

Experimental dynamic thermal properties determination of EPDM/NBR panels with a shape stabilized Phase Change Material based on summer daily temperatures of four cities in Italy

Francesco Valentini^{a,*}, Maurizio Grigante^b, Alessandro Prada^b, Luca Fambri^a,
Andrea Dorigato^a, Alessandro Pegoretti^{a,*}

^a University of Trento, Department of Industrial Engineering and INSTM Research Unit, Via Sommarive 9, 38123 Trento, Italy

^b University of Trento, Department of Civil, Environmental and Mechanical Engineering, Via Mesiano 77, 38123 Trento, Italy

ARTICLE INFO

Keywords:

Thermal management
Phase change materials
Buildings
Decrement factor
Time lag
Admittance
Insulation

ABSTRACT

In this work, the evaluation of E-PCM panels based on an elastomeric matrix containing a shape-stabilized paraffinic phase change material with a melting point of 28 °C was carried in a climatic chamber, simulating the summer daily temperature profile of four geographical locations in Italy at different latitudes. The characterization, carried out on testing boxes insulated using the E-PCM panels, allowed the determination of the delay (time lag) and of the dampening (decrement factor) in the propagation of the heat wave when passing from the outer to the inner surface of the walls; the results were correlated to two important parameters, the characteristic admittance and the heat capacity. From the difference between the heat fluxes on the outer and inner surface of the panels it was also possible to quantify the amount of stored energy and to do a comparison with a reference insulating panel (aerogel). Aerogel panels, despite the low thermal conductivity but due to the limited heat capacity and characteristic admittance, were unable to provide an effective insulation during summer conditions while E-PCM panels led to excellent outcomes. Results showed that with a peak of 33 °C in the external temperature, the phase change material limited the internal one at 27 °C with a maximum delay in the peak temperature of 6 h, an overall decrement factor of 0.4, time lag of 3 h and stored energy of 740 kJ/m² per day. Finally, also the influence of the testing speed on the response of the E-PCM was evaluated through repetition of heating/cooling cycles in the temperature range 19–35 °C, highlighting the necessity of improving the thermal conductivity of the system in case of fast-response applications (cycle length < 3.5 h) and/or to optimize the PCM amount in the panel depending on the energy to be absorbed.

1. Introduction

As highlighted in most of the European Union (EU) planning energy strategies [1–3], in the close future energy storage technologies are expected to play an important role to achieve the ambitious objectives pertaining the global warming mitigation, the climate changes and the increasing depletion of the conventional energy resources. According to the International Energy Agency (IEA) [4], the buildings sector (including tertiary and residential buildings) is considered energy intensive since it accounts for nearly 40 % of the final energy consumption of which, more than 50 %, is due to space heating and cooling [5]. In particular, building conditioning represents a worldwide energy consumption practice which contributes with relevant impact to the

global warming and climate changes [6,7]. Since the buildings envelope is responsible of the direct heating and cooling loads [8], actions aiming at improving their energy saving performances, jointly with installations of high-performing energy plants, represent the key factors to achieve the net-zero carbon emissions in building sector by 2050 as reported in the guidelines of the IEA [9].

Nowadays, one of the most promising technology expected to have a remarkable enhancement in building energy-saving consists in the incorporation of Phase Change Materials (PCMs) in building envelopes. Indeed, over the last ten years, their use has attracted an increasing attention for the opportunities offered by their thermo-physical properties, such as: versatile melting temperature range (from 12 to 38 °C to cover environmental thermal comfort needs), large latent heat capacity,

* Corresponding authors.

E-mail addresses: francesco.valentini@unitn.it (F. Valentini), alessandro.pegoretti@unitn.it (A. Pegoretti).

<https://doi.org/10.1016/j.enbuild.2024.114503>

Received 5 March 2024; Received in revised form 6 June 2024; Accepted 28 June 2024

Available online 28 June 2024

0378-7788/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

high density, thermal and chemical stability in the long-run duration, proper thermal conductivity, consistent melting, limited corrosiveness, non-toxicity, adaptability with the building applications [10,11]. The working principle of PCMs consists in exploiting their phase transition from solid to liquid when temperature rises: in this case large amount of thermal energy can be stored in the PCM. On the other side, when temperature decreases and the material changes from liquid to solid, an equivalent amount of energy is released to the surrounding. Therefore, when properly integrated in concrete [12,13], mortars [14–16], bricks [17] and/or other components such as walls, floor, roof and windows [18,19], the PCMs can significantly modify the thermal behaviour of the global structure since they act as efficient dynamic Thermal Energy Storage (TES) media. At first, this behaviour can have a relevant role in shifting the peak loads to the off-peak hours, making the indoor thermal conditions less sensitive with respect to the outdoor ones with positive effects on the indoor thermal well-being perception. Secondly, it can significantly reduce the heating/cooling loads of buildings, thus contributing to the expected saving energy actions. Despite these undoubted advantages, the challenge to consolidate the use of the PCMs applications is actually represented by the development of effective and innovative solutions to incorporate these materials into the building envelopes [20–24]. In this regard, the major issues can be traced back to the volume variations during phase change process, the limited heat transfer due to reduced thermal conductivity of most the PCMs and, the most relevant one, the leakage when the PCM passes from solid to liquid state. In the last years several methods based on macro-encapsulation [25], micro-encapsulation [26,27], shape-stabilization within polymeric [28–30] or porous ceramic matrices [31] have attracted increasing attention. Among these, particular advantages have been recognized to the shape-stabilized PCMs (SS-PCM) which can be classified as composite panels where the PCM, stabilized by using a suitable support material, is retained into a containment material to avoid its leakage during the phase change process. The interest for this incorporation method is mainly due to the large apparent specific heat, the possibility to optimize the thermal conductivity, the flexibility and good mechanical strength of the resulting composites, the possibility of keeping stable the shape during phase change and the good performances under multiple thermal cycles [32,33]. Besides, the production methods are cost effective [34] since they require few steps compared to those currently required for the PCM encapsulation. These features have proven to be particularly attractive for their potential applications within external building envelopes as well as into inner linings such as inner wall, ceiling and floor [35,36]. Nevertheless, from the detailed work by Cardenas-Ramirez et al. [37] and other recent reviews papers [38–40], it emerges that experimental studies involving SS-PCMs are focused on evaluating their potentialities as energy storage mediums, for example in cooling equipment boxes [41], food preservation [42], solar energy [43] and further industrial applications, both experimentally and numerically, as those reported in the recent paper reviews [39]. Experimental studies, specifically dedicated to evaluate the thermal performances of SS-PCMs on building envelopes are still very limited.

The panel developed and investigated in this study belongs to the SS-PCM category, and it combines an Ethylene-Propylene Diene Monomer (EPDM) rubber (i.e. Supporting material) with a paraffin wax (i.e. PCM) stabilized with organomodified montmorillonite [44]. A Nitrile Butadiene Rubber (NBR) envelope contains the PCM when in the molten state during phase change process. This study represents a fundamental step of an extended experimental campaign specifically focused on investigating the thermal performances of the proposed solution. This study expands the knowledge of the thermal behaviour of SS-PCM technology: from the Authors knowledge, published experimental works [39,45] are mainly limited to monitor the temperature profiles without evaluating crucial inertia parameters as time lag and decrement factor. The novelties of this work can be summarized as follows:

- dynamic parameters as *thermal admittance*, *decrement factor* and *time lag time* were experimentally determined specifically for PCM panel technology;
- the impact of the heat capacity of the investigated panels was highlighted with particular attention to the suitability of PCMs as panel insulation solution for summer climatic conditions;
- the increasing performances of the proposed E-PCM solution were verified when applied to climatic condition simulating real daily temperature variations referred to four cities in Italy;
- the amount of the stored heat was determined and the impact of cyclic thermal variations on the PCM performances verified.

2. Experimental activities

2.1. Materials

Vistalon® 2504 EPDM rubber was purchased from Exxon Mobil (Irving, TX, USA). Paraffinic wax Rubitherm RT28HC, with a melting temperature of around 28 °C and specific melting enthalpy (ΔH_m) of 250 J/g was purchased from Rubitherm GmbH (Berlin, Germany). Carbon black N550, purchased from Omsk Carbon group (Omsk, Russia) was used as reinforcing filler. Zinc oxide (curing activator), stearic acid (curing activator and lubricating agent) and sulphur (vulcanizing agent) were purchased from Rhein Chemie (Cologne, Germany). Tetramethylthiuram disulphide (TMTD) and zinc dibutyl dithiocarbamate (ZDBC), purchased from Vibiplast srl (Castano Primo (MI), Italy), were used as accelerators. The elastomeric compound used for the preparation of the samples consisted of: Vistalon® 2504 (100 phr), sulphur (3 phr), zinc oxide (3 phr), stearic acid (1 phr), carbon black (20 phr), TMTD (0.87 phr) and ZDBC (2.5 phr). Organomodified montmorillonite (oMMT) Cloisite® 20 was obtained from BYK-Chemie GmbH (Wesel, Germany). NBR (nitrile-butadiene rubber) foils (thickness equal to 0.4 mm), with high acrylonitrile content (45 %) were purchased on the market. Commercial wood panels (poplar multilayer, thickness 5 mm) and aerogel panels (thickness 13 mm) were found on the market and utilized for the preparation of the experimental boxes (see Section 2.2.2).

2.2. Samples preparation

2.2.1. Preparation of E-PCM panels

Elastomeric panels, whose detailed preparation, pictures and characterization are reported in [44], consisted of an EPDM matrix containing paraffin premixed with oMMT, and by an external envelope made of NBR rubber used to avoid paraffin leakage. EPDM/paraffin blends with a paraffin content of 56 wt% were prepared by solution mixing using a tilting kneader operating at a temperature of 60 °C: the EPDM compound, preheated at 40 °C was first added in the chamber; around half of the paraffin amount, preheated at 80 °C, was then gradually added until complete dissolution of the EPDM compound. The remaining paraffin was manually mixed to the oMMT (PCM/oMMT ratio of 3:1, with respect to the global PCM content) and then gradually added in the chamber reaching a total mixing time of 150 min. The compound was then transferred in a mould covered with a 0.4 mm layer of NBR rubber (ENV) used in order to avoid paraffin leakage. The vulcanization process of the resulting compound was carried out in a Carver laboratory press at a pressure of 2 bar, for 20 min at a temperature of 170 °C. In this way, square sheets with dimensions of around 300 × 300 × 5 mm³ were obtained.

