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Research paper

Hourly thermal analysis of innovative concrete bricks using sawdust and phase change material

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ABSTRACT

Thermal insulators and energy storage materials have shown progressive thermal performance when integrated with construction materials. However, integrating both of them may result in better enhancements in extreme hot locations, utilising their ability to resist excess heat. In this research, concrete bricks were fabricated by involving sawdust (SD) and phase change material (PCM) into plastic containers and tested under severe hot conditions for a full thermal cycle. Three concrete bricks integrated with SD, PCM, and PCM/SD were developed and examined against a fourth brick that involved empty containers as a reference. The thermal behaviour and energy contribution of the developed bricks were assessed considering the temperature shrinkage between the outer and inner surface temperatures and time lagging. Results displayed that the PCM brick was dominant over other bricks, showing a maximum temperature shrinking of 7.25 °C, with a time lag of over 4 h. Compared to the reference brick, the PCM brick has reduced and lagged the inner surface temperature by about 3 °C and 70 min, respectively. However, the PCM/SD brick also indicated better thermal performance than the SD brick, indicating superiority of thermal energy storage over thermal insulation to develop high-performance buildings.

1. Introduction

In recent years, there has been a superior emphasis on reducing energy consumption in countries with hot climates, while simultaneously maintaining thermal comfort. Buildings account for around 30 % of global energy consumption, mostly to meet heating and cooling demand, with 26 % of energy-related CO_2 emissions [1]. Considering the building envelope, the wall plays a vital role in building thermal energy as it regulates internal temperature from direct or indirect sources [2]. As reported in the literature, building walls constitute a significant thermal weakness, contributing to roughly 33 % of total heat gain in poorly insulated structures [3].

Conventional concrete walls are common in construction owing to their greater structural strength; however, their comparatively high thermal conductivity (typically between 1.5 and 2.5 W/m·K) significantly contributes to indoor heat gain, especially in hot areas [4]. Elevated temperatures expedite the hydration of concrete, resulting in fast water evaporation and heightening the possibility of shrinkage fractures [5]. Moreover, the material's resilience and durability might be diminished by extended exposure to heat, compromising structural integrity, while thermal expansion may lead to dimensional distortions [6]. In addition, concrete is considered inappropriate for passive cooling methods in hot areas because it is an inadequate thermal insulator. These issues underscore the pressing necessity for building professionals to better understand and enhance the thermal insulation characteristics of concrete to guarantee both structural integrity and energy efficiency in today's building design [7].

The thermal performance of buildings is predominantly determined by their conductivity, which measures heat transfer rates through the material [8]. For example, dense concrete or clay solid units demonstrate thermal conductivities ranging from 0.8 to 1.5 W/m·K [4]. In contrast, lightweight bricks, which are composed of clay or pumice with thermal conductivity values of 0.12–0.3 W/m·K, are more thermally efficient [9]. Consequently, enhancing the material composition of bricks is essential for minimising building energy demands.

Researchers have studied various modifications in brick production

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to enhance energy efficiency, including the integration of additional materials that create microporosity, decreasing thermal conductivity by generating air pockets inside the brick structure [10–13]. Zhang et al. [14] enhanced the insulation properties of bricks by incorporating micropore additive agents before the firing process and creating artificial holes during casting. The thermal conductivity of bricks was assessed through two primary factors: the composition of the materials used in the fabrication and the geometric configuration of the bricks. Ahmad et al. [15] demonstrated that the incorporation of wheat husk additives resulted in a significant reduction in thermal conductivity by facilitating the formation of porous microstructures during the firing process. Nonetheless, this porosity facilitated mortar penetration during wall construction, unintentionally increasing wall density.

