. In contrast, the major drawback of FAs is their cost, which ranges from five to ten times that of technical-grade paraffin. An analysis on the entire life cycle gives a detailed evaluation of wider benefits in terms of burdens of production and disposal [20,21]. The benefits could be further amplified by producing FAs from recycled materials. As a matter of fact, they can be extracted from by-products, such as exhausted cooking oils. Besides the obvious economic savings, their impact on the cultivation of food commodities is avoided.

Even though glycerine (also known as glycerol), which belongs to the polyol compounds, has not been traditionally considered among the PCMs, its thermal properties make it an excellent candidate to be used as TES in buildings [22], thanks to its price trend in recent years. In fact, biodiesel production generates about 10%—by weight—of glycerol as the main by-product, creating too much surplus crude glycerol that has an impact on the glycerol market. As a consequence, the cost of crude glycerol has fallen from \$0.25 to \$0.05 per pound (0.10 \$/kg). Therefore, the development of sustainable processes to up-cycle this organic raw material is increasingly more important and should be stimulated [23].

At the end of the preliminary analysis presented in this paragraph, the E4iBuildings project focused on evaluating performance over the entire life cycle, performing a comparative analysis in the later stages. For this reason, glycerine, which combines excellent cost effectiveness with environmental sustainability, was preferred [24]. Unfortunately, the melting point of glycerine is not fitting for summer use, therefore FAs were selected as PCM for external panels thanks to their better environmental performances, notwithstanding their higher price compared to paraffins. The materials selected for the further steps are described in Table 1, together with their technical-economical features.

**Table 1.** Phase change material (PCM) prices and physical properties [17].

	Phase-Change Materials		Melt. Point	Latent Heat	Price	
			(°C)	(kJ/kg)	(\$/kg)	(c\$/kJ)
Paraffins	Hexadecane	$C_{16}H_{34}$	18.2	237	2.00	0.84
	Octadecane	$C_{18}H_{38}$	29.0	244	1.87	0.77
Fatty Acids	Caprylic acid (octanoic)	$C_8H_{16}O_2$	16.7	149	11.1	7.47
	Capric acid (decanoic)	$C_{10}H_{20}O_2$	31.6	152	10.1	7.32
	Lauric acid (dodecanoic)	$C_{12}H_{24}O_2$	43.8	178	9.70	5.67
Polyols	Glycerine	$C_3H_8O_3$	17.9	199	0.12	0.06

The use of micro-encapsulation ( $\mu$ e-PCM) in construction materials is a mature technique and its application is growing. The inclusion of larger amounts of  $\mu$ e-PCM is limited by the ensuing loss of concrete workability, and also by the decrease in final strength [14,25,26]. As a consequence, a maximum amount of around 12–15 kg/m<sup>3</sup> of PCM can be added, resulting in a low energy storage capacity. Lightweight aggregates (LWAs) can be suitably exploited as a carrier for PCMs, because of their inherent porosity: they can embed at least 20% by volume of PCM, which means 100–150 kg/m<sup>3</sup> of PCM in a typical lightweight concrete [22]. This value is about ten times higher than the amount of PCM embedded with conventional micro-encapsulation in ordinary concrete.

Shape-stabilised PCMs (ss-PCM) is thus a promising technique that should be developed in the future, with more focus on application in buildings [14]. Many materials have already been tested as PCM carriers, such as diatomite [19], expanded perlite [27] or clay [28]: these materials are all abundant and easily available. However, for successful utilisation in building applications, especially in cement-based materials, it needs to be ensured that these materials do not interfere with the hydration

process and its products, affecting the cement-aggregate bond and reducing the mechanical properties and durability of the building materials [14].

### 2.3. Multilayer Panels

The design of cladding needs to take the geographic conditions into consideration, in order to match summer and winter behaviour. PCMs perform better in temperate climates where they can work for a longer time-period, with frequent daily temperature changes around their phase-change value. For this reason the choice of the best PCM is mainly driven by its PTt [12].

Several studies have tried to optimize the position of PCM inside sandwich panels by considering different environmental conditions and PCMs' melting temperature: some of them using an experimental approach [29,30], while others used numerical simulations [12,31]. Starting from these results, where continental temperate climates require both AC and heating, a good combination is represented by claddings made by two different layers with an insulation core.

These sandwich panels are already common in precast concrete buildings, either for industrial or commercial use. A significant innovation may be the embedding of PCMs only within the most external layers, where their thermal properties are better used, unlike the core, where embedding PCMs is more difficult from the technological point of view. Moreover, by focusing on the inner and outer layers, two different melting points (PTt) can be chosen, to fit summer needs for the outdoor layer, or the winter needs for the interior one [22].