2.2.2. Preparation of testing boxes

The testing boxes were prepared by applying five elastomeric panels on the internal side of the walls and of the ceiling of a wood box (Fig. 1), thus covering an insulating volume of approximately 300 × 300 × 300 mm³ and by a surface area of around 0.45 m². During the tests the boxes were placed on a phenolic foam basement (thickness 10 cm, density 35



Fig. 1. Representative picture of the boxes (volume = 0.27 m³) used for the tests: top view (a) and bottom view with E-PCM insulation (b).

kg/m³, thermal conductivity 0.027 W/m·K at 40 °C, thermal resistance 3.75 m²·K/W, specific heat 1750 J/kg·K) in order to avoid any heat transfer to/from the testing boxes. For a proper insulation during the tests, the bottom side of each box was inserted in a profile cut in the phenolic foam panel and sealed using a flexible polyurethane foam. A wood box without insulation and a wood box insulated with five aerogel panels were used as references. The decision to adopt wooden panels as basic structures to sustain the E-PCM panels has been driven, first of all, by the characteristics of the utilized climatic chamber which makes difficult to analyse more complex structures as concrete block buildings. However, the insulated timber structure here obtained can be classified as a lightweight construction panel for which, as highlighted in several works [46,47], the insertion of PCMs for thermal energy management is much more effective than their insertion in high-massive structures. Regarding the position of the panels on the internal side of the boxes, it should be pointed out that, despite the significant work already done [48–52], the outcomes pertaining to the optimal position of PCM are still contradictory, in particular for lightweight structures as the wooden one here analysed. The choice to place it internally is supported by the purpose of limiting the increase of the indoor temperature and in this case the optimal position suggested is closer as possible to the inner surface.

The list of the tested boxes along with their codes is reported in Table 1.

2.3. Experimental methodologies

2.3.1. Characterization of single components

The specific heat c_p of the materials (wood, aerogel, E-PCM) was determined following the ASTM E1269-11 standard but at lower testing speed (2 °C/min) due to the presence of PCM that requires low testing speed during differential scanning calorimetry (DSC), as already observed in a previous work [53]. Wood and aerogel samples were oven-

dried before the test in order to exclude the presence of water. Three specimens for each sample were tested with a Mettler DSC30 calorimeter under a nitrogen flow of 100 ml/min performing thermal cycles consisting in:

- isotherm at −15 °C for 4 min;
- heating ramp from −15 °C to 45 °C at 2 °C/min;
- isotherm at 45 °C for 4 min.

Comparing the DSC curves obtained testing a sapphire reference of known specific heat, the determination of the c_p of the samples in the range −5 to 40 °C was obtained. The temperature interval was chosen to allow the determination of the c_p above and below the melting peak of paraffin that, at 2 °C/min, starts at 15 °C and ends at 30 °C (see Fig. S2). Due to the impossibility of directly measuring c_p values of the system wood + insulator, these were evaluated as average between the values measured for each material weighted to the mass of each specific material within the box.

Thermal conductivity measurements were carried out using a Netzsch HFM 446 heat flow meter according to ISO 8301 standard. The tests were carried out on squared specimens with surface area of 200 × 200 mm² at a temperature of 10 °C and 40 °C applying a temperature difference of 20 °C between the cold and hot plate of the instrument. The two temperature values were chosen in order to perform the test below (10 °C) and above (40 °C) the melting point of paraffin. Tests were performed on the system wood + insulator.

The specific thermal resistance of the material was determined according to Eq. (1):

$$R^* = \frac{d}{\lambda} \quad (1)$$

where R^* is the specific thermal resistance, d is the thickness of the material and λ is the thermal conductivity.

2.3.2. Climatic data simulation

In order to test the thermal behaviour of the E-PCM samples, insulated boxes were subjected to heating/cooling cycles using a climatic chamber (Memmert HPP260eco). The testing temperatures were chosen according to the climatic data of 4 reference locations in Italy:

- Verona (45°26'N, 10°59'E, 57 m.a.s.l.) [54];
- Trento (46°03'N, 11°08'E, 255 m.a.s.l.) [55];
- Roma (41°53'N, 12°48'E, 62 m.a.s.l.) [56];
- Palermo (38°06'N, 13°21'E, 75 m.a.s.l.) [57].

The four selected locations represent an interesting case study because they allow to evaluate the thermal response of the E-PCM panels when subjected to different external forcing conditions: from the city

Table 1

Characteristics of the reference wood box and of the insulated ones.

Box code	Insulation	Total thickness [mm]	Total mass [kg]	Surface mass [kg/m ²]	Density ^a [kg/m ³]
Ref	–	5 mm	1.04	2.3	430
Aerogel	aerogel	5 + 13 mm	2.27	5.0	306
E-PCM 5 mm	E-PCM	5 + 5 mm	3.66	8.1	735
E-PCM 10 mm	E-PCM	5 + 10 ^b mm	6.28	13.9	799

^a Density values referred to the single panels composing each box (e.g. wood, aerogel, E-PCM).

^b The thickness of 10 mm is obtained using two E-PCM panels with a thickness of 5 mm each.

characterized by the highest daily temperature range (Trento), to the mildest one (Palermo). As reported in literature [58], the PCMs insertion in the building envelope is more effective when applied in climatic areas characterized by higher temperature range. This makes reason of having selected the second week of July 2022, which turned out to be the hottest of that year, to which refer this analysis. For the four cities, the average of the hourly temperatures recorded during the second week of July 2022 was simulated using the climatic chamber as the sum of single steps with duration of 1-hour (see Fig. 2, for complete data please refer to Fig. S1). Each simulation was replicated 3 times.

In order to test the influence of the cycle duration on the thermal energy storage capability of E-PCM samples, insulated boxes were also subjected to heating/cooling cycles of different duration using a climatic chamber (Memmert HPP260eco), in a temperature interval from 19 to 35 °C, according to the scheme reported in Fig. 3. The testing temperatures were chosen according to climatic data measured in Trento (46°03'N, 11°08'E, 255 masl) on the 26th July 2022 due to the very large temperature variation recorded: minimum temperature of 19.5 °C and maximum temperature of 34.3 °C. The cycle duration was set to 7, 3.5 and 2 h; 15 repetitions were performed for each duration.

2.3.3. Dynamic parameters determination

During the daily variation of the outdoor temperature in summer, a heat wave propagates through the wall of a building from outside to inside and its amplitude decreases depending on the composition and on the thickness of wall [59]. The magnitude of the variation of the internal temperature of a building depends on the magnitude of the daily variations of heat inputs (i.e. ambient conditions) and on the thermophysical properties of the wall (i.e. ability of the wall to absorb heat). In the literature several methods were developed to correlate the internal temperature of a building (and the related heat flux through the wall) to the external conditions since they cannot be carried out only on the base of steady state assumptions. Parameters as *thermal admittance*, *decrement factor* and *time lag*, introduced in the 1970 s [60,61], are constantly recommended in International Standards such as ISO 13786:2007 [62]. In building technology, thermal inertia can be indicated with different terms, as example: thermal effusivity, heat penetration, thermal admittance. In particular, the concept of *thermal admittance* is specifically used when the thermal inertia is subjected to a periodicity of a thermal cycle that, in building environment, usually corresponds to a daily variation cycle approximately described with a period of 24 h [63–66]. The ratio between the heat flux into the wall and the corresponding variation of surface temperature is defined as its thermal

admittance (y). The thermal admittance of a wall is an important factor in calculating the thermal response to cyclic temperature variations because, differently from the thermal transmittance U -value [W/m^2K] that refers to the steady state, depends on density and specific heat of wall material. According to Davies et al. [60,67], it is possible to define a basic material property, the *characteristic admittance* (a). The decreasing ratio of the amplitude of the heat wave when passing from the outer to the inner surface of a wall is named *decrement factor*, while the *time lag* accounts for the delay in the propagation of the heat wave from the outer surface to the inner surface of the material. Unfortunately, different interpretations of decrement factors and time lag are present: correlating internal wall temperature to external air temperature [68], internal wall temperature to external wall temperature [69,70], internal air temperature to external air temperature [71] and many others [37,59,68,72,73]. In this work the correlation between internal and external air temperature was considered.

The decrement factor (f) was evaluated as the ratio between the inner and outer thermal amplitudes, as show in Eq. (2):

$$f = \frac{T_{air,in,max} - T_{air,in,min}}{T_{air,out,max} - T_{air,out,min}} \quad (2)$$

where, $T_{air,in,max}$, $T_{air,out,max}$, $T_{air,in,min}$ and $T_{air,out,min}$ are the maximum and minimum temperatures of the air inside and outside the testing box. The time lag (Φ), was evaluated according to Eq. (3):

$$\Phi = t_{T_{surf,in,max}} - t_{T_{surf,out,max}} \quad (3)$$

where, $t_{T_{surf,in,max}}$ and, $t_{T_{surf,out,max}}$ are the time in hours when the inner and outer surfaces reach the maximum temperature.