For thermal enhancement purposes, a wide range of plant-derived waste materials, including coal [16], olive pomace [17], mushroom substrate [18], sugarcane bagasse, rice husks [19], and sawdust [20], have been examined as potential additives in brick manufacturing. For instance, Demir [21] examined the addition of sawdust, tobacco ash, and grass into bricks at different concentrations (0–10 wt %) and concluded that organic pore-forming materials can effectively produce bricks that have a lower environmental impact. Ahmed et al. [22] assessed the incorporation of pomegranate peel waste in conventional bricks. All samples exhibited decreased thermal conductivity relative to conventional bricks, resulting in energy saving from 17.55 % to 33.13 % and a reduction in CO_2 emissions between 7.50 % and 24.50 %.

Recent research works have increasingly focused on integrating the phase change material (PCM) into building elements to improve their thermal performance. The PCM serves as an effective thermal energy storage medium, absorbing heat during the day, melting phase and releasing it at night while freezing. This cyclic phase transition allows PCM to store and release thermal energy, thus promoting more stable indoor temperatures in buildings [23]. When effectively integrated into building walls, with attention to phase change temperature, optimal quantity, and placement, PCMs can significantly decrease building energy consumption by up to 18 % and extend peak thermal load shifts by as much as 10.3 h [24]. Many studies have investigated the effect of incorporating PCM into brick walls. Zhang et al. [25] performed a numerical analysis to assess the effects of PCM incorporation and filling quantity on the thermal performance of hollow brick walls. The results indicated that an increase in the quantity of PCM improved the thermal inertia of the wall and stabilised indoor temperature remarkably. Saxena et al. [26] integrated Eicosane and OM35 (as PCMs) with melting temperatures of 36–38 °C and 35 °C, respectively, into traditional Indian bricks. The study reported a temperature reduction of 5–6 °C in the bricks and an 8–12 % decrease in heat flow relative to conventional bricks. Laaouatni et al. [27] proposed an actively ventilated building block incorporated with PCM, demonstrating that the incorporation of PCM resulted in a reduction of the inner surface temperature by approximately 3.4 °C to 4.7 °C. A study aimed at enhancing the thermal performance of external walls through the integration of PCMs was conducted to evaluate the heat transfer characteristics of PCM-enhanced hollow bricks under different conditions. The results indicated that the integration of PCM markedly diminished indoor temperature variations and enhanced the stability of the indoor thermal environment [28]. The thermal efficacy of PCM-enhanced bricks was experimentally evaluated based on temperature differential throughout the brick, time lag, and attenuation of surface temperature variability [29]. Findings indicated that PCM-integrated bricks outperformed conventional bricks, achieving a temperature drop of up to 5 °C and a time lag of 30 to 60 min. Heniegal et al. [30] developed a lightweight cement brick made of 75 % popcorn coarse aggregate and 50 % PCM, in which experiments were made for two identical rooms: one constructed with traditional bricks, while the other was built with the developed bricks. The thermal performance of rooms in terms of the indoor air and surface temperatures was analysed under the desert weather of Suez, Egypt. Experimental findings displayed that the developed bricks have minimised the indoor temperature by about 5.5 °C with a peak time delay by up to 2 h, over the reference room. Furthermore, the study applied annual analysis using EnergyPlus software, disclosing annual energy saving and thermal comfort improvement by 5 %-10 % and 63.83 %, emphasising the potential of PCM to maintain thermally efficient buildings. Čekon et al. [31] constructed a double-skin glass block coupled with PCMs to quantify the PCM thermal energy storage potential in a double-skin façade, for managing the thermal dynamics during the peak cooling period. Outcomes exhibited that the PCM integration into a double-skin façade has minimised the energy demand by 20 % in the daytime, along with 6.6 kWh/m^2 thermal gain reduction at nighttime. Besides, the PCM façade's peak surface temperature declined by 15 K with a time delay of 2 h, equivalent to an energy load reduction by 1.14 kWh/m^2 at high solar radiation. Li et al. [32] explored the dual thermal influence of radiative cooling coating and PCM to absorb, store and release the thermal energy from indoor and outdoor air during daytime and maintain indoor thermal comfort at night. For this aim, a numerical dynamic model was developed for the Xicheng industrial block under Shenzhen, China weather conditions. Simulation findings revealed that integrating this technique in roofing or facades has significantly reduced peak indoor temperatures and net heat gain by up to 12.91 °C and 18.78 %, respectively. Hassan et al. [33] numerically explored the thermal effectiveness of incorporating nano-enhanced PCM into clay blocks for energy-efficient buildings. Study findings showed that increasing the nano particle concentration from 0 % to 10 % has maintaned the indoor surface temperature at 23.3 °C- 26.6 °C, with a maximum peak temperature delay of 0.8 h, and reduced the heat flux by 13 %. Moreover, the study indicated potential cooling power consumption reduction of 16 % at the highest nano concentration.