In the following, two different multilayer concrete panels are studied, in order to compare their thermal behaviour in two cities in Southern Europe. The main objective is to highlight the benefits ensuing from the addition of PCM as regards the reduction of temperature variations, and also as regards the need for heating and/or cooling. Moreover, two types of multilayer panels are considered, with the objective of assessing the effectiveness of PCMs in panels characterized by different geometry and materials.

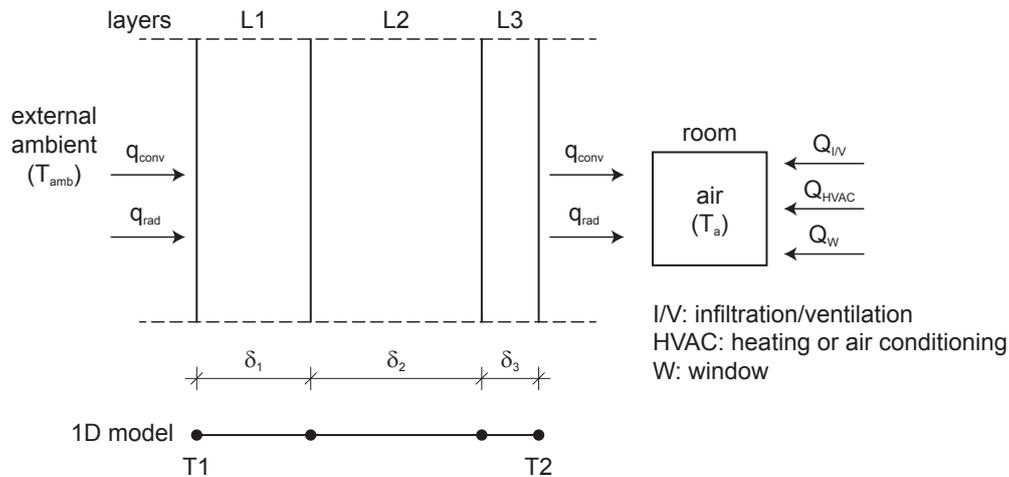
## 3. Numerical Modelling

The main contributions that are usually considered in the heat balance of a dwelling room are shown in Figure 2: besides the heat transferred through the envelope, there are also the contributions of windows and openings ( $Q_W$ ), the effect of infiltration and ventilation ( $Q_{I/V}$ ), and the power supplied by heating and air conditioning systems ( $Q_{HVAC}$ ). Since the analyses presented herein are primarily focused on the assessment of the thermal behaviour of precast cladding that are typically used for industrial and commercial buildings, the two contributions  $Q_W$  and  $Q_{I/V}$  that usually depend on the characteristics of the room under consideration and on the difference between the inside and outside ambient temperatures ( $T_a$  and  $T_{amb}$  respectively) are neglected. Note that in Figure 2 it is assumed that the external temperature is on the left of the panel, therefore L1 is the external layer and L3 is the internal layer.

The thermal performance of the panels is investigated by means of numerical models that were created with the commercial finite element package ABAQUS [32]. The analyses are based on the following assumptions:

- The heat transfer between the external layer of the panel and the outside environment takes place by convection and by radiation;
- The heat transfer inside the panel takes place by conduction, and can be modelled as one-dimensional;
- The layers of the panel consist of homogeneous and isotropic materials;
- The density and conductivity are constant with temperature;
- The specific heat is constant with temperature, since the latent heat due to the phase transition of the PCM is considered separately (explicit model);
- The contact thermal resistance between the layers is negligible: as a consequence, both the temperature and the heat flux are continuous inside the panel;

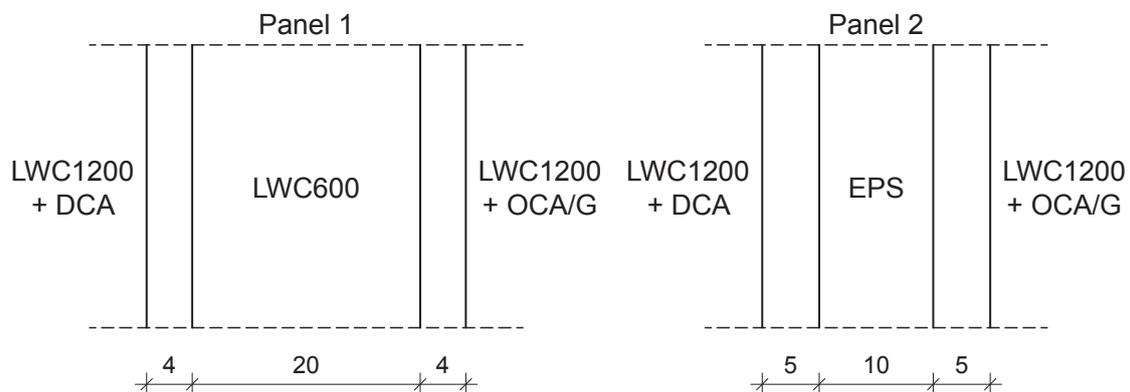
- The behaviour of the external and internal layers is fully reversible.



