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TECHNICAL ARTICLE

Experimental Evaluation of Thermal Energy Storage (TES) with Phase Change Materials (PCM) for Ceiling Tile Applications

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Thermal energy storage systems (TES) are an effective technology to improve the energy efficiency while reducing the energy consumption in buildings. The integration of phase change materials (PCMs) as latent thermal energy is a popular method to incorporate them into the building envelope, reducing the energy demand and helping maintain the thermal comfort. In this experimental evaluation, the application of S23 ceiling panels to enhance the building performance is investigated. To analyse the PCM panels, a test room was artificially heated securing the melting temperature for the material; the results show that the S23 panels were able to absorb and increase the room temperature by 5 °C. During the cooling period, the PCM ceiling tiles help maintain higher room temperatures, up to +1.5 °C. The S23 panel temperature was able to drop below its melting point after 6 hours of cooling, demonstrating its capacity to complete the thermal cycle. The panel thermal conductivity range was found between 0.19–0.24 W/(m·K). It can be concluded that the addition of the S23 ceiling panels can be considered as an innovative solution for the application of passive TES in building envelopes, leading to energy savings by absorbing, storing and helping maintaining the ambient room temperature, therefore reducing the requirement for artificial heating and cooling.

Keywords: building application; energy storage; phase change materials; thermal energy performance

1. Introduction

Worldwide energy demand has increased due to the improvement of the living standards, this has led to a growing interest in sustainable energy solutions that contribute to a reduction in the CO_2 emissions. In Europe, the building sector represents 40% of the total energy consumption and nearly 50% of this energy is utilized for space heating and cooling. For this reason, improving the building envelope is considered a suitable solution to reduce the heating and cooling energy demand and improve the thermal comfort (Marin *et al.*, 2016). Thermal energy storage (TES) is an effective method to reduce the energy consumption, decreasing the on-peak load and shifting it to off-peak periods. This technology helps reduce the breach between the energy supply and energy demand by storing the available energy and using it during inaccessible periods (Kalaiselvam, Parameshwaran and Harikrishnan, 2012; Zeinelabdein, Omer and Gan, 2018).

Thermal energy storage also known as heat and cold storage can be stored in form of sensible heat (SHTES), latent heat (LHTES), and thermochemical storage (TCES); allowing the energy storage to be released when the energy demand requires it (Mehling, 2008). The advantage of this technology is that they operate at relative low temperature range (within the human thermal comfort temperatures), making them suitable for passive building applications.

The main parameter for the sensible heat refers to the specific heat capacity. This factor calculates the necessary energy to increase 1 kg of the material to 1 °K. The sensible heat can be calculated as follows:

$$Q = m \cdot \int_{Tf}^{Ti} Cp\, dT$$

where:

- m= mass (kg)
- Ti= initial temperature (K)
- Tf= final temperature (K)
- Cp= specific heat capacity (J·kg K)

The latent heat considers the heat stored or released during the phase change of the material. Throughout this period, the temperature remains constant and at this stage the material can absorb considerable energy quantities. The total amount of energy is determined by the enthalpy value and is measured during the material phase transition as shown in the following equation:

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$$\Delta Q = m \cdot \Delta h$$

where:

- m= mass (kg)
- Δh= enthalpy change (J · kg)

The utilization of phase change materials (PCMs) as latent thermal energy are ideal for thermal management and storage, due to their capacity to absorb, store and release latent heat during the phase transition (Yang *et al.*, 2020). PCMs offer considerable advantages, such as high thermal density and relatively constant phase transition temperature during the melting and solidification process. Nevertheless, the major factor affecting the PCM performance correspond to the low thermal conductivity (Elmaazouzi *et al.*, 2020). The thermal conductivity (λ) refers to the capacity of a given material to transfer heat while the material remains static. In general, a material in solid state presents higher thermal conductivity in comparison to the liquid state due to the molecular interaction to transport heat (Mehling, 2008).

The definition of λ (W/mK) is determined by Fourier's law, which is for 1-dimensional steady state heat conduction and is described as follows:

$$Q = A \cdot \lambda \cdot \frac{dT}{dx}$$

PCMs can be classified as organics, inorganics and eutectics. Some of the most popular inorganic PCMs are salt hydrates, consisting of a mixture of salt and water in a discrete mixing ratio. Generally, these water molecules are paired with the salt molecules creating a crystal structure (Mehling, 2008). Salt hydrates are characterized by their high storage density with respect to the mass and volume. The thermal conductivity of salts can be considered as high and in general they are chemically stable. The major drawback of salt hydrates is phase segregation, due to their chemical composition consisting on of different substances with variable densities.

The building envelope regulates the heat exchange between outdoor and indoor environment, affecting the energy requirements and human thermal comfort (Marin *et al.*, 2016). The incorporation of PCMs in buildings is mainly achieve through the addition of the material into structural components such as walls, windows, roofs or ceilings and commonly they are applied as passive systems. Auxiliary components such as HVAC systems and solar heating units can be coupled with PCMs. Adding thermal mass into building elements helps to control any abrupt temperature fluctuations, particularly in lightweight structures; decreasing the overheating in summer and preventing heat loss during winter (Skovajsa, Koláček and Zálešák, 2016). Another advantage for the PCMs integration in the building structure is having a large surface area directly in contact with the indoor environment, therefore allowing an effective heat transfer.