Previous studies have presented the thermal advantages of integrating plant-based additives, such as sawdust, and energy storage materials, such as PCM, into bricks. However, most research has examined these approaches separately. Besides, the proposed modifications were examined under moderate weather conditions, leaving gaps regarding their thermal performance in severe hot climates. The combined effect of bio-based additives and PCM in realistic concrete brick layouts is not well understood. Therefore, this research provides an opportunity to investigate the thermal performance of novel bricks that integrate both sawdust and PCM, intending to enhance thermal performance in hot regions.

2. Materials and methods

2.1. Experimentation and fabrication of bricks

Four concrete bricks were fabricated and tested in a severe hot location of Al Amarah city (Latitude: 31.84° & Longitude: 47.14°), Iraq. All concrete bricks were designed and fabricated with 10 × 15 × 25 cm dimensions, an intermediate size between common bricks and blocks in Iraq, adopting a 1:2:4 mixing ratio (Portland cement: sand: gravel) to attain compressibility of 20 Mpa compatible with the block production requirements [34,35]. Moreover, a total of six thin-walled plastic containers were immersed in each brick, holding different waste materials. These containers are a common waste product in the health and medical sector, used to collect liquid samples and employed in this work to support the global efforts towards recyclability. Each container has a diameter of about 4 cm with 6.8 cm length, which is able to collect up to 85 cm^3 of storage material.

In the first concrete brick, empty containers were immersed to prepare a bare brick (B-B) for comparison. The second brick was composed of sawdust containers (SD-B), while the third was provided with PCM (PCM-B) and the fourth with three PCM containers and three SD containers (PCM/SD-B). Sawdust was employed in this study, which was collected from a local wood mill, thanks to its low thermal conductivity, which stabilises temperatures and reduces heat transfer through bricks, improving their thermal resistance. These waste materials were dried completely to afford lightweight bricks, which is an advantage in the building industry. In the PCM/SD-B, the PCM containers were placed in the front edge of the brick, while the other three SD containers were placed in the rear edge. This configuration was adopted since the PCM effectively work when placed towards the outdoor side for best melting and freezing phases, consistent with recent literature studies [36]. It is worth mentioning that the brick design by immersing containers during the moulding process may complicate the production process, especially for mass production, limiting the technique's feasibility. However, such a design provides a better thermal contact between the concrete and containers from all sides, which guarantees a better heat transfer during heat charging and discharging, the core of this research. Fig. 1 displays a schematic view of the bricks and their installation in the experimental rig, while Fig. 2 shows the realistic fabrication process of the experimental bricks.

The modified bricks were included in a dense polystyrene box in which only one face of each brick was visible to the outdoor conditions, while the rest were buried inside the box. Furthermore, the slots and ports between each brick edge of the box were afterwards sealed using high-insulation potential foam after installing temperature sensors on both sides of the bricks.

The SD and PCM used in this work are two popular waste materials in Iraq, in which the SD is commonly wasted in the wood industry, while the PCM is a paraffinic-based jelly material produced in petroleum refineries. The characteristics of these materials are indicated in Table 1, and the final experimental setup is shown in Fig. 3.