**Figure 2.** Typical contributions to the heat balance of a room/building.

The heat transfer process was modelled by means of 1D finite elements, with 2 nodes and linear shape functions. The basic element created, with a length equal to the thickness of the whole panel, was divided into three parts by means of intermediate primary nodes (Figure 2). The resulting parts were then further subdivided into finite elements with a maximum size of 2 mm. The adopted discretization is adequate for accurately capturing the thermal field inside the panel, and thus for adequately evaluating the thermal flux through the panel. The main output parameters of the model are the boundary temperatures  $T_1$  and  $T_2$ .

The geometry and materials of the two composite panels studied in the following are shown in Figure 3. The external and internal layers (L1 and L3 respectively) consist of light-weight concrete (LWC1200, density = 1200 kg/m<sup>3</sup>) containing PCMs for both panels. The middle layer (L2) consists either of light-weight concrete (LWC600, density = 600 kg/m<sup>3</sup>; Panel 1) or of insulation (polystyrene, density = 200 kg/m<sup>3</sup>; Panel 2). It is worth noting that Panel 1 is characterized by a larger thickness, because the intermediate layer consists of lightweight concrete: consequently, a larger thickness is required to reduce the thermal transmittance of the panel.



**Figure 3.** Geometry and materials of the two panels considered in the numerical analyses.

### 3.1. Boundary Conditions

The thermal performance of the two panels was evaluated under real temperature scenarios: Figure 4 shows the temperatures recorded in Bucharest (Romania), while Figure 5 shows the

temperatures recorded in Seville (Spain), over an interval of one year. These two scenarios were chosen from among a large set of European cities after some preliminary analyses, because their temperature–time histories better highlight the benefits resulting from the addition of PCMs [24]. Both temperature–time histories were worked out by enveloping the temperatures recorded over several years.

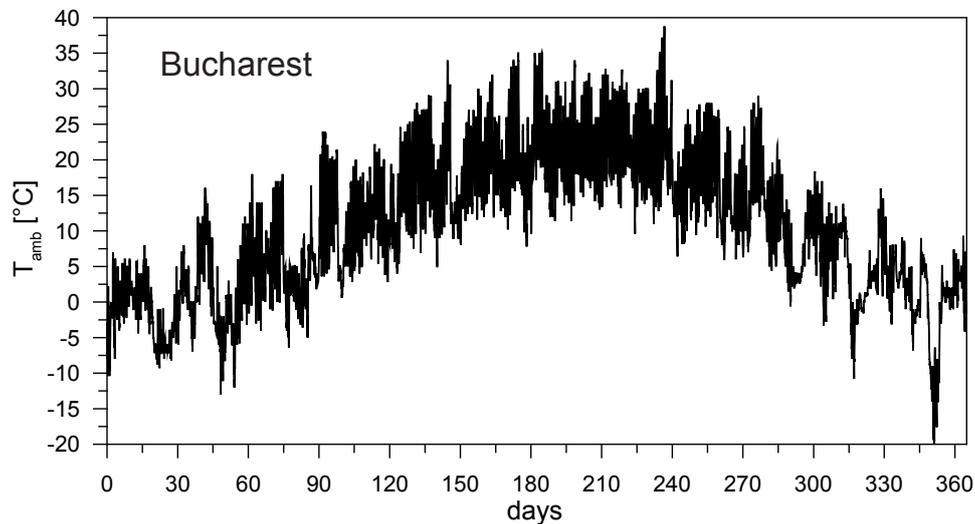


Figure 4. Ambient temperature recorded in Bucharest (Romania).

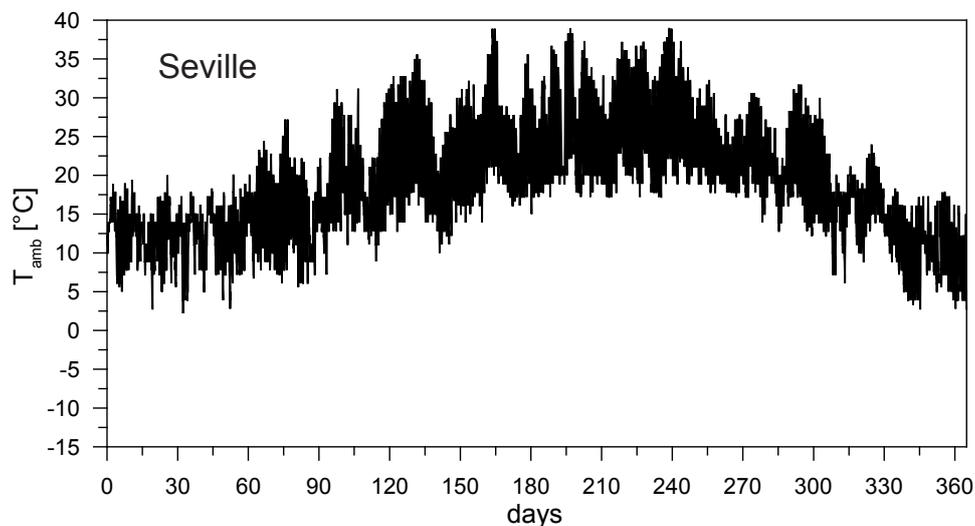


Figure 5. Ambient temperature recorded in Seville (Spain).