PCM-TES has been extensively investigated prior 1980, the implementation of PCM for energy conservation in the building structure was first mentioned in 1975 by Barkmann and Wessling (Barkmann and Wessling, 1975); since then a considerable amount of research has been developed (Iten, Liu and Shukla, 2016). Examples of such technologies are PCM panels, PCM-enhanced walls, nano-PCM, PCM windows, among others. Piselli et al. investigated the performance of PCM for passive cooling applications, finding that by integrating PCM into the building envelope significant cooling savings were achieved, generating a reduction up to 300 kWh/year for mild climates in Italy (Piselli *et al.*, 2020). Similarly, Kishore et al. investigated the addition of PCM into the building walls, the results exhibited a reduction in the annual heat gain and heat losses of 47.2% and 8.3%, respectively (Kishore *et al.*, 2020).

Alawadhi utilized PCM in the windows shutters to reduce the building heat gain. The investigation aimed to employ the PCM latent heat to avoid the heat entering the building. The experiment tested n-Octadecane with a melting temperature of 27 °C, n-Eicosane with a melting temperature of 37 °C and P116 with a melting temperature of 47 °C, the results concluded that the PCM with the highest melting temperature (47 °C) presented the best thermal performance, obtaining heat gain reductions up to 23.29% (Alawadhi, 2012). Sayyar et al. used experimental and numerical approaches to evaluate the thermal performance of a nano-PCM integrated in gypsum wallboards. The nano-PCM consisted of a fatty-acid PCM coupled with graphite nano-sheets. The results show that the control cell presented a temperature range from 13 °C to 32 °C. In contrast, the nano-PCM wall had a temperature range from 18.5 °C to 26.5 °C; demonstrating the ability of the PCM to reduce the indoor temperature fluctuations (Sayyar *et al.*, 2014). Voelker et al. studied the impact on the room temperature of gypsum plaster and a salt mixture; the study concluded that the utilization of phase change materials in buildings increased the thermal mass and contributed to an enhancement of the thermal protection during summer. Nevertheless, it was found that the system could get oversaturated if the PCM was not properly discharged after a few consecutive days. To counteract such effect, the authors proposed the application of a night ventilation system to facilitate the PCM full cycle (Voelker, Kornadt and Ostry, 2008). Another study by Saxena et al. analysed the performance of PCM embeded bricks, finding a heat transfer reduction between 40 to 60% during daytime and a temperature reduction of 4.5 °C to 9.5 °C in comparison to conventional bricks (Saxena, Rakshit and Kaushik, 2020).

Maleki et al. proposed the application of nano-capsules containing PCM in the walls and roof plaster to boost the thermal comfort. The results indicate that the PCM system could reduce the indoor air temperature fluctuations and help maintain indoor thermal comfort for most of the year (Maleki *et al.*, 2020). Qunli et al. developed a cooling ceiling composed of an insulation layer, a mortar embedded with the capillary pipes and a PCM layer. The mathematical model concluded that the energy storage ratio of the phase change energy storage system was higher in comparison of a concrete ceiling (Qunli *et al.*, 2017). Ceiling tiles are a practical method to integrate the PCMs into building structure, increasing thermal mass, reducing temperature fluctuations, and assisting in energy performance by regulating the indoor temperature (Velasco-Carrasco *et al.*, 2020). Memon et al. investigated the thermal performance of lightweight aggregate concrete (LWAC) containing macro encapsulated paraffin in Hong Kong. The results of the indoor test revealed that the macro encapsulated paraffin–LWAC panel was able to decrease the interior indoor temperature by 2.9 °C, flattening the temperature fluctuation. The outdoor test found that the room temperature was optimized when there was a considerable temperature difference between day and night (Memon, Cui, Zhang, & Xing, 2015).

In this paper, the effects of integrating PCM ceiling tiles to enhance the indoor thermal performance has been experimentally investigated. The technology proposed is based on a commercial PCM panel developed by PCM Products Ltd© .The selected PCM was S23, which has a melting point of 23 °C and possess a phase change range compatible with the human thermal comfort temperatures (22 to 26 °C in moderate climates), this allows the use of the latent heat to improve the thermal inertia while decreasing the energy consumption. The fundamental difference between standard solutions and the proposed technology focuses on the encapsulation design, specifically tailored to promote the heat exchange between the PCM and the ambient temperature. Numerous studies of ceiling cooling systems with PCM have been studied. Nonetheless, most of the research focuses on numerical simulations, lacking real-scale testing.

2. Methodology

2.1 Experimental setup

The experiment was conducted in a testing room at The University of Nottingham. The test room is allocated in a Georgian period house part of the Architecture and Built Environment Department. The testing room surface is 8.3 m², with a height of 3.31 m; the room contains two windows covering a surface area of 2.99 m². The room has brick walls with gypsum and paint finishing, with a total thickness of 15 cm; the ceiling is formed out of concrete with a thickness of 15 cm and the windows are single glazed. For experimental purposes, the panels were placed in the top section of a shelving system to represent the ceiling hight as shown in **Figure 1**.