According to Davies et al. [60,67], the characteristic admittance for an homogenous slab of defined thickness can be described by Eq. (4):

$$a = \alpha^* e^{\frac{\pi}{4}} \quad (4)$$

where a is the magnitude of the characteristic admittance, defined by Eq. (5)

$$a = \sqrt{\frac{2\pi}{P} \lambda \rho c_p} \quad (5)$$

where P is the period of the temperature cycle, λ is the thermal conductivity, ρ is the density and c_p is the specific heat. The physical unit of a [W/m^2K] is provided by its magnitude and the quantity $\lambda \cdot \rho \cdot c_p$, sometimes named as thermal inertia [63], measures the ability of a

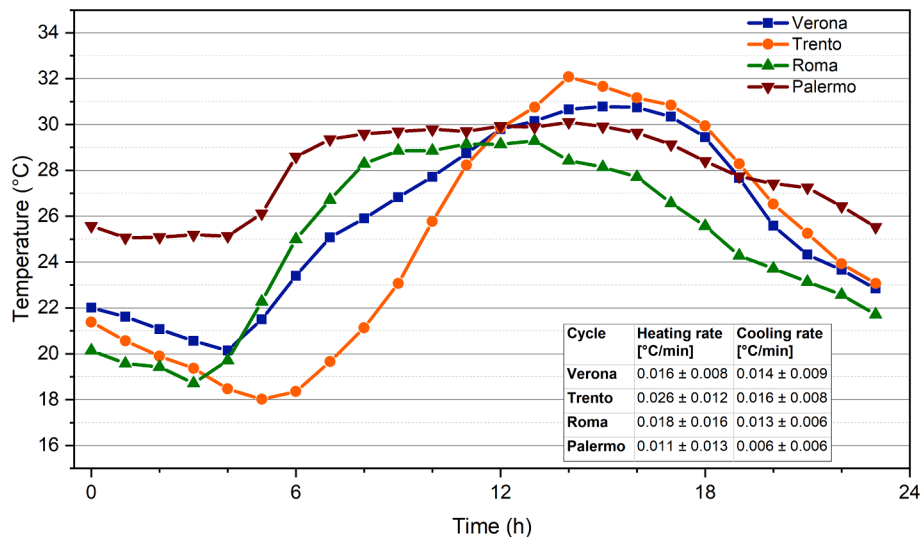


Fig. 2. Temperature profiles applied in the climatic chamber, corresponding to the average hourly temperatures recorded in the four Italian locations during the second week of July 2022. The average heating and cooling rates evaluated along each cycle are also reported. Data taken from [54–57].

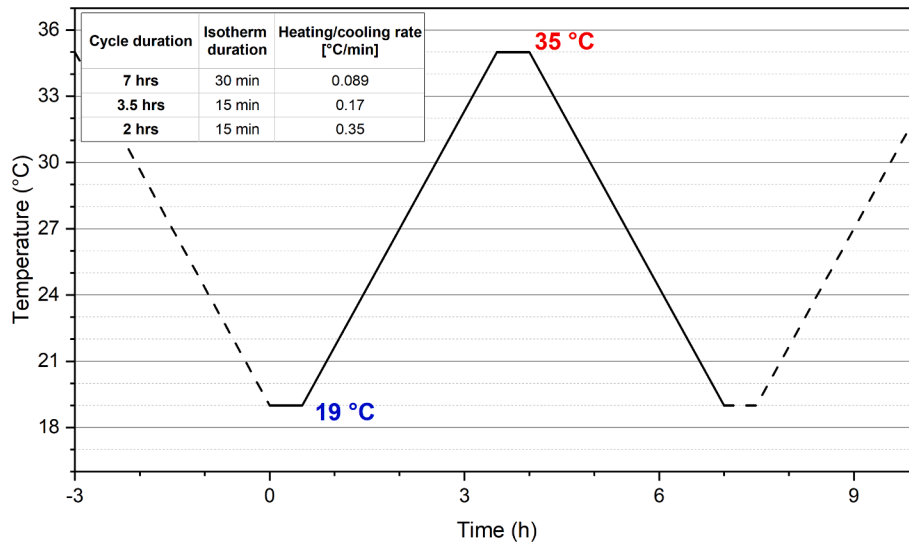


Fig. 3. Temperature profile applied in the climatic chamber for the test lasting 7 h; the cycle parameters of the other tests are also reported.

material to both conduct and store heat [74]. The second term of Eq. (4) corresponds to a phase lag of 45° (3 h in a 24 h period) of the temperature with respect to heat flux [74]. In this work the magnitude of the characteristic admittance was evaluated using λ and c_p values determined at 40°C (see Section 2.3.1). Starting from the c_p values it was also possible to evaluate an important physical property of the boxes involved in the study: the heat capacity, described by Eq. (6):

$$C = c_p \cdot m \quad (6)$$

where c_p [J/g·K] is the specific heat of the material and m [g] is the mass of each specific material within the box.

The temperature values as a function of time were recorded using an Agilent 34970A data acquisition unit equipped with 4PT-100 (four wires) located (i) inside the box, (ii) on the internal wall, (iii) on the external wall, (iv) outside the box (i.e. air temperature in the climatic chamber). Moreover, the heat flux on the external and internal side of the box was measured using heat flux meters (Hukseflux HFP01) with a sensing area of $8 \times 10^{-4} \text{ m}^2$, sensitivity of $60 \times 10^{-6} \text{ V/(W/m}^2\text{)}$ and measurement range from -2000 to $+2000 \text{ W/m}^2$. The sampling interval both for temperature and heat flux was set to 60 s. The heat flux variation $\Delta\varphi$ was evaluated from the difference in the heat fluxes through the external and the internal surfaces of the sample, as shown in Eq. (7):

$$\Delta\varphi = (\varphi_{\text{out}} - \varphi_{\text{in}}) \cdot A \quad (7)$$

where φ_{out} and φ_{in} are the heat fluxes measured on the external and internal wall in $[\text{W/m}^2]$, respectively, and A is the exposed surface of the box equal to $\sim 0.45 \text{ m}^2$.

From the integration of the curve of the heat flux variation as function of time it was possible to determine the stored (negative $\Delta\varphi$ values) and released energy (positive $\Delta\varphi$ values) of the tested samples, as shown in Eq. (8):

$$E = \int_0^t \Delta\varphi(t) dt \quad (8)$$

where E is the stored (o released) energy in [J], $\Delta\varphi$ is heat flux variation in [W] and t is the time in [s]. The specific stored energy E^* [J/m^2] was evaluated considering an exposed surface of the box equal to $\sim 0.45 \text{ m}^2$. A reference period of 24 h was taken as reference for the evaluations.

3. Results and discussion

3.1. Characterization of single components

For a first evaluation of the ability of samples to store heat and for a proper determination of the thermal conductivity, the specific heat of single constituents was determined in a temperature interval from -5 to 40°C , excluding the range of the phase transition in case of E-PCM sample ($10 - 30^\circ\text{C}$ at 2°C/min). From the results shown in Fig. 4 it is possible to observe that the specific heat value of wood is around $1.1 - 1.2 \text{ J/g}\cdot\text{K}$, with small standard deviation values and a limited temperature influence in the selected temperature interval. The reported values are comparable to those reported in the literature (around $1.3 \text{ J/g}\cdot\text{K}$ for dry wood [75]). The values obtained for aerogel are lower with respect to those reported in the literature that are around 0.8 to $1.1 \text{ J/g}\cdot\text{K}$ at 40°C [76,77]; this difference can be explained considering possible differences in the composition of the tested aerogels and due to the different techniques used for the measurement: guarded flat plate in the first case, heat flow meter in the second one and differential scanning calorimetry in this work. For the E-PCM sample it is possible to observe that approaching the phase transition of the PCM (28°C) the specific

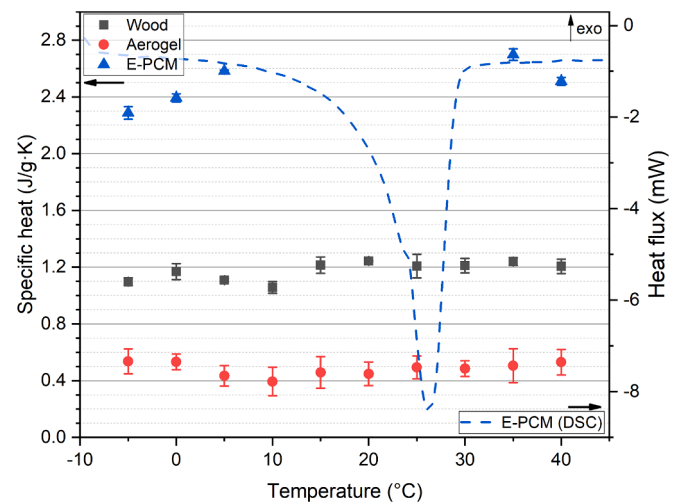


Fig. 4. Specific heat values of single components at 2°C/min and representative DSC curve of E-PCM sample (heating scan at 2°C/min) to identify the phase transition's temperature interval.

heat increases and then decreases when the material is completely molten leading to a strong temperature-dependence. This behaviour could be avoided further decreasing the testing speed in order to narrow the melting peak around the theoretical temperature (not recommended for c_p measurements), or enlarging the temperature range considered for the test far away from phase transitions (not of interest due to the application of the material straddling the melting peak).

From the thermal properties referred to the walls of wood boxes and reported in Table 2 and 3, it is possible to observe a limited influence of temperature on thermal conductivity and thermal resistivity with differences of around 5–7 % between values at 10 °C and at 40 °C. This behaviour is particularly interesting for E-PCM samples because it means that the physical state of the PCM (solid or liquid) does not influence the thermal conductivity of the elastomeric panel. The reference panel is characterized by a thermal conductivity of around 0.073 W/m·K causing an increase of the overall thermal conductivity of the aerogel sample that reaches values of around 0.025 W/m·K with respect to its nominal value of 0.019 W/m·K. E-PCM samples are characterized by values of 0.106 W/m·K in case of 5 mm thick and 0.127 W/m·K in case of 10 mm ones.

3.2. Climatic data simulation and determination of dynamic parameters

Fig. 5(a–d) reports the result of the thermal cycling tests on the prepared boxes in the four considered locations. The reference box without any insulation (Fig. 5a), shows temperature profiles of the internal air and internal wall that overlap the external temperature profiles demonstrating the inability to provide an appreciable insulation with the imposed conditions. In case of E-PCM 5 mm sample (Fig. 5c) it is possible to observe a limited beneficial effect due to the presence of the PCM: for two locations (Trento and Roma) the maximum temperatures are decreased of around 2 and 1 °C, respectively, in comparison to the reference (see Table 4). The E-PCM 10 mm sample, instead, shows outstanding properties with the maximum temperature that is up to 5 °C lower with respect to the reference sample and the peak maximum delayed of around 4–6 h with respect to the external temperature peak. The profile of the heat fluxes on the external side of the boxes is representative of the temperature situation on the internal one: in the reference box, due to the coincidence of internal and external temperature the heat flux is almost null, while it is maximized due to the presence of the PCM that creates a noticeable temperature difference between the internal and external side of the box in case of E-PCM samples that are characterized by values up to 30 W/m². Due to the limited temperature difference between the internal wall and the internal air, the heat flux on the internal side is very limited.