The heat transfer between the ambient (either outside or inside) and the external or internal layer of the panel takes place by means of convection. The heat flux due to convection is based on Newton's law:

$$q = h \cdot (T_{amb} - T_{surf}) \quad (1)$$

where

- $q$  is the thermal flux per unit surface ( $\text{W}/\text{m}^2$ );
- $h$  is the convection coefficient ( $\text{W}/(\text{m}^2 \cdot ^\circ\text{C})$ );
- $T_{amb}$  is the ambient temperature (either outside or inside);

- $T_{surf}$  is the temperature of the surface in contact with the ambient ( $T_1$  or  $T_2$ , respectively, in Figure 2).

The following values were assumed in the analyses for the convection coefficients, following the ASHRAE prescriptions [33]:

- $h_{int} = 8.3 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C}) = 29,880 \text{ J}/(\text{h} \cdot \text{m} \cdot ^\circ\text{C})$
- $h_{ext} = 17 \text{ W}/(\text{m}^2 \cdot ^\circ\text{C}) = 61,200 \text{ J}/(\text{h} \cdot \text{m} \cdot ^\circ\text{C})$

In all the analyses presented herein, the internal ambient temperature  $T_a$  was considered constant ( $=20 \text{ }^\circ\text{C}$ ). Finally, the panels were considered as being directly exposed to sunlight: as a consequence, the contribution of the solar radiation was implemented as a concentrated heat flux entering the external layer.

### 3.2. Materials Properties

The heat transfer inside the panel takes place by conduction, which is governed by Fourier's equation:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} \quad (2)$$

The solution requires the knowledge of three main properties of the materials involved:

- density  $\rho$  ( $\text{kg}/\text{m}^3$ )
- conductivity  $\lambda$  ( $\text{W}/(\text{m} \cdot ^\circ\text{C})$ )
- specific heat  $c$  ( $\text{J}/\text{kg}$ )

Phase transitions can be taken into account either implicitly, by assuming a temperature-dependency of the specific heat in Equation (2), or explicitly, by adding a term related to the latent heat consumed during the phase transition. In both cases, the problem is non linear, because of the temperature-dependency, thus obliging to resort to numerical analysis.

Table 2 shows the properties of the different materials considered in the analyses. The properties of normal-strength concrete are reported as well, for the sake of comparison.

**Table 2.** Physical and thermal properties of the materials considered in the thermal analyses.

Material	Density ( $\text{kg}/\text{m}^3$ )	Conductivity ( $\text{W}/(\text{m} \cdot ^\circ\text{C})$ )	Specific Heat ( $\text{J}/\text{kg}$ )
NSC	2400	1.64	1000
Insulation	200	0.035	1500
LWC600	600	0.2	840
LWC1200	1200	0.4	840

A brief description of the four materials follows:

- NSC: normal-strength concrete, with standard values of density and specific heat; as for the conductivity, its value was determined as the average between the two extreme values proposed in EN 1992-1-2 at  $0 \text{ }^\circ\text{C}$ ;
- Insulation: the values of the conductivity and specific heat are standard values commonly found in the literature [12]; the density value allows for the water absorbed during the casting process;
- LWC600: light-weight concrete, with density =  $600 \text{ kg}/\text{m}^3$ ; the value of the specific heat was taken from EN 1994-1-2, whereas the conductivity was evaluated in accordance with [34], taking into consideration that conductivity decreases as the density decreases;
- LWC1200: light-weight concrete, with a density =  $1200 \text{ kg}/\text{m}^3$ ; the values of specific heat and conductivity were evaluated as for LWC600.

The PCMs considered in the analyses are fatty acids and glycerine. Typical physical and thermal properties [22] are shown in Table 3. As previously mentioned, the PCMs are added to the external and internal layer (L1 and L3) of the investigated panels, in order to improve their thermal performance under variable ambient temperatures. The addition of PCMs calls for a modification of the base properties of the materials, as given in Table 2, through the introduction of latent heat. Moreover, it is assumed that the PCM is able to fill the air voids trapped in the base material (or in the aggregates): as a consequence, the density of the new material (LWC1200 + PCM) is obtained by summing the weight of the amount of PCM added and the density of the base material. The new density is then used for working out the mass fraction of PCM, allowing the latent heat of the new material to be evaluated through a weighted average. As for the melting temperature, in the analyses the melting temperature in the internal layer was considered equal to 19.7 °C. As for decanoic capric acid (DCA) the value was kept constant (melting temperature  $T_m = 31.6$  °C). All the above considerations are summarized in Table 4. The phase transition was modelled explicitly by considering the latent heat and the transition temperature among the input variables. As is usually done, the phase transition is considered to take place within a range of temperatures, whose midpoint is the melting temperature. In the analyses, an interval of 2 °C (=melting temperature  $\pm 1$  °C) was considered. It is worth noting that modelling the phase transition implicitly, by suitably modifying the specific heat, leads to the same results. Note that the addition of PCM causes modifications also to the thermal conductivity and specific heat: however, for the sake of simplicity, and to see the effect of the PCM only in terms of latent heat, in the analyses the values of conductivity reported in Table 2 were used.