2.2 Materials

PlusICE S23 is a salt hydrate developed by PCM Products Ltd© with a melting temperature of 23 °C, the thermal properties are described in **Table 1**. The capsule material depicted in **Figure 2** consists of a rectangular plastic container measuring 24 cm × 49 cm, the design contemplates circular rings on the top and bottom in order to facilitate the panel stacking when required. Each panel has a total weight of 3.5 kg and for the experimental purposes a set of 20 panels were manufactured, having a net PCM weight of 52 kg that represents 28% of the ceiling area.

2.3 Thermal conductivity analysis

The thermal conductivity was measured using the HFM-100 Heat Flow Meter method, in which two flux sensors were utilized to measure the thermal conductivity and thermal resistance. The equipment sensors have a thermal conductive range between 0.005 to 0.5 W/(m·K) and the temperature range of –20 °C to 70 °C. To validate the accu-

Table 1: PCM properties (PCM Products Ltd, 2020).

S23 properties	Units
Phase change temperature	23 (°C)
Density	1,530 (kg/m³)
Latent Heat Capacity	200 (kJ/kg)
Specific Heat Capacity	2.20 (kJ/kgK)
Thermal Conductivity	0.54 (W/(m·K))

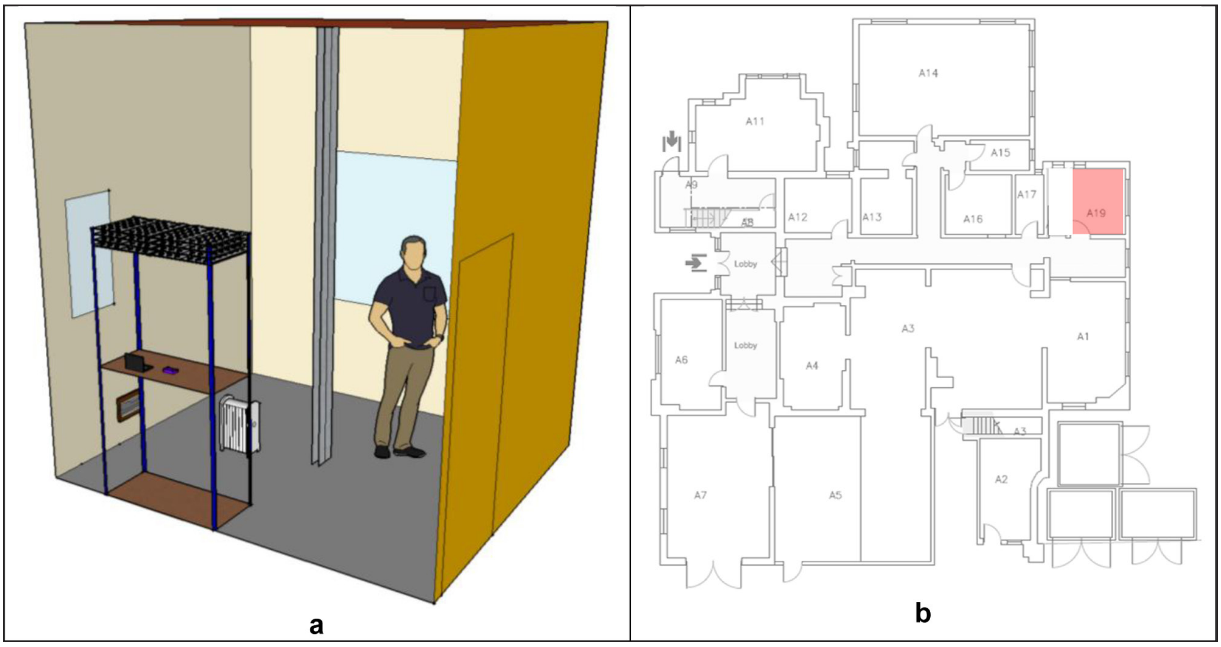

Figure 1: a) Testing room with PCM panels **b)** House layout, testing room in red (The University of Nottingham, 2020).

racy of the measurement an expanded polystyrene board was tested as a calibration material; furthermore, each test was repeated three times to corroborate the results. As the original panel exceeds the equipment dimensions a small-scale sample was provided by the same manufacturer as shown in **Figure 3**.

2.4 Room measurement equipment

The aim of this measurements was to determine the change in the ambient temperature during the charging and discharging process. The panels were charged using radiators with a heat capacity of 2 kW and the room temperature loss was monitored after ensuring the complete charging of the PCM. The temperature measurements were made using Type K thermocouples and all readings were collected by the data logger (DT85), with a standard deviation of ±0.3 °C. The sensors were placed in the four walls, ceiling, floor, windows, radiators and inside the PCM panel as shown in **Figure 4**, a total of 16 thermocouples where placed inside the room and the average temperature was noted for the results analysis. In addition, 10 THD sensors (EL-USB-2) were placed in the testing room, having a standard temperature deviation of ±0.55 °C, 2.25% for the relative humidity and 1.7 °C for the dew point.

Figure 2: PlusICE S23 panel (PCM Products Ltd, 2020).

Figure 3: Thermal conductivity S23 sample panel.