Interestingly, the aerogel insulation (Fig. 5b), despite its low thermal conductivity, is unable to provide any benefit to the insulation of the wood box in dynamic conditions. This behaviour can be explained looking at the results of dynamic properties reported in Table 5: it is possible to observe that the time lag Φ of the E-PCM 10 mm samples reaches values as high as 3 h with a decrement factor f of 0.42 that result much better with respect to those of the aerogel that is characterized by

Table 2
Thermal properties of the insulated walls at 10 °C.

Sample	λ_{10} [W/m·K]	R^*_{10} [m ² ·K/W]	c_{p-10} [J/g·K]
Ref	0.073 ± 0.003	0.064 ± 0.001	1.057 ± 0.041
Aerogel	0.025 ± 0.001	0.733 ± 0.007	0.698 ± 0.057
E-PCM 5 mm	0.106 ± 0.002	0.120 ± 0.001	2.148 ^a ± 0.013
E-PCM 10 mm	0.127 ± 0.002	0.162 ± 0.002	2.329 ^a ± 0.009

Note: values referred to the insulated wall of testing boxes (i.e. wood + insulator). In case of c_p a weighted average between values measured for wood and insulator was performed according to mass values in Table 1 and c_p of Fig. 4. ^a values obtained at 5 °C, please refer to Fig. 4. λ : thermal conductivity, R : specific thermal resistance, c_p : specific heat.

Table 3
Thermal properties of the insulated walls at 40 °C.

Sample	λ_{40} [W/m·K]	R^*_{40} [m ² ·K/W]	c_{p-40} [J/g·K]
Ref	0.079 ± 0.003	0.059 ± 0.001	1.206 ± 0.051
Aerogel	0.026 ± 0.001	0.706 ± 0.007	0.839 ± 0.054
E-PCM 5 mm	0.112 ± 0.002	0.115 ± 0.001	2.139 ± 0.025
E-PCM 10 mm	0.136 ± 0.002	0.152 ± 0.002	2.294 ± 0.025

Note: values referred to the insulated wall of testing boxes (i.e. wood + insulator). In case of c_p a weighted average between values measured for wood and insulator was performed according to mass values in Table 1 and c_p of Fig. 4. λ : thermal conductivity, R : specific thermal resistance, c_p : specific heat.

a time lag of 0.5 h and by a decrement factor of 0.94. The magnitude of characteristic admittance values reported in Tables 5 (around 0.7 W/m²K for aerogel and 1.7 W/m²K for wood), albeit not considering the presence of the PCM, provide an explanation for the behaviour of the aerogel insulation that, due to the low density, low specific heat and limited mass is not able to store heat and to impede the propagation of the heat wave with completely different behaviour with respect to that observed under steady-state conditions during the thermal conductivity test. This behaviour, as observed by Asan, can be explained due to the fact that time lag and decrement factor are not only influenced by the thermal conductivity of the material, but also by the specific heat, by the density and by the thickness of the insulating layer, in other word by its heat capacity [59]. In the specific case of this study, as reported in Table 5, the heat capacity of E-PCM 10 mm sample (13.3 MJ/K) is 6 times higher with respect to that of the aerogel sample. Using a mechanical equivalent, the mass of a building is representative of another property that can be described as *thermal inertia* [78]. The same was also observed by Aste et al. that, comparing materials characterized by same thermal transmittance but different thermal inertia, reported significant differences in terms of energy demand, up to 10 % in heating and 20 % in cooling [79]. Looking at the traditional architecture of the Mediterranean region, the concept of thermal inertia is perfectly represented by the presence of massive buildings that impede large temperature variations of the internal air with a beneficial effect on the occupants comfort during the hot season [80].

In this study the thickness of the insulation layer was very limited and this explains the low f and short Φ values found for the Ref and for the Aerogel box but clearly demonstrates the efficacy of the PCM in improving the thermal inertia and the dynamic thermal insulation properties of the walls.

Looking at the heat flux variation as function of time shown in Fig. 6 it is possible to appreciate the different thermal behaviour of the four boxes: the presence of PCM causes the formation of a shoulder in the heat flux profile occurring at the same time of the peak maximum recorded for the Ref and Aerogel boxes while the peak, corresponding to the maximum temperature difference between the internal and external air is reached few hours later. The negative values of the heat flux variations correspond to negative heat flux values recorded on the external side of the boxes during the hottest hours of the day and mean that there is a heat flux from the environment to the wall that is cold due to the PCM at solid state that is melting with an endothermic reaction. The highest absolute values of heat flux variation are recorded in Verona and Trento due to the large thermal excursions between day and night (18–32 °C, see Fig. 2) that maximize the efficacy of the PCM, while the lowest in Palermo due to the very limited thermal excursion between day and night (25–30 °C, see Fig. 2) that does not allow, in the coldest hours of the night, the complete crystallization of the PCM. As shown in Fig. S2 during tests at 1 °C/min, the PCM completely crystallizes at 18 °C; at much lower cooling rates, like in this work (see Fig. 2), the crystallization temperature is probably around 25 °C as it also possible to observe from the plateau during cooling of E-PCM 5 mm curves in Fig. 5c. From the values of the stored energy obtained integrating the negative portion of the heat flux variation curves and reported in

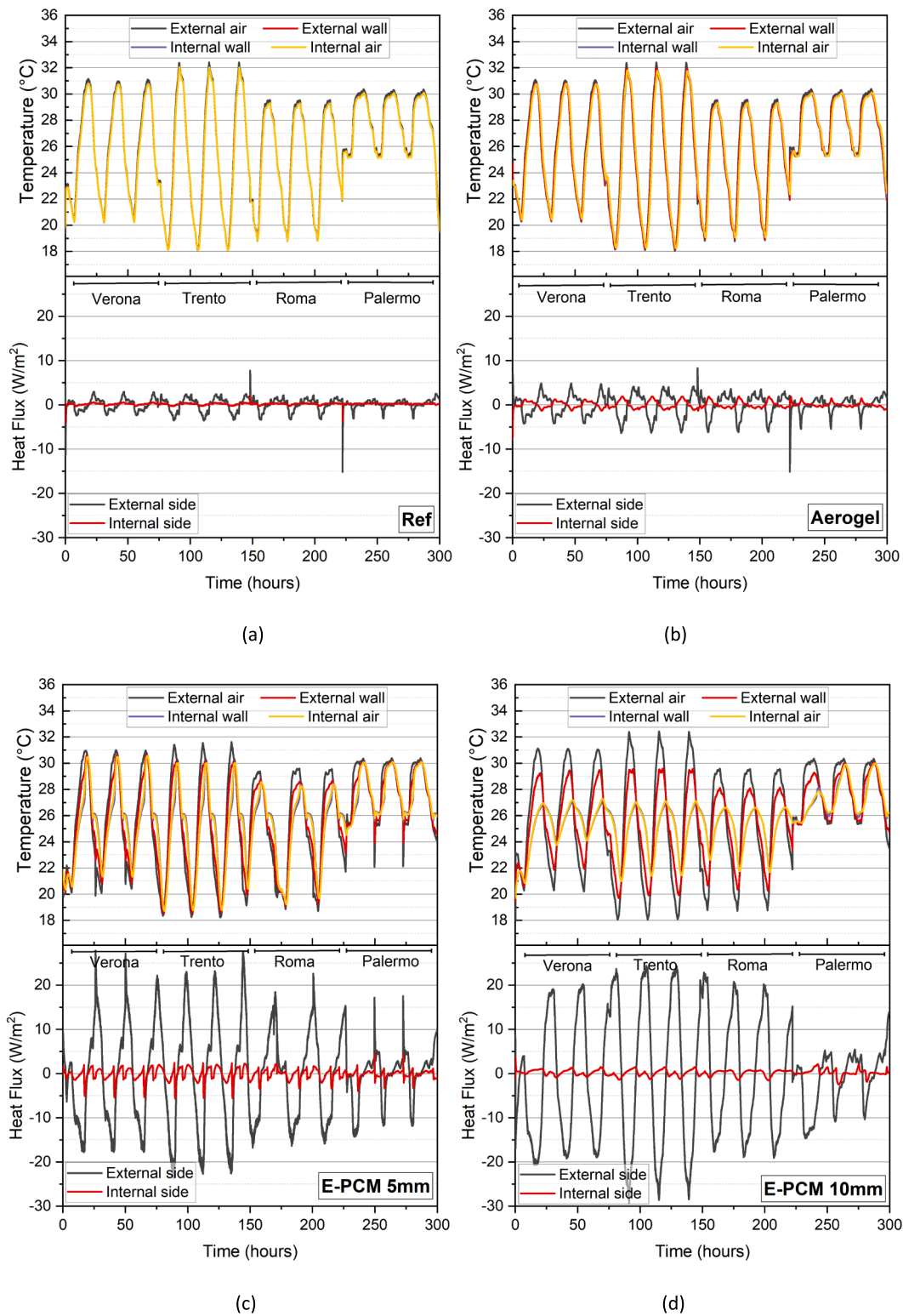


Fig. 5. Evaluation of the thermal energy storage capability at different latitudes of the test boxes with different insulations: (a) Ref, (b) Aerogel, (c) E-PCM 5 mm, (d) E-PCM 10 mm.

Table 6, it is possible to observe that the largest amount of stored energy occurs for the location where the largest temperature variations between day and night are recorded (Trento) allowing a complete crystallization of the PCM during the night period and the maximum efficacy during the day. The stored energy, evaluated over a period of 24 h, ranges from 131 to 333 kJ for the E-PCM10, corresponding to a specific stored energy of

290 to 741 kJ/m², similar to the values estimated through numerical models by Tunçbilek et al. for insulating PCM panels with the same thickness [81]. Starting from the melting enthalpy associated to the phase transition of the PCM (96.7 kJ/kg, see Table S1) it is possible to estimate a total amount of energy involved in the phase transition of the E-PCM 10 mm box of around 510 kJ (6.28 kg – 1.3 kg (mass of the wood)

Table 4

Results of the temperature monitoring tests on the prepared boxes.