Table 3. Typical physical and thermal properties of PCMs.

Material	Density (kg/m <sup>3</sup> )	Conductivity (W/(m·°C))	Specific Heat (J/kg)	Melting Temperature (°C)	Latent Heat (kJ/kg)
Capric acid (octanoic)	900	0.35	1950–2110	16.7	149
Capric acid (decanoic)	900	0.35	2090	31.6	152
Glycerine	-	-	-	17.9	199

Table 4. Physical and thermal properties of PCM-modified concrete used in the numerical analyses.

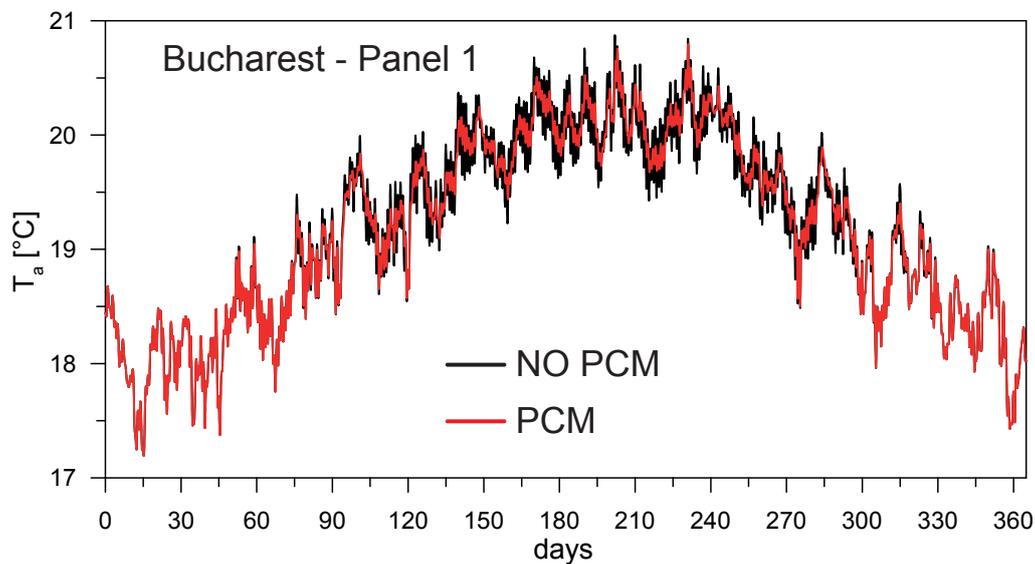
Material	Density (kg/m <sup>3</sup> )	PCM Mass Fraction (%)	Melting Temperature (°C)	Latent Heat (J/kg)
LWC1200 + OCA/G	1440	9–11	19.7	13500
LWC1200 + DCA	1440	9–11	31.6	13500