2.2. Instrumentation

Temperature sensors of T-type were used to measure the surface temperature of bricks. Two sensors were attached to the inner and outer surfaces of each brick. Besides, two other sensors were placed in the open air at an appropriate level to track the outdoor temperature variation. The sensors were connected to a Mega 2560-type Arduino data logger and were set to record temperature with a 10-minute time step. Furthermore, a mobile solar power meter was utilised to measure the solar radiation every 30 min during sunshine hours. Besides, a thermal camera was employed to visualise the outer surface temperature of each brick at different hours. The characteristics of the instruments used in the current research are indicated in Table 2.

2.3. Performance evaluation of test bricks

The thermal behaviour of modified bricks was examined in terms of the reduction of maximum inner surface temperature, temperature fluctuations and peak temperature shifting. The reduction in the maximum inner surface temperature was calculated as the temperature difference between the outer and inner surfaces of each brick (i.e., T_o - T_i). In which T_o stands for the maximum outer surface temperature, while T_i refers to the maximum inner surface temperature of the brick (in °C). Damping of temperature fluctuations, commonly called the decrement factor, indicates the ability of bricks to damp the temperatures considering the maximum and minimum ones for both the inner and outer surfaces, according to Eq. (1) [38]:

$$\text{Decrement factor} = \frac{T_{i,max} - T_{i,\ min}}{T_{o,max} - T_{o,\ min}} \tag{1}$$

where $T_{i,\text{max}}$ and $T_{i,\text{min}}$ refer to the maximum and minimum temperatures on the inner surface of test bricks during the whole thermal cycle. Similarly, $T_{o,\text{max}}$ and $T_{o,\text{min}}$ represent the maximum and minimum temperatures on the outer surface of test bricks (in °C).

The peak temperature shifting, commonly known as the time lag, is another aspect to be calculated, considering the time at peak temperature on the inner and outer surfaces of bricks. Mathematically, the time lag was calculated using Eq. (2) [39], in which $\tau_{\text{Ti,max}}$ refer to the time at peak inner surface temperature, while $\tau_{\text{To,max}}$ is the time at the peak outer surface temperature of bricks (in min).

$$\text{Time lag} = \tau_{\ T_{i,max}} - \tau_{T_{o,max}} \tag{2}$$

3. Results and discussion

3.1. Study location

The test was conducted under the hot weather conditions of Al Amarah City, Iraq. This desert location is characterised by high solar radiation values and long sunshine hours during summer months, especially in June, July, August and September. Besides, the ambient temperature (Tamb) is too high throughout the day, exceeding 47 °C during the day, and 30 °C at night, making the use of air-conditioning systems a must. Besides, the direct solar radiation recorded during the day was also high, surpassing 1000 W/m^2 in the period from 11:30 to 15:30. Fig. 4 displays the solar radiation during the experiment.

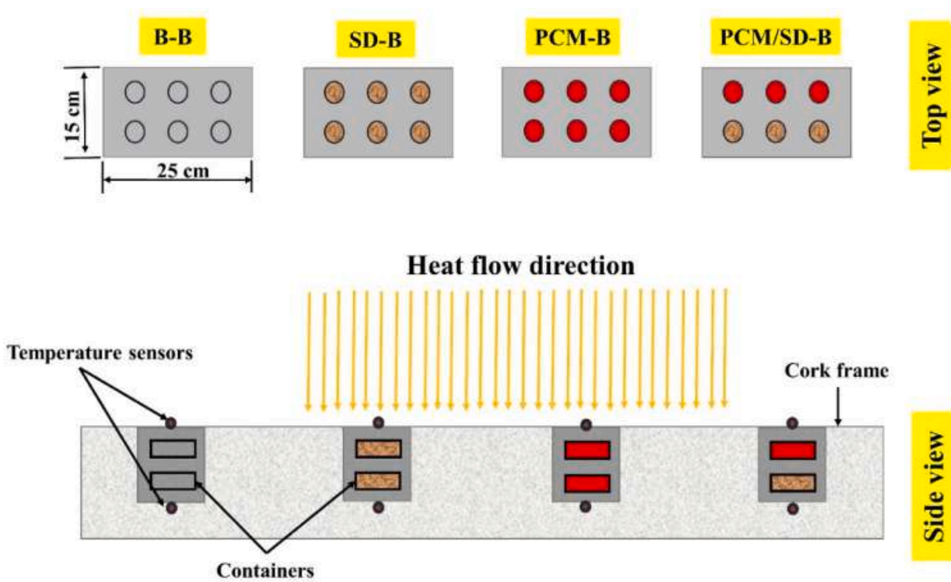

Fig. 1. Schematic views of the modified bricks.