Box	Verona		Trento	
	$T_{air,max}$ [°C]	$t_{Tair,max}$ [hr]	$T_{air,max}$ [°C]	$t_{Tair,max}$ [hr]
Ref	30.8 ± 0.1	22.1 ± 3.2	32.0 ± 0.1	24.3 ± 0.6
Aerogel	30.7 ± 0.1	22.8 ± 3.4	31.8 ± 0.1	25.5 ± 0.5
E-PCM 5 mm	30.5 ± 0.1	23.3 ± 3.2	30.0 ± 0.1	23.8 ± 1.4
E-PCM 10 mm	27.1 ± 0.2	26.2 ± 3.6	27.1 ± 0.1	30.2 ± 0.7

Box	Roma		Palermo	
	$T_{air,max}$ [°C]	$t_{Tair,max}$ [hr]	$T_{air,max}$ [°C]	$t_{Tair,max}$ [hr]
Ref	29.3 ± 0.1	24.3 ± 0.4	30.1 ± 0.1	25.1 ± 1.8
Aerogel	29.3 ± 0.1	24.5 ± 0.4	30.1 ± 0.1	25.5 ± 1.7
E-PCM 5 mm	28.4 ± 0.2	24.8 ± 4.6	30.1 ± 0.1	25.8 ± 2.7
E-PCM 10 mm	26.6 ± 0.1	28.7 ± 0.3	29.2 ± 1.2	27.1 ± 3.4

$T_{air,max}$: maximum internal air temperature, $t_{Tair,max}$: time at which the maximum internal air temperature is reached.

Table 5

Heat capacity and dynamic thermal parameters of the prepared boxes.

Box	C [MJ/K]	a [W/m ² ·K]	ϕ [hr]	f [-]
Ref	1.2 ± 0.05 ^a	1.73 ± 0.05 ^b	0.05 ± 0.04	0.97 ± 0.01
Aerogel	2.3 ± 0.05 ^a	0.70 ± 0.03 ^b	0.49 ± 0.21	0.94 ± 0.02
E-PCM 5 mm	6.9 ± 0.03 ^a	3.58 ± 0.06 ^b	0.61 ± 0.31	0.75 ± 0.15
E-PCM 10 mm	13.3 ± 0.02 ^a	4.26 ± 0.07 ^b	3.03 ± 1.19	0.42 ± 0.20

^a heat capacity (C) evaluated using c_p values determined at 40 °C and listed in Table 3.

^b magnitude of characteristic admittance values (a) evaluated using λ and c_p values determined at 40 °C and listed in Table 3. ϕ : time lag, f: decrement factor.

* 96.7 kJ/kg). This value is quite lower with respect to the maximum energy stored by this panel in Trento and this may be related to an oversizing of the E-PCM insulation that leads to an incomplete use of the PCM during the cycle. On the contrary, in case of E-PCM 5 mm box, due to the lower PCM amount fully involved in the phase transition, the difference between the theoretical value (253 kJ) and the maximum recorded during the test (191 kJ in Trento) is more limited.

The second part of this work was devoted to the study of the influence of thermal cycles' length on the TES efficacy of PCMs. The temperature profiles recorded for Aerogel and E-PCM 5 mm boxes during

tests with cycles of 7, 3.5 and 2 h are shown in Figs. 7–9, while the results are listed in Tables 7–9, respectively. The results of Ref and E-PCM 10 mm are reported in Figs. S3–S5 for the sake of brevity.

The 7-hours test is characterized by optimum conditions for the E-PCM 5 mm sample whose temperatures remain included between 26 and 32 °C with a reduction with respect of the imposed temperature of around 4 °C. From the temperature profile of the Aerogel box it is possible to appreciate the first difference with respect to Fig. 5b: due to the shorter duration of the cycle, the insulation ability of aerogel – despite the low air volume inside the box – is able to keep the internal temperature approximately 1.5 °C lower with respect to the outer. This is also demonstrated by the higher heat flux values that reach values of around 10 W/m² (30 W/m² for the E-PCM 5 mm). With a duration of 3.5 h it is possible to observe an additional reduction of the temperature oscillations for the E-PCM 5 mm sample that is now limited within 26 and 30 °C and also for the Aerogel whose maximum temperature does not exceed 32 °C. The fastest tests (Fig. 9) are characterized by very limited temperature variations in the E-PCM 5 mm sample (less than 4 °C) with an evident inability of the PCM to completely melt and crystallize due to its low thermal conductivity that does not allow a fast

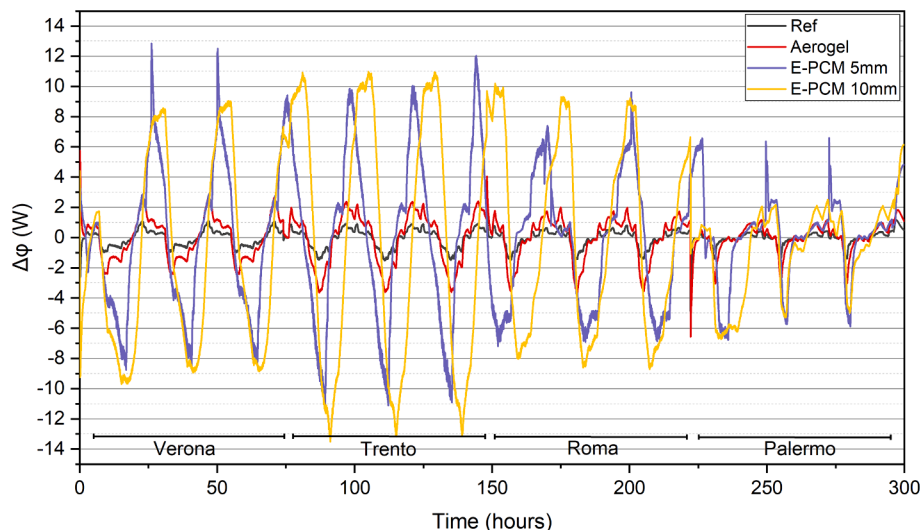
Table 6

Daily stored energy in the prepared boxes.

Box	Verona		Trento	
	E [kJ]	E* [kJ/m ²]	E [kJ]	E* [kJ/m ²]
Ref	22.2 ± 0.6	49.3 ± 1.4	27.8 ± 0.6	61.8 ± 1.4
Aerogel	54.6 ± 0.4	121.4 ± 0.9	69.9 ± 0.7	155.4 ± 1.5
E-PCM 5 mm	179.0 ± 13.1	397.8 ± 29.2	190.9 ± 0.9	424.2 ± 1.9
E-PCM 10 mm	285.0 ± 27.7	633.3 ± 61.6	333.6 ± 7.8	741.4 ± 17.3

Box	Roma		Palermo	
	E [kJ]	E* [kJ/m ²]	E [kJ]	E* [kJ/m ²]
Ref	21.5 ± 0.4	47.7 ± 1.0	14.7 ± 3.3	32.7 ± 7.3
Aerogel	56.3 ± 5.6	125.0 ± 12.4	24.5 ± 0.3	54.5 ± 0.7
E-PCM 5 mm	175.4 ± 7.9	389.7 ± 17.6	74.8 ± 36.0	166.2 ± 80.0
E-PCM 10 mm	235.2 ± 11.3	522.7 ± 25.0	130.9 ± 110.5	290.8 ± 245.7

E: stored energy, E*: specific stored energy.

**Fig. 6.** Heat flux variation as function of time in the prepared boxes.

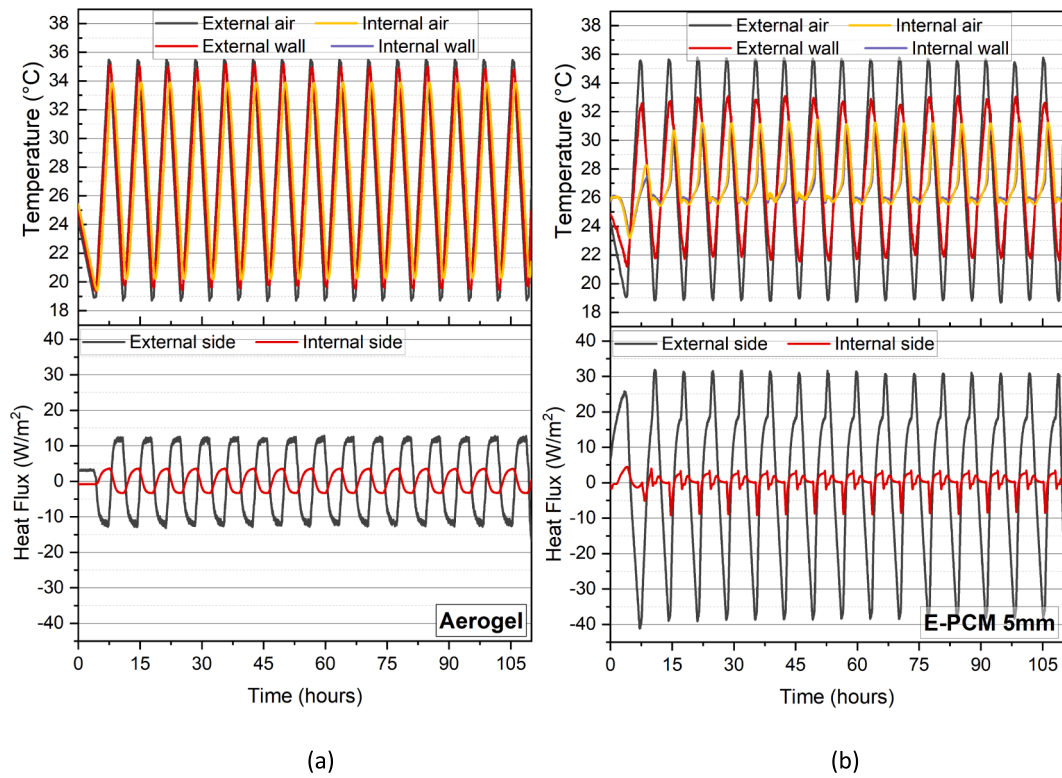


Fig. 7. Evaluation of the thermal energy storage capability during 7-hours cycles of (a) Aerogel, (b) E-PCM 5 mm test boxes.