#### 4. Results and Comments

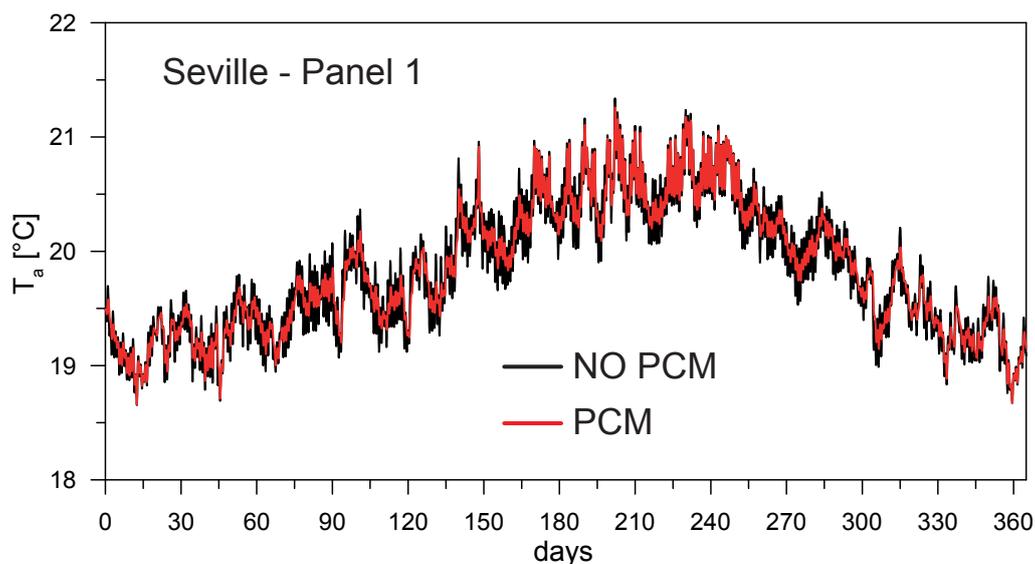
Figures 6 and 7 show the variation of the temperature on the internal surface  $T_2$  of the panel, as a function of time for Panel 1, for the two temperature–time scenarios respectively. Clearly,  $T_2$  is the key parameter used to work out the heat flux entering/exiting the room, if the heat transfer only takes place through the panel (since the other contributions  $Q_W$  and  $Q_{I/V}$  are neglected). In both figures, the effect of adding PCM (red curves) is visible by the fact that the temperature variations are reduced: as a matter of fact, the red curves (PCM) are in some way enveloped by the black curves (NO PCM). Moreover, the addition of PCM appears to be more effective in the hot season, when the internal temperature exhibits variations around the value of 20 °C. It is worth noting that the temperature variation over the whole year, evaluated as the difference between the maximum and the minimum temperature, is approximately equal to 4 °C for Bucharest, and to 3 °C for Seville.

Figures 8 and 9 show the variation of the temperature on the internal surface of the panel, as a function of time for Panel 2, for the two temperature–time scenarios respectively. Also in this case, the addition of PCM brings a reduction of the temperature variations, however the temperature

variation over the whole year is reduced with respect to the case of Panel 1 (less than 2 °C for Bucharest, and less than 1 °C for Seville).