Fig. 2. Production procedure of test bricks.

Table 1
Physical and thermal characteristics of experimental materials [37].

Material	Melting temperature (°C)	Thermal conductivity (W/m.K)	Heat of fusion (kJ/kg)	Specific heat (kJ/kg.K)	Density (kg/m^3)
PCM	40–44	0.21 (for solid and liquid)	190	2.1 (for solid and liquid)	930 (solid) 830 (liquid)
polystyrene	240 °C	0.035	——	1.4	25
Sawdust	——	0.06	——	——	200–260

Table 2
Instrument characteristics according to the manufacturer's technical data sheet.

Instrument	Temperature sensors	Solar power meter	Thermal camera
Brand	T-type	SM206	WB-80VOLTCRAFT$_{®}$
Manufacturer	TEMPSENS (India)	BESTONE INDUSTRIAL Ltd. (China)	VOLTCRAFT® (Germany)
Range	-270 °C – 370 °C	0.1~399.9 W/m^2	-20 °C – 600 °C
Resolution	————	0.1 W/m^2	≤ 254 m.K
Accuracy	± 0.5 °C	±10 W/m^2	±2 % ±2 °C (tested @25 °C)

Fig. 3. Experimental setup.

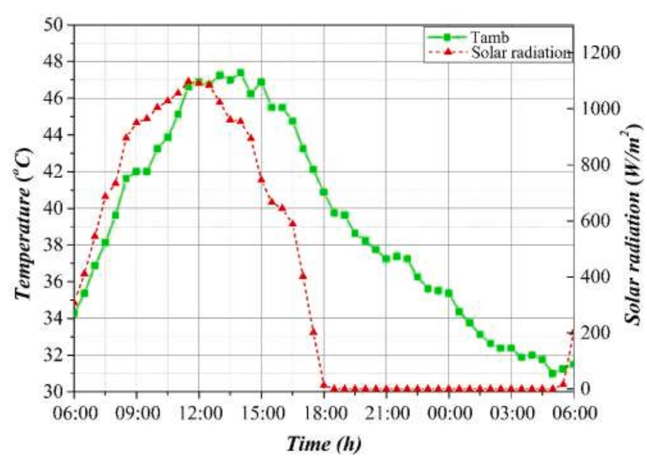

Fig. 4. Ambient temperature and solar radiation measured at the site.

3.2. Analysis of surface temperature

Figs. 5–8 displays the timely variation of inner and outer surface temperatures (Ti and To, respectively) with respect to the ambient temperature of experimental bricks. Fig. 5 demonstrates the variation of outer and inner surface temperatures of the B-B, along with the ambient temperature. Overall, the temperature fluctuations of the outer and inner surfaces are more stable than the ambient temperature. During early morning hours, inner and outer surface temperatures varied with ambient temperature, which gradually increased towards noon, and decreased at sunset. The outer and inner surface temperatures reached the maximum of 58.25 °C at 12:10 and 53.1 °C at 15:10, respectively, attaining 5.15 °C temperature shrinkage, while the maximum ambient temperature was 48 °C at 13:50. After 15:00, the B-B outer and inner surface temperatures were decreases as the ambient temperature decreased, showing higher inner surface temperature than the outer surface temperature until 18:00. This thermal behaviour of B-B is reasonable taking into account its high thermal properties, specifically thermal mass and thermal conductivity, making them sensitive to the changes in ambient temperature which influence the inner and outer