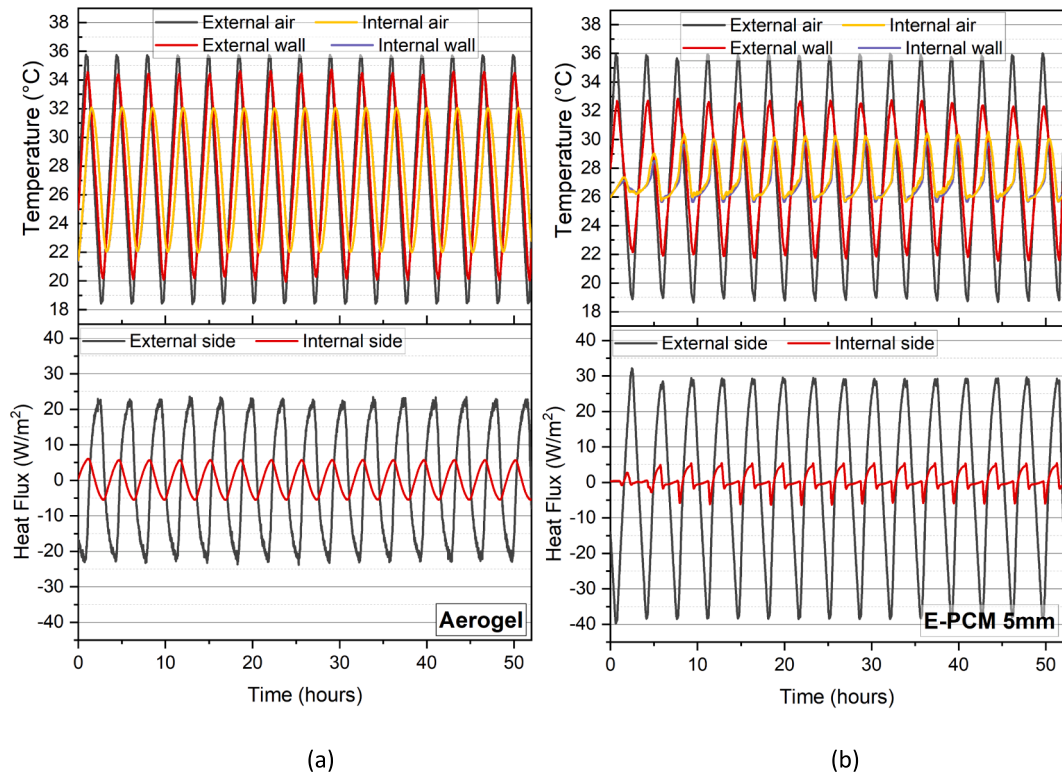


Fig. 8. Evaluation of the thermal energy storage capability during 3.5-hours cycles of (a) Aerogel, (b) E-PCM 5 mm test boxes.

response upon very rapid temperature variations. This behaviour is even clearer looking at the curves obtained for the E-PCM 10 mm sample (Figs. S3–S5): only a minimum amount of PCM is able to complete its cycle with reduced efficacy with respect to slower tests.

From the results summarized in Tables 7–9 it is possible to observe that reducing the cycles duration there is a reduction of the temperature difference between the E-PCM and the Ref due to the limited heat dispersion caused by the rapidity of the test. Moreover, comparing the

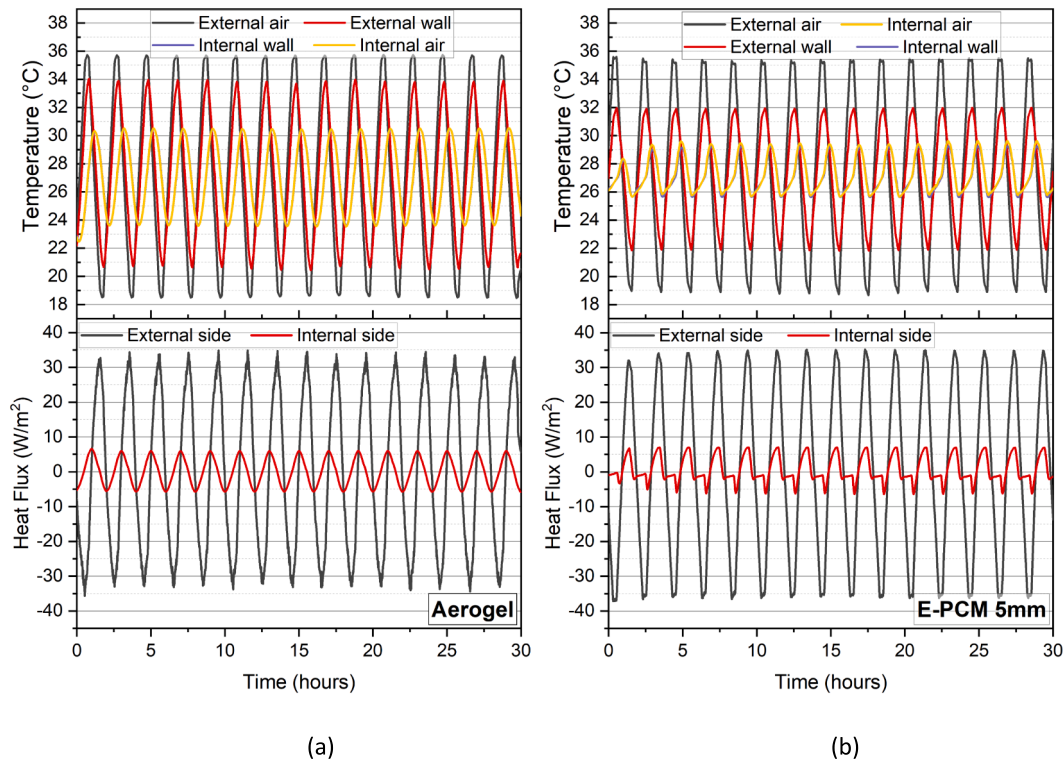


Fig. 9. Evaluation of the thermal energy storage capability during 2-hours cycles of (a) Aerogel, (b) E-PCM 5 mm test boxes.

Table 7

Results of thermal energy storage capability tests with duration of 7 h.

Box	$T_{air,max}$ [°C]	$T_{air,min}$ [°C]	φ [hr]	f [-]
Aerogel	33.9 ± 0.1	20.2 ± 0.1	0.46 ± 0.16	0.82 ± 0.01
E-PCM 5 mm	31.0 ± 0.7	25.6 ± 0.1	1.11 ± 0.16	0.32 ± 0.04
Δ	-2.9	$+5.3$	$+0.65$	-0.50

$T_{air,max}$: maximum internal air temperature, $T_{air,min}$: minimum internal air temperature, φ : time lag, f : decrement factor.

Table 8

Results of thermal energy storage capability tests with duration of 3.5 h.

Box	$T_{air,max}$ [°C]	$T_{air,min}$ [°C]	φ [hr]	f [-]
Aerogel	32.0 ± 0.1	22.1 ± 0.1	0.50 ± 0.07	0.58 ± 0.01
E-PCM 5 mm	30.2 ± 0.3	25.9 ± 0.1	0.66 ± 0.10	0.25 ± 0.02
Δ	-1.8	$+3.8$	$+0.16$	-0.28

$T_{air,max}$: maximum internal air temperature, $T_{air,min}$: minimum internal air temperature, φ : time lag, f : decrement factor.

Table 9

Results of thermal energy storage capability tests with duration of 2 h.

Box	$T_{air,max}$ [°C]	$T_{air,min}$ [°C]	φ [hr]	f [-]
Aerogel	30.5 ± 0.1	23.6 ± 0.1	0.41 ± 0.02	0.40 ± 0.01
E-PCM 5 mm	29.4 ± 0.3	25.8 ± 0.1	0.36 ± 0.05	0.22 ± 0.02
Δ	-1.1	$+2.2$	-0.05	-0.18

$T_{air,max}$: maximum internal air temperature, $T_{air,min}$: minimum internal air temperature, φ : time lag, f : decrement factor.

time lag and decrement factor values, it is also possible to observe a decrease in the gap between the two samples increasing the testing speed. In particular this decrease is much more evident for time lag

values because, as observed by Asan, while decrement factor is mainly affected by the heat capacity, the time lag is influenced both by heat capacity and thermal conductivity [59]. This test also demonstrates that the selected amount of PCM is appropriate for cycles with minimum duration of 7 h; for shorter tests the amount of PCM should be decreased or its thermal conductivity enhanced in order to avoid the under-exploitation of its performances.

Finally, from the admittance values as function of time, evaluated considering a period length corresponding to the tests presented in this work (24, 7, 3.5 and 2 h) and shown in Fig. 10, it is interesting to notice that, decreasing the period of the temperature cycle, the admittance values increases and in particular, the gap between light and massive

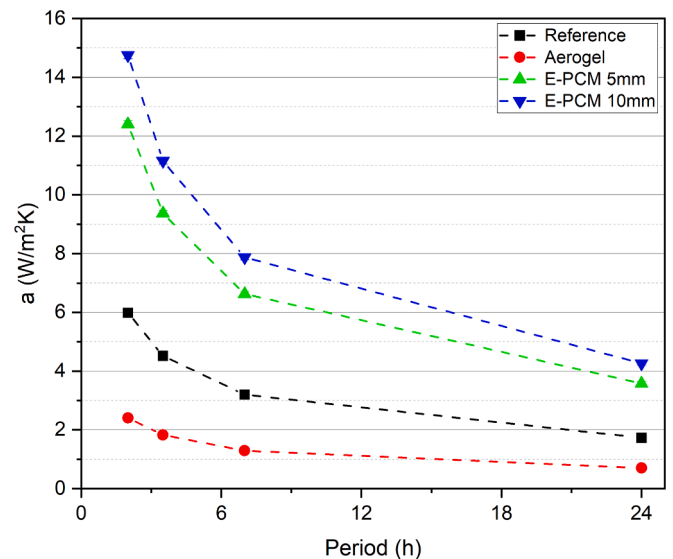


Fig. 10. Magnitude of the characteristic admittance for the materials of testing boxes at different period durations (24, 7, 3.5 and 2 h) at 40 °C.

samples increases: this means that the faster the temperature variation, the highest is the efficacy of materials with high thermal inertia in minimizing the propagation of the heat wave.