**Figure 6.** Panel 1: temperature on the internal surface of the panel as a function of time (Bucharest).

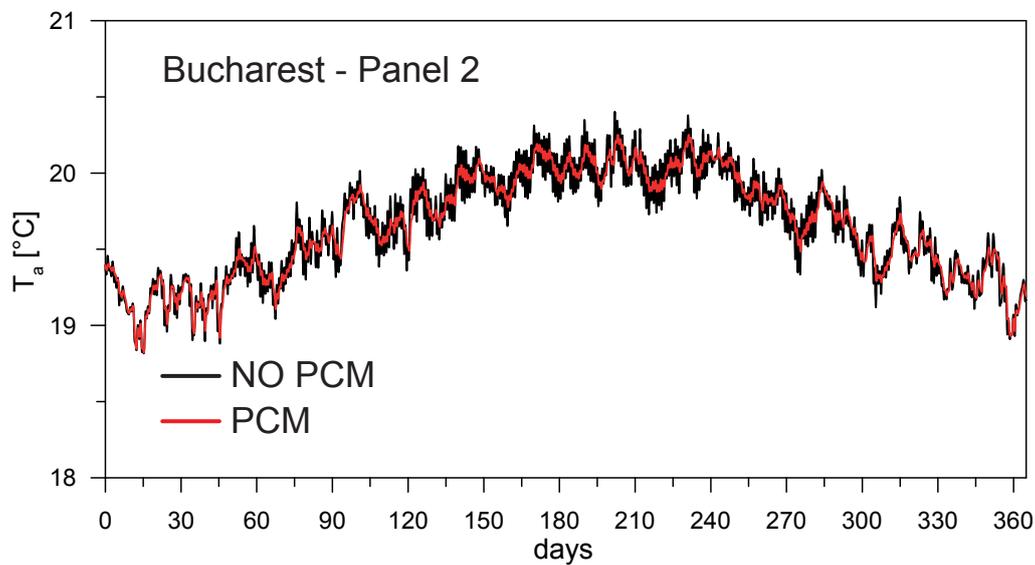


**Figure 7.** Panel 1: temperature on the internal surface of the panel as a function of time (Seville).

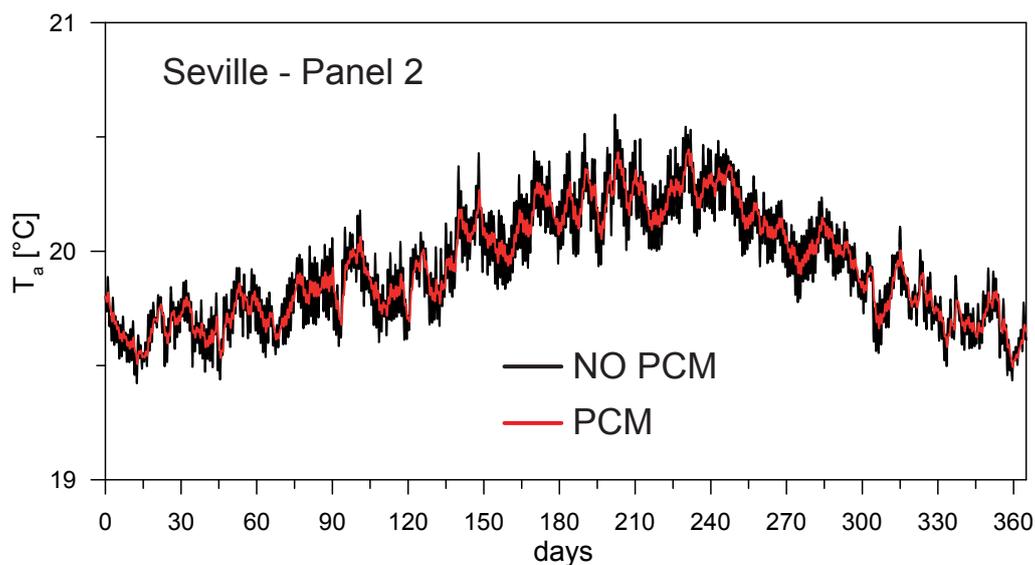
Taking a closer look at the thermal behaviour of Panel 2 (Bucharest, Figure 8) makes it possible to better highlight the role of PCMs. Both in the cold (Figure 10a) and in the hot season (Figure 10b), the addition of PCMs causes a reduction in the temperature variations that is more evident within the range that characterizes the phase transition (in this study: 18.7–20.7 °C). Clearly, since the energy required for heating and cooling depends on the difference between the temperature of the internal surface of the envelope ( $T_2$ , Figure 2) and the inside ambient temperature (that is set equal to 20 °C), the benefits ensuing from adding PCMs are more evident in Figure 10b.

The thermal performance of the two panels over the whole year can be more adequately evaluated by working out the maximum values of the incoming and outgoing heat flux ( $Q_{in}$  and  $Q_{out}$  respectively) that are relevant for the instantaneous power required from the heating/cooling system, and by calculating the total incoming and outgoing values of energy ( $E_{in}$  and  $E_{out}$  respectively) through

integration of the convective heat flux resulting from the difference between the temperatures shown in Figures 4–7 and the constant temperature  $T_{set} = 20\text{ }^{\circ}\text{C}$ .



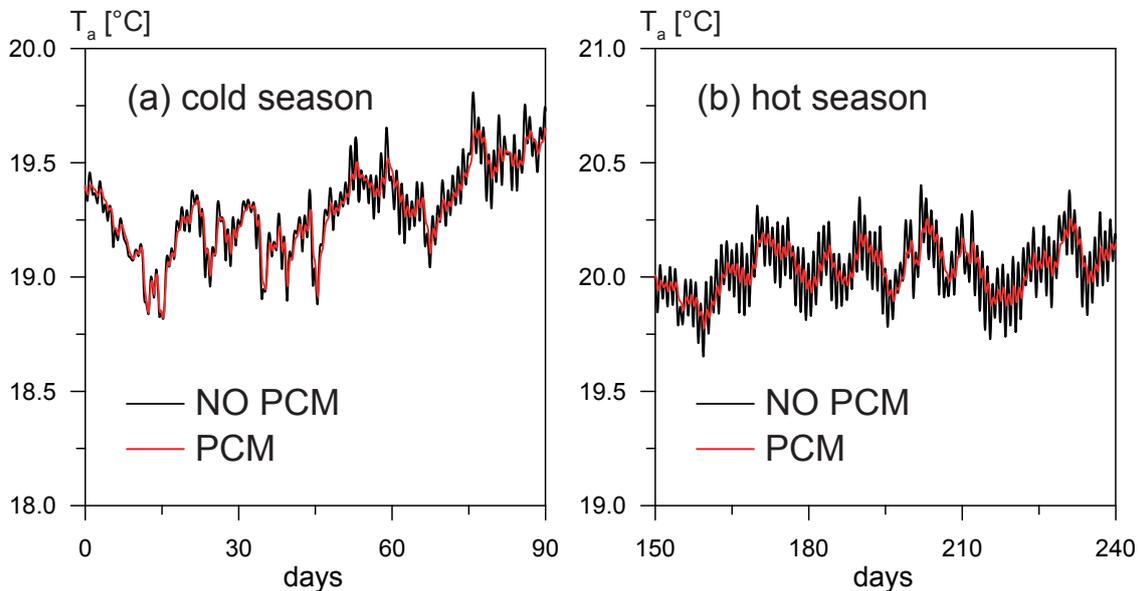
**Figure 8.** Panel 2: temperature on the internal surface of the panel as a function of time (Bucharest).