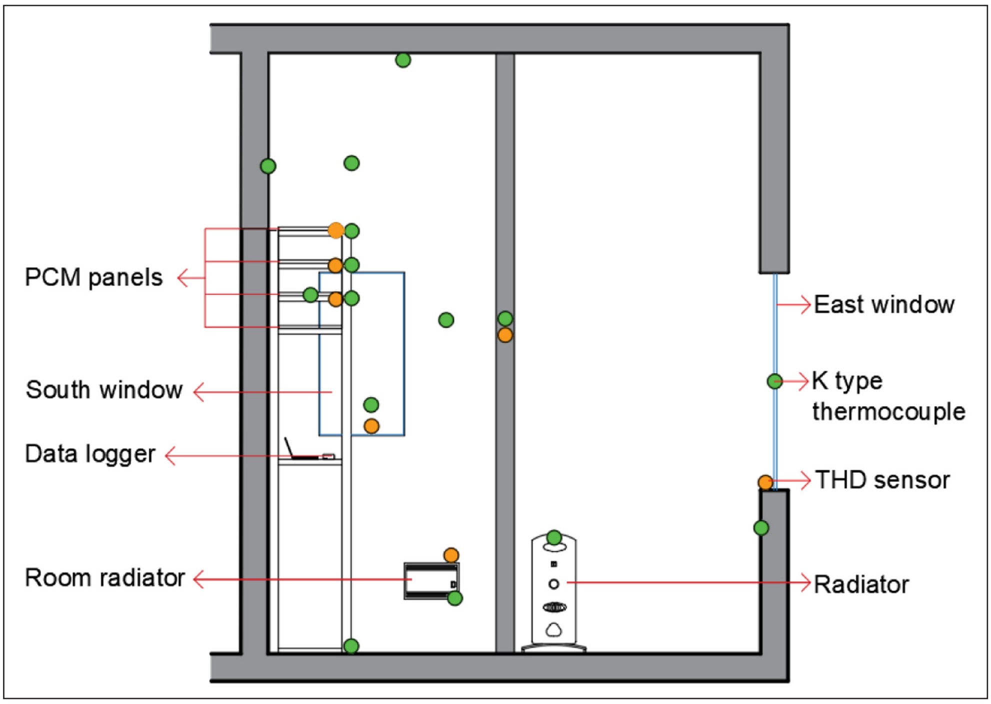

Figure 4: Testing room section with components.

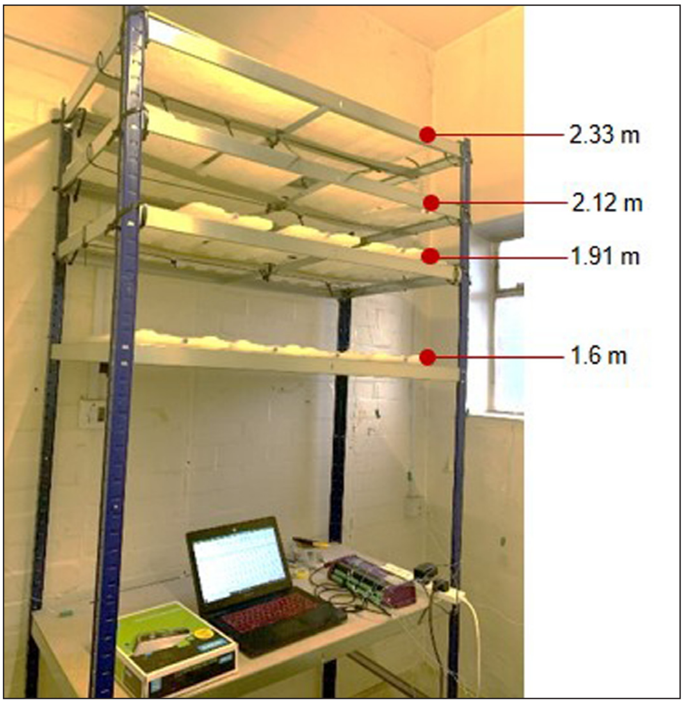

Figure 5: Panels in shelving system.

2.5 Measurement procedure

Figure 5 displays the shelving system with the PCM panels in the testing room. The heating devices were switched on for a minimum duration of 6 hours, thus heating up the room and consequently the PCM panels. The heating temperature exceed the enthalpy phase of the PCM, additionally the PCM panels were visually inspected to verify the complete phase transition to a full liquid state. After the heating phase, the regeneration period was monitored, using the natural heat loss to the ambient. The average room temperature without PCM for the heating period was 27.6 °C.

The average temperature variation between the two sensors was of –0.11 °C. The temperature comparison is shown in **Figure 6**. The testing results present the average temperature of both sensors.

3. Results and Discussion

3.1 Thermal conductivity analysis

The operational parameters of the thermal conductive analysis are described in **Table 2** and correspond to three different mean temperatures, comparing the effect of the phase transition (solid, transitioning, liquid). When