4. Conclusions

In this study the thermal management ability of E-PCM panels used for the thermal insulation of testing boxes was studied under dynamic conditions: time lag, decrement factor, characteristic admittance and stored energy were determined simulating the summer conditions of four different Italian locations. The presence of PCM in the insulating material was able to limit the internal temperature at 27 °C (external temperature ~33 °C) for three of the four studied locations (Verona, Trento and Roma) with a maximum delay in the peak temperature of 6 h. According to the results it was observed that the largest benefits due to the PCM addition in the wall were recorded for the city of Trento due to the large temperature variation between day and night. The dynamic properties showed a decrement factor of 0.4 and a time lag of around 3 h with an evaluated daily thermal energy storage capability of around 741 kJ/m² for the E-PCM 10 mm testing box. The comparison with a commercial material (Aerogel), showed that despite its very low thermal conductivity, it has limited efficacy because thermal insulation during summer conditions is dominated by the heat capacity of materials. For this reason, massive materials (characterized by high characteristic admittance values, such as E-PCM panels – that also combine the intrinsic ability to store heat due to the presence of phase change material) show much better properties with respect to light and highly insulating ones. The evaluation of the behaviour of the E-PCM boxes at different cycles length in a temperature range between 19 and 35 °C showed that the optimum behaviour of E-PCM is recorded with a cycle length of 7 h, faster cycles result in a very limited temperature variation due to the high amount of phase change material that, also due to the low thermal conductivity, is unable to completely melt and crystallize. Future work will be devoted to consider the role of humidity for improving the simulation, to study the thermal properties of E-PCM panels in a real wall design, and to develop highly-conductive materials suitable for fast-response applications (e.g. electronics).

CRediT authorship contribution statement

Francesco Valentini: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maurizio Grigianti:** Writing – review & editing, Writing – original draft, Validation, Methodology. **Alessandro Prada:** Methodology, Conceptualization. **Luca Fambri:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Andrea Dorigato:** Writing – review & editing, Supervision. **Alessandro Pegoretti:** Methodology, Conceptualization.

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.

Acknowledgements

This work was partially funded by Provincia Autonoma di Trento (Italy) through Legge 6/99, project “Compositi elastomerici a transizione di fase [E-PCM] prat. n. 23-16”. Dr. Sereno Sacchet is gratefully acknowledged for the support in the experimental work and for the fruitful discussions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enbuild.2024.114503>.

References

- [1] M. Haller, S. Ludig, N. Bauer, Decarbonization scenarios for the EU and MENA power system: Considering spatial distribution and short term dynamics of renewable generation, *Energy Policy* 47 (2012) 282–290.
- [2] European Commission. REPowerEU. 2023 Visited on 02/02/2024; Available from: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_it.
- [3] International Energy Agency. RePowerEU Plan : Joint European action on renewable energy and energy efficiency. 2023 Visited on 02/02/2024; Available from: <https://www.iea.org/policies/15691-repower-eu-plan-joint-european-action-on-renewable-energy-and-energy-efficiency>.
- [4] International Energy Agency. *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*. 2013 Available from: <https://www.iea.org/reports/transition-to-sustainable-buildings>.
- [5] U. Berardi, A cross-country comparison of the building energy consumptions and their trends, *Resour. Conserv. Recycl.* 123 (2017) 230–241.
- [6] H. Wan, T. Cao, Y. Hwang, R. Radermacher, S.O. Andersen, S. Chin, A comprehensive review of life cycle climate performance (LCCP) for air conditioning systems, *Int. J. Refrig* 130 (2021) 187–198.
- [7] L. Xu, L. Dai, L. Yin, X. Sun, W. Xu, R. Yang, X. Wang, Y. Zhang, Research on the climate response of variable thermo-physical property building envelopes: A literature review, *Energ. Buildings* 226 (2020) 110398.
- [8] International Energy Agency. *Global Status Report for Buildings and Construction: towards a zero-emissions, efficient and resilient buildings and construction sector*. 2019; Available from: <https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019>.
- [9] International Energy Agency. *Net Zero by 2050*. 2021; Available from: <https://www.iea.org/reports/net-zero-by-2050>.
- [10] Y.B. Tao, Y.-L. He, A review of phase change material and performance enhancement method for latent heat storage system, *Renew. Sustain. Energy Rev.* 93 (2018) 245–259.
- [11] H. Jouhara, A. Żabnieńska-Góra, N. Khordeghah, D. Ahmad, T. Lipinski, Latent thermal energy storage technologies and applications: A review, *Int. J. Thermofluids* 5–6 (2020) 100039.
- [12] A. Adesina, Use of phase change materials in concrete: current challenges, *Renew. Energy Environ. Sustain.* (2019) 4.
- [13] A. D'Alessandro, A.L. Pisello, C. Fabiani, F. Ubertini, L.F. Cabeza, F. Cotana, Multifunctional smart concretes with novel phase change materials: Mechanical and thermo-energy investigation, *Appl. Energy* 212 (2018) 1448–1461.
- [14] P. Sukontasukkul, T. Sutthiphasilp, W. Chalodhorn, P. Chindaprasit, Improving thermal properties of exterior plastering mortars with phase change materials with different melting temperatures: paraffin and polyethylene glycol, *Adv. Build. Energy Res.* 13 (2) (2019) 220–240.
- [15] M. Kheradmand, M. Azenha, J.L.B. de Aguiar, J. Castro-Gomes, Experimental and numerical studies of hybrid PCM embedded in plastering mortar for enhanced thermal behaviour of buildings, *Energy* 94 (2016) 250–261.
- [16] M.J. Abden, Z. Tao, Z. Pan, L. George, R. Wührer, Inclusion of methyl stearate/diatomite composite in gypsum board ceiling for building energy conservation, *Appl. Energy* 259 (2020) 114113.
- [17] X. Wang, H. Yu, L. Li, M. Zhao, Experimental assessment on the use of phase change materials (PCMs)-bricks in the exterior wall of a full-scale room, *Energ. Convers. Manage.* 120 (2016) 81–89.
- [18] J. Košný, K. Biswas, W. Miller, S. Kriner, Field thermal performance of naturally ventilated solar roof with PCM heat sink, *Sol. Energy* 86 (9) (2012) 2504–2514.
- [19] K.A.R. Ismail, C.T. Salinas, J.R. Henriquez, Comparison between PCM filled glass windows and absorbing gas filled windows, *Energ. Buildings* 40 (5) (2008) 710–719.
- [20] R. Baetens, B.P. Jelle, A. Gustavsen, Phase change materials for building applications: A state-of-the-art review, *Energ. Buildings* 42 (9) (2010) 1361–1368.
- [21] L. Navarro, A. de Gracia, D. Niall, A. Castell, M. Browne, S. McCormack, P. Griffiths, L.F. Cabeza, Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system, *Renew. Energy* 85 (2016) 1334–1356.
- [22] L.F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, A.I. Fernández, Materials used as PCM in thermal energy storage in buildings: A review, *Renew. Sustain. Energy Rev.* 15 (3) (2011) 1675–1695.
- [23] Z. Pavlík, J. Fořt, M. Pavlíková, J. Pokorný, A. Trnčík, R. Černý, Modified lime-cement plasters with enhanced thermal and hygric storage capacity for moderation of interior climate, *Energ. Buildings* 126 (2016) 113–127.
- [24] M.I. Nizovtsev, A.N. Sterlyagov, Effect of phase change material (PCM) on thermal inertia of walls in lightweight buildings, *J. Build. Eng.* 82 (2024) 107912.
- [25] E. Oró, L. Miró, M.M. Farid, L.F. Cabeza, Improving thermal performance of freezers using phase change materials, *Int. J. Refrig* 35 (4) (2012) 984–991.
- [26] T. Khadiran, M.Z. Hussein, Z. Zainal, R. Rusli, Encapsulation techniques for organic phase change materials as thermal energy storage medium: A review, *Sol. Energy Mater. Sol. Cells* 143 (2015) 78–98.