**Figure 9.** Panel 2: temperature on the internal surface of the panel as a function of time (Seville).

The results are summarized in Tables 5 and 6, where the values of heat flux and total energy are expressed in  $\text{kW}/\text{m}^2$  and  $\text{kWh}/\text{m}^2$  respectively. Panel 2, as should be expected, exhibits a better overall thermal performance with respect to Panel 1, mainly because of its lower value of thermal transmittance ( $U_2 = 0.304\text{ W}\cdot\text{m}^{-2}\cdot^{\circ}\text{C}^{-1}$  vs.  $U_1 = 0.725\text{ W}\cdot\text{m}^{-2}\cdot^{\circ}\text{C}^{-1}$ ), which results in lower values of heat flux and total energy in all cases. With regards to the heat flux in Panel 2, with the first temperature scenario (Bucharest) there is a significant reduction of the peak value in the hot season ( $-39\%$ ), while no significant reduction is observed in the cold season; on the contrary, with the second temperature scenario (Seville) there are sizable reductions both in the cold and in the hot seasons ( $-23\%$ ). In Panel 1, reductions of the maximum values of heat flux (both incoming and outgoing) are observed for both temperature scenarios, but the values are definitely lower (from  $-2\%$  to  $-8\%$ ). These results are in agreement with previous results on similar building elements [12]. Looking at the

values of total energy, the effect of adding PCM is more significant in all cases in Panel 2. As in the case of the heat flux, however, its effects are more evident in the hot season in Bucharest when cooling is required, with sizable reductions in the incoming energy (−14% for Panel 1; −21% for Panel 2), and thus a corresponding reduction in the cooling power required.



**Figure 10.** Panel 2: temperature on the internal surface of the panel as a function of time (Bucharest): (a) January–March; (b) May–July.

**Table 5.** Values of incoming and outgoing heat flux (in kW/m<sup>2</sup>).

Panel	Buc- $Q_{in}$	Buc- $Q_{out}$	Sev- $Q_{in}$	Sev- $Q_{out}$
1 (with PCM)	6.62	23.29	10.45	11.11
1 (w/o PCM)	7.26	23.29	11.11	11.17
2 (with PCM)	2.08	9.77	3.70	4.20
2 (w/o PCM)	3.34	9.82	4.97	4.80

**Table 6.** Values of total incoming and outgoing energy (in kWh/m<sup>2</sup>).

Panel	Buc- $E_{in}$	Buc- $E_{out}$	Sev- $E_{in}$	Sev- $E_{out}$
1 (with PCM)	3.09	63.02	12.41	23.91
1 (w/o PCM)	3.61	63.53	12.83	24.36
2 (with PCM)	1.27	26.40	5.19	10.01
2 (w/o PCM)	1.61	26.76	5.47	10.32

## 5. Concluding Remarks

The numerical results presented in the paper allow the following conclusions to be drawn:

- The addition of PCMs to the internal and external concrete layers of sandwich panels is beneficial, for both temperature–time scenarios and type of panel, with energy savings that can be as high as 20% in Panel 2 (characterized by a higher thermal resistance);
- PCMs also cause a significant reduction (−39%) in the peak energy required for heating and cooling;
- For the two temperature–time scenarios considered, the effect of PCMs appears to be relatively more significant in the hot season, when energy is required for cooling;

- With regards the two types of panel investigated, the effect of PCMs is relatively more significant in Panel 2, where the intermediate layer consisting of insulation leads to a lower value of thermal transmittance, therefore to overall lower values of the heat flux and of the resulting total energy;
- Despite the fact that adding PCMs is always beneficial, it can in no way overcome poor thermal behaviour (as is the case for Panel 1, where no insulation is present in the intermediate layer).

The presented results clearly highlight the potentialities of adding PCMs to cladding panels with concrete layers. Clearly, the basic assumptions concerning the heat balance of the numerical model (i.e., neglecting the contributions due to infiltration, ventilation and windows) are tailored for the particular application considered, namely envelopes of industrial and commercial buildings: if residential buildings are at issue, the aforementioned contributions might play a significant role, possibly leading to lower values of peak power and energy savings. Drawing ultimate conclusions on this aspect would, however, be rather incautious, in consideration of the several parameters coming into play when the focus is on residential buildings (such as, for example, occupancy, dimensions and position of the room). These aspects, together with a due experimental verification of the thermal behaviour of lightweight concrete containing PCMs, could be topics for future research work.

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## Abbreviations

The following abbreviations are used in this manuscript:

DCA	Decanoic capric acid
EU	European Union
FAs	Fatty acids
G	Glycerine
LCA	Life cycle analysis
LTE	Latent thermal energy
LWAs	Lightweight aggregates
LWC	Light-weight concrete
NSC	Normal-strength concrete
OCA	Octanoic capric acid
PCMs	Phase change materials
$\mu$ e-PCM	Micro-encapsulated-PCM
PTt	Phase transition temperature
ss-PCM	Shape-stabilised-PCM
STE	Sensible thermal energy
TES	Thermal energy storage

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