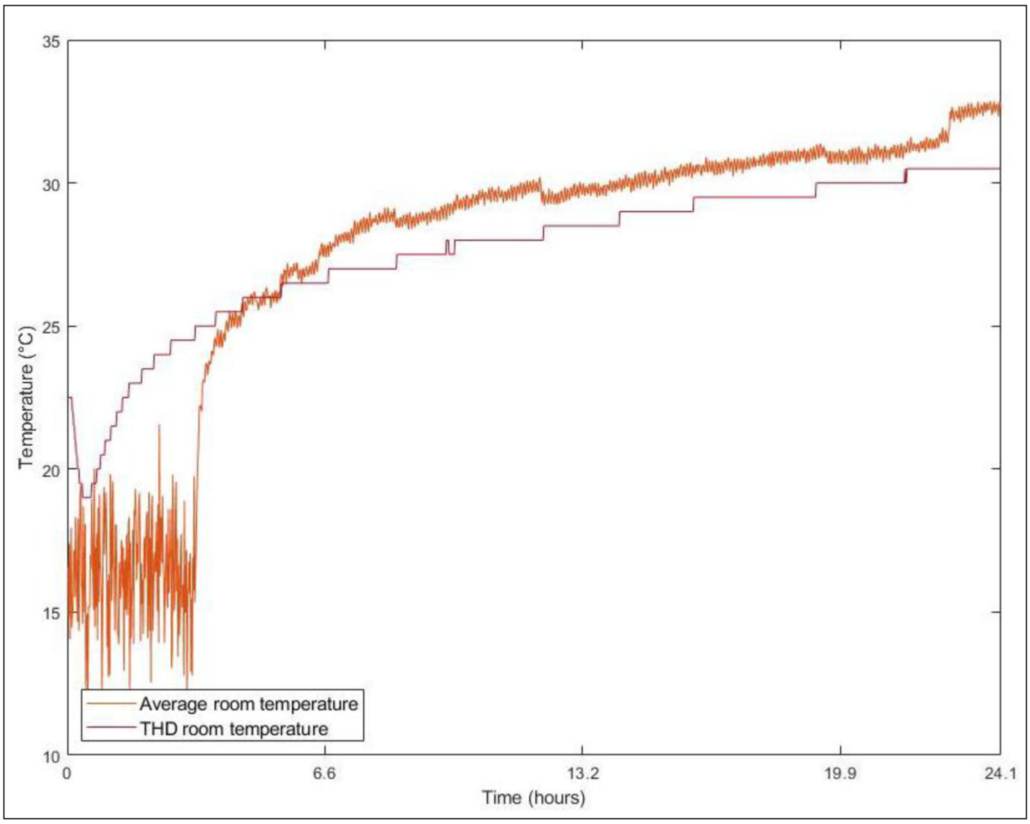

Figure 6: Room temperature heating comparison.

Table 2: S23 thermal conductive results.

PCM	Mean Temperature (°C)	Upper Plate Temperature (°C)	Lower Plate Temperature (°C)	TC (W/(m·K))	Thickness (mm)	Weight (kg)
S23	–10	–20	0	0.19	30.8	0.388
S23	20	10	30	0.23	30.8	0.388
S23	40	30	50	0.24	30.8	0.388

the test was performed at a solid state (mean temperature –10 °C), the thermal conductivity was found to be 0.19 W/(m·K), the lowest value recorded during the experiment. In the second evaluation the mean temperature was considered at 20 °C, in this temperature range the panel had already started the phase transition and the thermal conductivity was found at 0.23 W/(m·K). The highest thermal performance was presented at a mean temperature of 40 °C, at this stage the panel was fully transition to a liquid state, having a thermal conductivity of 0.24 W/(m·K).

According to the manufacturer data the thermal conductivity of the S23 is 0.54 W/(m·K), this value is higher than the obtained results and it is due to the encapsulation material. In the case of the salt hydrates, their corrosiveness reduce the encapsulation options, thus plastic materials are an appealing solution (Velasco-Carrasco *et al.*, 2020). The importance of the container material is pivotal for the PCM to perform adequately in indoor environments and in this case, it is expected a slight reduction from the plastic capsule in comparison to the natural thermal conductivity of the PCM. **Table 3** shows the thermal conductivity of PCMs with similar melting temperatures found on the literature for comparison purposes.

The thermal conductivity observed across the six samples exemplify the performance of the S23 in comparison to commercially available PCMs with similar melting points. In this case, the S23 panel presents competitive performance in comparison to pure PCM samples. These results validate the application of the plastic capsule container as an advantageous method for building integration.

3.2 Room testing

Figure 7 represents a typical data recorded during the heating and cooling period. The room was heated for a duration of 6.8 hours, while the cooling period of had a duration of 17 hours. The average room temperature during the heating period was 26.3 °C and after the cooling period was 16.3 °C with a final temperature of 15.2 °C.

Figure 8 shows the extended heating and cooling period, having an average temperature of 27.6 °C and 19.5 °C respectively. It is seen that the room temperature increased constantly during the heating period reaching

Table 3: PCM thermal conductivity comparison.

PCM	Melting Temperature (°C)	Liquid [W/(m·K)]	Solid [W/(m·K)]	Reference
Paraffin C13–C24	22–24	0.21	–	(Cabeza *et al.*, 2011)
RT22	22	0.20	0.20	(*Rubitherm GmbH*, 2020)
RT24	24	0.20	0.20	(*Rubitherm GmbH*, 2020)
RT 25	25	0.17 ± 0.01	0.19 ± 0.01	(Weinläder, Beck and Fricke, 2005)
S27	27	0.48 ± 0.04	0.79 ± 0.03	(Weinläder, Beck and Fricke, 2005)
L30	30	0.56 ± 0.03	1.02 ± 0.05	(Weinläder, Beck and Fricke, 2005)