- [27] P. Schossig, H. Henning, S. Gschwander, T. Haussmann, Micro-encapsulated phase-change materials integrated into construction materials, *Sol. Energy Mater. Sol. Cells* 89 (2–3) (2005) 297–306.
- [28] S. Phadungphatthanakoon, S. Poompradub, S.P. Wanichwecharungruang, Increasing the thermal storage capacity of a phase change material by encapsulation: preparation and application in natural rubber, *Appl. Mater. Interfaces* 3 (9) (2011) 3691–3969.
- [29] C. Alkan, K. Kaya, A. Sari, Preparation, thermal properties and thermal reliability of form-stable paraffin/polypropylene composite for thermal energy storage | SpringerLink, *J. Polym. Environ.* 17 (2009) 254.
- [30] W.-I. Cheng, R.-M. Zhang, K. Xie, N. Liu, J. Wang, Heat conduction enhanced shape-stabilized paraffin/HDPE composite PCMs by graphite addition: Preparation and thermal properties, *Sol. Energy Mater. Sol. Cells* 94 (10) (2010) 1636–1642.
- [31] A. Zambotti, E. Caldesi, M. Pellizzari, F. Valentini, A. Pegoretti, A. Dorigato, G. Speranza, K. Chen, M. Bortolotti, G.D. Sorarù, M. Biesuz, Polymer-derived silicon nitride aerogels as shape stabilizers for low and high-temperature thermal energy storage, *J. Eur. Ceram. Soc.* 41 (11) (2021) 5484–5494.
- [32] M. Xiao, B. Feng, K. Gong, Preparation and performance of shape stabilized phase change thermal storage materials with high thermal conductivity, *Energ. Convers. Manage.* 43 (1) (2002) 103–108.
- [33] A. Sari, Form-stable paraffin/high density polyethylene composites as solid-liquid phase change material for thermal energy storage: preparation and thermal properties, *Energ. Convers. Manage.* 45 (13–14) (2004) 2033–2042.
- [34] K. Pielichowska, K. Pielichowski, Phase change materials for thermal energy storage, *Prog. Mater. Sci.* 65 (2014) 67–123.
- [35] G. Fang, F. Tang, L. Cao, Preparation, thermal properties and applications of shape-stabilized thermal energy storage materials, *Renew. Sustain. Energy Rev.* 40 (2014) 237–259.
- [36] V. Chinnasamy, J. Heo, S. Jung, H. Lee, H. Cho, Shape stabilized phase change materials based on different support structures for thermal energy storage applications—A review, *Energy* 262 (2023) 125463.
- [37] C. Cárdenas-Ramírez, M.A. Gómez, F. Jaramillo, A.F. Cardona, A.G. Fernández, L. F. Cabeza, Experimental steady-state and transient thermal performance of materials for thermal energy storage in building applications: From powder SS-PCMs to SS-PCM-based acrylic plaster, *Energy* 250 (2022) 123768.
- [38] Y. Zhang, Z. Jia, A. Moqet Hai, S. Zhang, B. Tang, Shape-stabilization micromechanisms of form-stable phase change materials—A review, *Compos. A Appl. Sci. Manuf.* 160 (2022) 107047.
- [39] S. Zhang, D. Feng, L. Shi, L. Wang, Y. Jin, L. Tian, Z. Li, G. Wang, L. Zhao, Y. Yan, A review of phase change heat transfer in shape-stabilized phase change materials (ss-PCMs) based on porous supports for thermal energy storage, *Renew. Sustain. Energy Rev.* 135 (2021) 110127.
- [40] K. Liu, Z.F. Yuan, H.X. Zhao, C.H. Shi, F. Zhao, Properties and applications of shape-stabilized phase change energy storage materials based on porous material support—A review, *Mater. Today Sustain.* 21 (2023) 100336.
- [41] Q. He, W.N. Zhang, A Study on latent heat storage exchangers with the high temperature phase change material, in: A.A.M. Sayigh (Ed.), *World Renewable Energy Congress VI*, Pergamon, Oxford, 2000, pp. 1044–1047.
- [42] W. Chalco-Sandoval, M.J. Fabra, A. López-Rubio, J.M. Lagaron, Optimization of solvents for the encapsulation of a phase change material in polymeric matrices by electro-hydrodynamic processing of interest in temperature buffering food applications, *Eur. Polym. J.* 72 (2015) 23–33.
- [43] V. Shringi, S. Kothari, N.L. Panwar, Experimental investigation of drying of garlic clove in solar dryer using phase change material as energy storage, *J. Therm. Anal. Calorim.* 118 (1) (2014) 533–539.
- [44] F. Valentini, A. Dorigato, L. Fambri, M. Bersani, M. Grigante, A. Pegoretti, Production and characterization of novel EPDM/NBR panels with paraffin for potential thermal energy storage applications, *Therm. Sci. Eng. Progr.* 32 (2022).
- [45] A.R. Abdulmunem, N.F. Hussein, P.M. Samin, K. Sopian, H.A. Hussien, H. Ghazali, Integration of recycled waste paper with phase change material in building enclosure, *J. Storage Mater.* 64 (2023) 107140.
- [46] Y. Sun, S. Wang, F. Xiao, D. Gao, Peak load shifting control using different cold thermal energy storage facilities in commercial buildings: A review, *Energ. Convers. Manage.* 71 (2013) 101–114.
- [47] S.E. Kalnæs, B.P. Jelle, Phase change materials and products for building applications: A state-of-the-art review and future research opportunities, *Energ. Buildings* 94 (2015) 150–176.
- [48] S. Liu, J. Wang, L. Meng, C. Hu, X. Meng, Location of the phase-change material layer on thermal performance of light-weight walls, *Int. J. Low-Carbon Technol.* 19 (2024) 127–134.
- [49] X. Jin, M.A. Medina, X. Zhang, On the importance of the location of PCMs in building walls for enhanced thermal performance, *Appl. Energy* 106 (2013) 72–78.
- [50] X. Jin, M.A. Medina, X. Zhang, Numerical analysis for the optimal location of a thin PCM layer in frame walls, *Appl. Therm. Eng.* 103 (2016) 1057–1063.
- [51] X. Jin, D. Shi, M.A. Medina, X. Shi, X. Zhou, X. Zhang, Optimal location of PCM layer in building walls under Nanjing (China) weather conditions, *J. Therm. Anal. Calorim.* 129 (3) (2017) 1767–1778.
- [52] Q. Al-Yasiri, M. Szabó, Building envelope-combined phase change material and thermal insulation for energy-effective buildings during harsh summer: Simulation-based analysis, *Energy Sustain. Dev.* 72 (2023) 326–339.
- [53] F. Valentini, L. Fambri, A. Dorigato, A. Pegoretti, Production and characterization of TES-EPDM foams with paraffin for thermal management applications, *Front. Mater.* 8 (2021) 101.
- [54] Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto. Dati meteorologici ultimi anni. 2022 Visited on 13/01/2023; Available from: <https://wwwold.arpa.veneto.it/>.
- [55] Meteotrentino. Archivio dei dati storici. 2022 Visited on 13/01/2023; Available from: <http://storico.meteotrentino.it/web.htm?ppbm=T0454&rs&l&df>.
- [56] Servizio integrato agrometeorologico Regione Lazio. Misura della temperatura rilevata con frequenza oraria. 2022 Visited on 13/01/2023; Available from: <https://www.siarl-lazio.it/E7.asp>.
- [57] Istituto Nazionale di Astrofisica. Osservatorio Astronomico di Palermo “G.S. Vaiana”. 2022 Visited on 13/01/2023; Available from: <http://meteo.astropa.unipa.it/public/>.
- [58] P. Arumugam, V. Ramalingam, P. Vellaichamy, Effective PCM, insulation, natural and/or night ventilation techniques to enhance the thermal performance of buildings located in various climates – A review, *Energ. Buildings* 258 (2022) 111840.
- [59] H. Asan, Numerical computation of time lags and decrement factors for different building materials, *Build. Environ.* 41 (5) (2006) 615–620.
- [60] M.G. Davies, The thermal response of an enclosure to periodic excitation: The CIBSE approach, *Build. Environ.* 29 (2) (1994) 217–235.
- [61] Milbank, N.O., J. Harrington-Lynn, and *Thermal Response and the Admittance Procedure*. 1974.
- [62] International Standard Organisation, *ISO 13786:2017 Thermal performance of building components. Dynamic thermal characteristics. Calculation methods*. 2017.
- [63] G.M. Soret, P. Vacca, J. Tignard, J.P. Hidalgo, C. Maluk, M. Aitchison, J.L. Torero, Thermal inertia as an integrative parameter for building performance, *J. Build. Eng.* 33 (2021) 101623.
- [64] Davies, M.G., *Building Heat Transfer*. 2004, Chichester, England: John Wiley & Sons.
- [65] S. Szokolay, *Introduction to Architectural Science: The Basis of Sustainable Design*, Routledge, London, 2014.
- [66] H. Ling, C. Chen, H. Qin, S. Wei, J. Lin, N. Li, M. Zhang, N. Yu, Y. Li, Indicators evaluating thermal inertia performance of envelopes with phase change material, *Energ. Buildings* 122 (2016) 175–184.
- [67] M.G. Davies, Transmission and storage characteristics of walls experiencing sinusoidal excitation, *Appl. Energy* 12 (4) (1982) 269–316.
- [68] A.M. Thiele, R.S. Liggett, G. Sant, L. Pilon, Simple thermal evaluation of building envelopes containing phase change materials using a modified admittance method, *Energ. Buildings* 145 (2017) 238–250.
- [69] H. Asan, Y.S. Sancaktar, Effects of Wall's thermophysical properties on time lag and decrement factor, *Energ. Buildings* 28 (2) (1998) 159–166.
- [70] H. Asan, Investigation of wall's optimum insulation position from maximum time lag and minimum decrement factor point of view, *Energ. Buildings* 32 (2) (2000) 197–203.
- [71] F. Kuznik, J. Virgone, Experimental assessment of a phase change material for wall building use, *Appl. Energy* 86 (10) (2009) 2038–2046.
- [72] J. Yang, H. Wu, X. Xu, G. Huang, T. Xu, S. Guo, Y. Liang, Numerical and experimental study on the thermal performance of aerogel insulating panels for building energy efficiency, *Renew. Energy* 138 (2019) 445–457.
- [73] P.M. Toure, Y. Dieye, P.M. Gueye, V. Sambou, S. Bodian, S. Tiguampo, Experimental determination of time lag and decrement factor, *Case Stud. Constr. Mater.* 11 (2019) e00298.
- [74] M.G. Davies, The thermal admittance of layered walls, *Build. Sci.* 8 (3) (1973) 207–220.
- [75] TenWolde, A., J.D. McNatt, and L. Krahn. *Thermal properties of wood and wood panel products for use in buildings*. 1988; Available from: <https://www.osti.gov/biblio/6059532>.
- [76] Á. Lakatos, A. Csík, I. Csarnovics, Experimental verification of thermal properties of the aerogel blanket, *Case Stud. Therm. Eng.* 25 (2021) 100966.
- [77] P. Scheuerpflug, M. Hauck, J. Fricke, Thermal properties of silica aerogels between 1.4 and 330 K, *J. Non Cryst. Solids* 145 (1992) 196–201.
- [78] M.G. Davies, The wall with lumped elements, in: *Building Heat Transfer*, John Wiley & Sons Ltd, Chichester, England, 2004, pp. 217–247.
- [79] N. Aste, A. Angelotti, M. Buzzetti, The influence of the external walls thermal inertia on the energy performance of well insulated buildings, *Energ. Buildings* 41 (11) (2009) 1181–1187.
- [80] C.A. Balaras, The role of thermal mass on the cooling load of buildings. An overview of computational methods, *Energ. Buildings* 24 (1) (1996) 1–10.
- [81] E. Tunçbilek, M. Arıcı, M. Krajčík, D. Li, S. Nizetić, A.M. Papadopoulos, Enhancing building wall thermal performance with phase change material and insulation: A comparative and synergistic assessment, *Renew. Energy* 218 (2023) 119270.