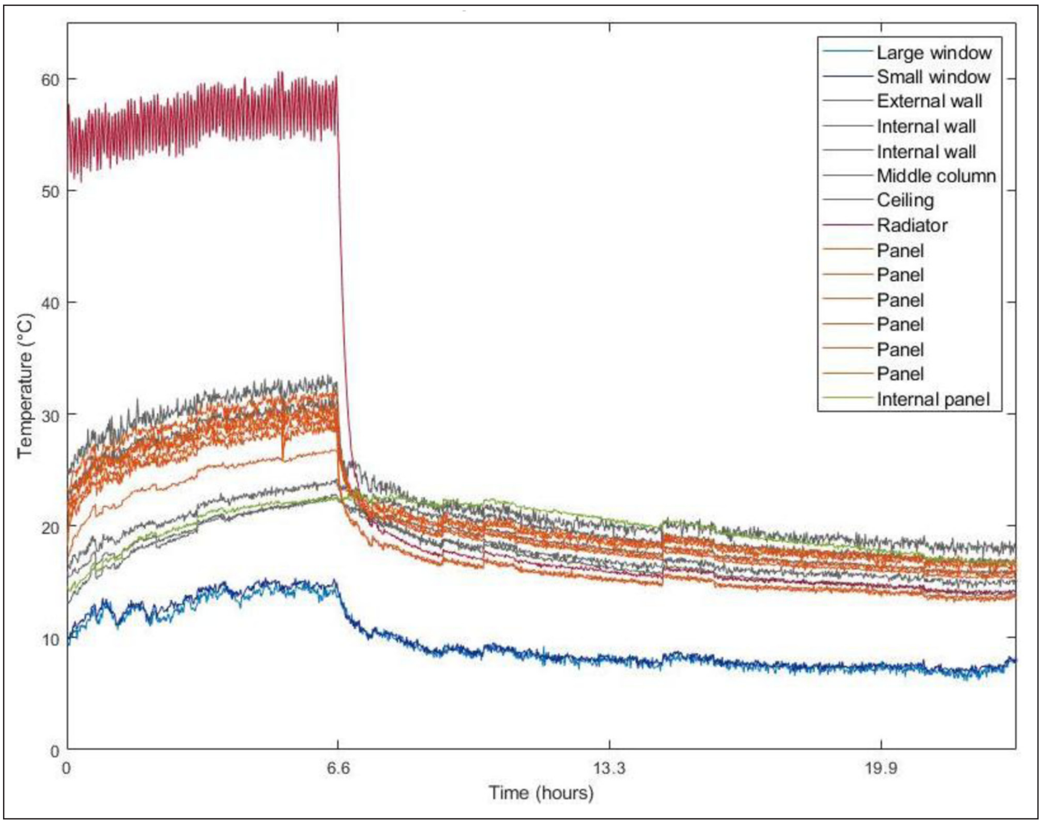

Figure 7: Room temperature monitoring.

a maximum temperature of 30.0 °C, after the radiator is swich off the temperature starts to decrease and the PCM panels are not able to retain the room heat, reaching 16.6 °C after 35 hours. This can be attributed to the temperature difference between the indoor and outdoor environment during the test day, having an ambient temperature range between 4 °C to 6 °C.

3.2.1 Melting process

The PCM effect over the room temperature can be observed in **Figure 9**. The heating period shows the progress of the increasing temperature, both with and without PCM panels. This graph represents four different testing days, one without PCM and the remnant having the S23 panels allocated in the room. The graph presents the radiator temperature and room average temperature. It is possible to see that for a day without PCM the radiator temperature corresponding to the top line achieve higher temperatures in comparison to the PCM testing days; in contrast the average room temperature presented the lowest ambient temperature. When the PCM panels are present, the radiator temperature tends to decrease after 2.5 hours, meaning that the panels are being charged and therefore reducing the heating temperature; this factor is proved by the average room temperature increment. The maximum room temperature of the testing room without PCM was 24.4 °C and 30.7 °C for the room with the S23 material.

Table 4 presents the numerical results of the heating experiment. The results show the average temperature representing each of the values presented in **Figure 9**. It can be noticed that the addition of the PCM decrease the heating temperature, creating a minimum temperature difference of 4.8 °C. Consequently, the is a rise in the average room temperature with the PCM, having a minimum temperature difference of 1.9 °C. These results lead to the

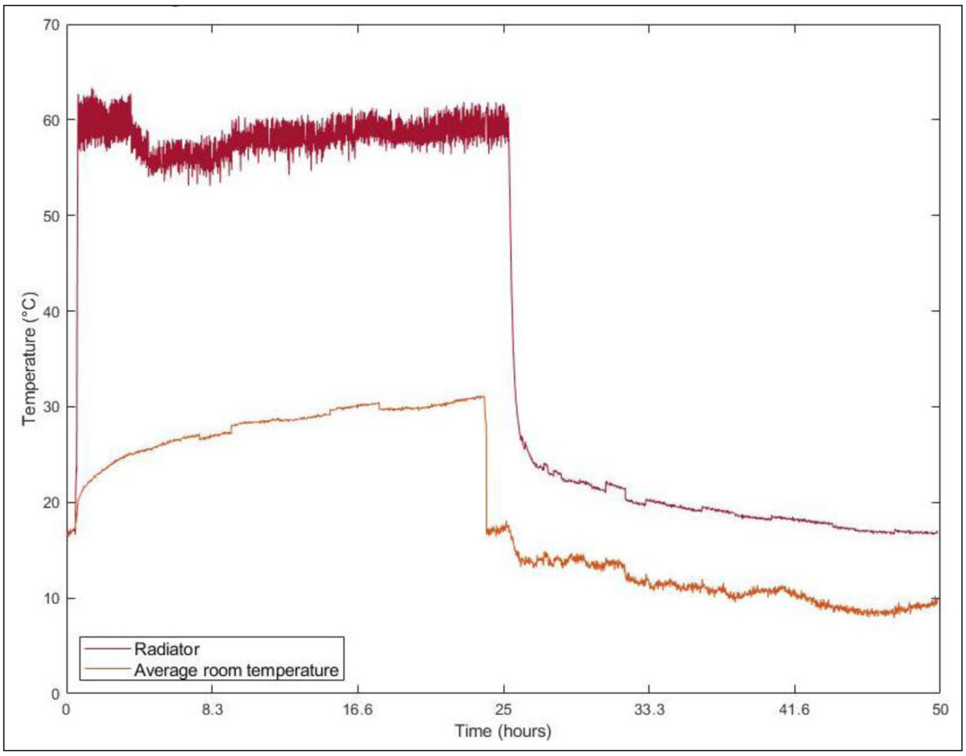

Figure 8: Room temperature monitoring heating and cooling.

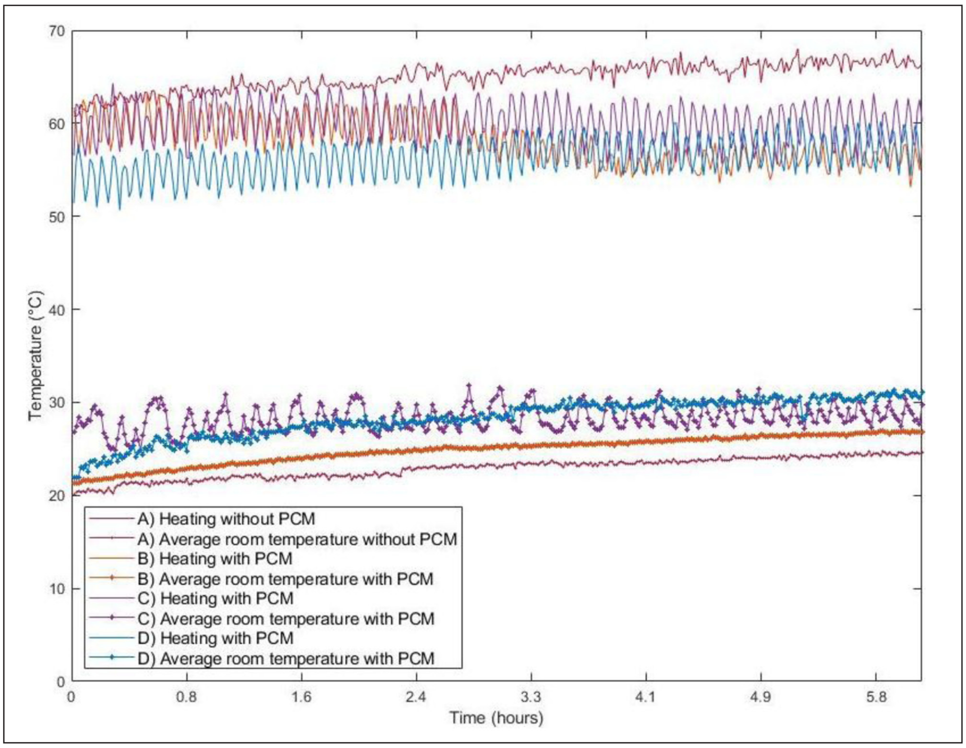

Figure 9: Room temperature heating comparison.

Table 4: Average temperature comparison results.

A) without PCM		B) with PCM		C) with PCM		D) with PCM	
Radiator (°C)	Room (°C)	Radiator (°C)	Room (°C)	Radiator (°C)	Room (°C)	Radiator (°C)	Room (°C)
65.0	22.9	58.0	24.8	60.2	28.2	56.3	28.3
ΔT		–6.9	+1.9	–4.8	+5.3	–8.7	+5.3

conclusion the 20 PCM ceiling tiles were able to increase the room temperature level by 5 °C.

3.2.2 Solidification process

The cooling mode measurements show the freezing progress of the PCM panels. It is possible to observe the effect of the room temperature when compared to the room without PCM. The heating devices were active for a 24-hour period, thus heating up the room. After this time-lapse, the radiator was swich off and the monitoring period started for 24 hours as seen in **Figure 10**. The graph presents higher room temperatures when the PCM panels are allocated in the room, this factor is clearly marked for the first 20 hours. After this period both temperatures appear to reach similar values, however the room temperature with the PCM ceiling tiles remains higher throughout the test. The starting temperature for the room without PCM was 34.3 °C and the end temperature 17.2 °C. In contrast, the S23 room temperature started at 36.7 °C and the presented an end temperature of 17.4 °C.

The numerical results obtained from the analysis of **Figure 10** are displayed in **Table 5**. For the PCM room it can be observed that the room temperature dropped to 14.6 °C during the first 6 hours, reaching a room temperature of 22.1 °C which is below the PCM melting point. These results show the ability of the PCM to start the regeneration process after 6 hours, allowing the thermal cycle process to be completed over a 24-hour period.

Conclusions

This study aims to support the application of PCM technologies as a passive alternative to generate energy saving, hence improving the building energy performance. The experiment has been used to explore the effect of adding insulation to the building envelope, its operating principle is based on storing the available heat through the melting process of the PCM and discharge it into the room space. The tested system has demonstrated the potential to provide energy savings, by reducing the peak indoor temperatures and therefore reducing the energy operation requirements for heating and cooling.

In this case, the S23 panel performance presents favourable results for building incorporation, as the panel is suitable to securely contain the PCM and at the same time promote the heat exchange interaction with the thermal environment. Due to the corrosive nature of the S23, a plastic encapsulation was adopted as a feasible solution. The main findings of this paper are as follows:

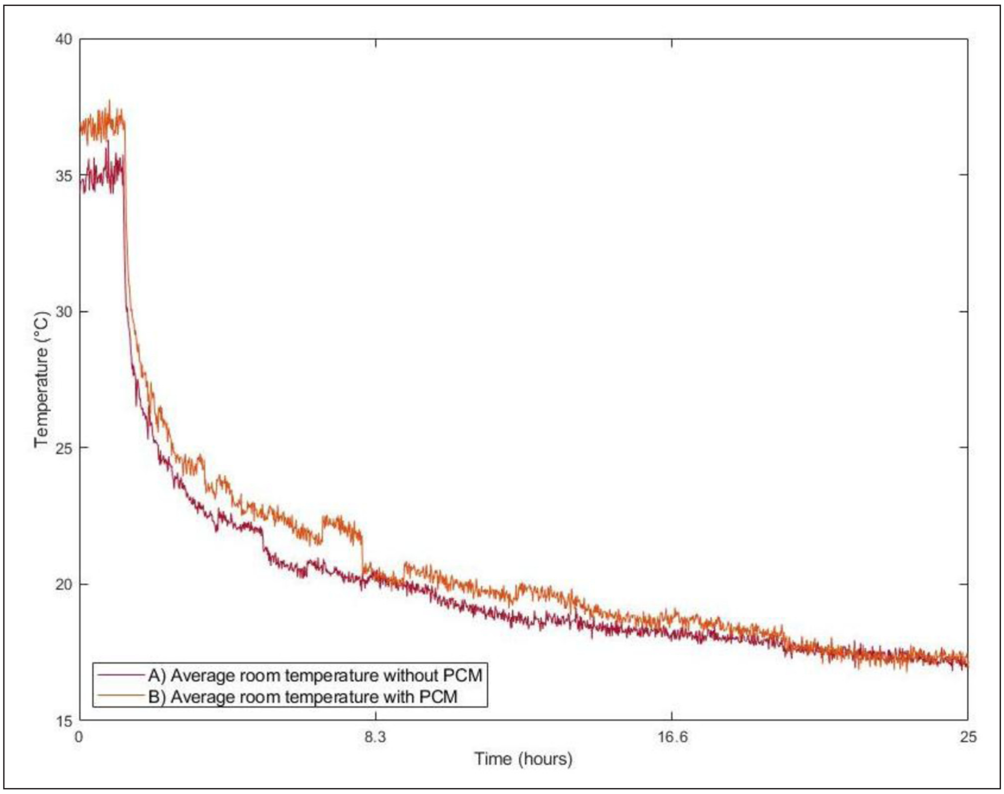

Figure 10: Room temperature cooling comparison.

Table 5: Results average temperature comparison.

(Time-lapse)	Start	6 (hr)	12 (hr)	18 (hr)	25 (hr)
A) Without PCM (°C)	34.3	20.5	18.5	17.9	16.9
B) With PCM (°C)	36.7	22.1	19.6	18.3	17.1
ΔT	–2.4	–1.5	–1.1	–0.4	–0.2

1. The thermal conductivity was found 0.19–0.24 W/(m·K), the S23 panel presents competitive performance in comparison to "pure" PCM materials, this confirms the application of the plastic capsule container as an advantageous method for building integration.
2. Adding the S23 panels decrease the heating temperature and as a result the average ambient temperature increased. This leads to the conclusion that having 20 PCM ceiling panels created an impact in the room temperature of 5 °C.
3. For cooling purposes, the S23 maintained higher room temperatures in comparison to the room without PCM. After a 6-hour period, the PCM panels temperature drop below its melting point; indicating the ability of the panel to cool down favouring the completion of the thermal cycle.
4. Phase segregation was observed during the melting period, a reduction in the panel dimensions would be advisable to counteract this drawback.
5. It is pivotal to ensure that the adequate climate conditions are provided for the specific PCM melting temperature, to ensure the completition of the thermal cycle.

From the above results, it can be concluded that the addition of the S23 ceiling panels can be considered as an innovative solution, having the potential to be considered as passive TES, leading to energy savings by reducing the energy demand thought storing the available energy and releasing the heat to the environment at inaccessible periods.

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Competing Interests

The co-author Saffa Riffat is the Editor in Chief of this journal and was removed from all editorial duties involving the review and processing of this submission.

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