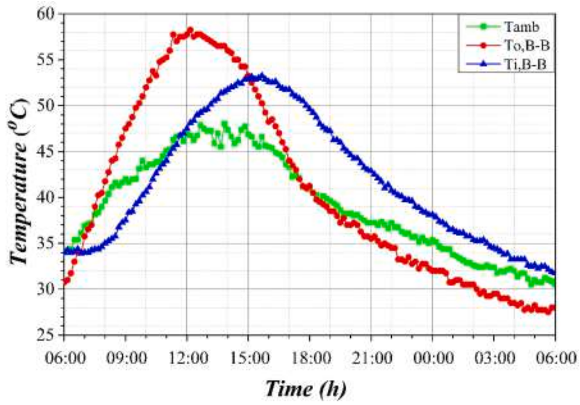

Fig. 5. Timely inner and outer surface temperature of B-B.

surface temperatures.

Fig. 6 shows the temperature behaviour of the concrete bricks integrated with sawdust (i.e., SD-B). It was recorded clear variation of the inner and outer surface temperatures of the SD-B even with early morning, maximum outer surface temperature was 58.75 °C at 12:10 when the ambient temperature 45.6 °C, meanwhile the maximum inner surface temperature was 52.4 °C at 15:50. The inner surface temperature SD-B was lower than that of B-B, by 1.2 °C, indicating lower heat transfer through the SD-B since the sawdust work as an insulation when incorporated into bricks. Thereby, adding sawdust to concrete bricks helped reduce the inner surface temperature, which eventually enhances thermal comfort in buildings. In addition, sawdust is an environmentally friendly material produced from recyclable plant waste that could be used for cost-effective buildings. Despite recording the same temperature behaviour for the SD-B after 15:00, the inner surface temperature of this brick was lower than that of the B-B.

Inclusion of PCMs containers into bricks is an advanced method to enhance the thermal performance of buildings due to the dynamic insulation potential of these materials. The PCM behaviour at high temperature helps store heat without a significant rise in the brick's temperature. However, at sunset when the ambient temperature drops beneath the PCM transition point, the PCM start to freeze slowly, releasing the stored heat towards the inner surface, which keeps it warm for a long time without proper ventilation. Fig. 7 displays the temperature behaviour of the inner and outer surface temperatures of PCM-B. At noon, when the ambient temperature was 46.9 °C, the outer surface temperature of the PCM-B reached a maximum of 58.25 °C. However, the inner surface temperature attained a maximum of 51 °C at 16:10. This temperature drop is high compared with the other tested bricks, with a notable time lag. The PCM inside the bricks helped to stabilise the brick's temperature with minimised values towards the inner surface, lagging the peak inner surface temperature more than the reference brick. Nevertheless, after sunset at 19:00, the inner surface temperature was gradually increasing due to the freezing phase, leaving the inner surface at a high temperature. Despite the negative behaviour of PCM during freezing, its thermal insulation potential has a remarkable role in reducing sudden changes in temperature on the inner surface of bricks.

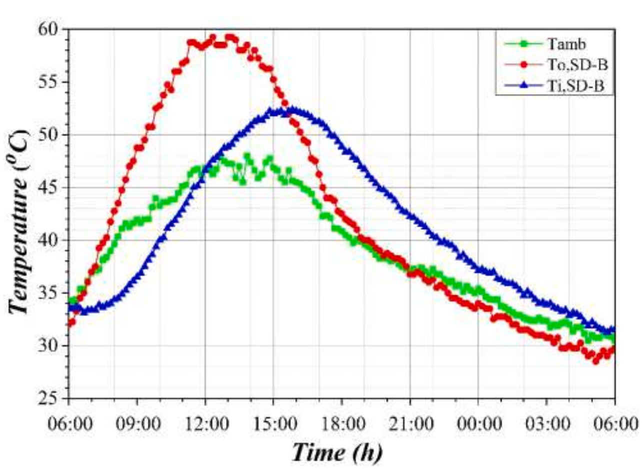

Fig. 6. Timely inner and outer surface temperature of SD-B.

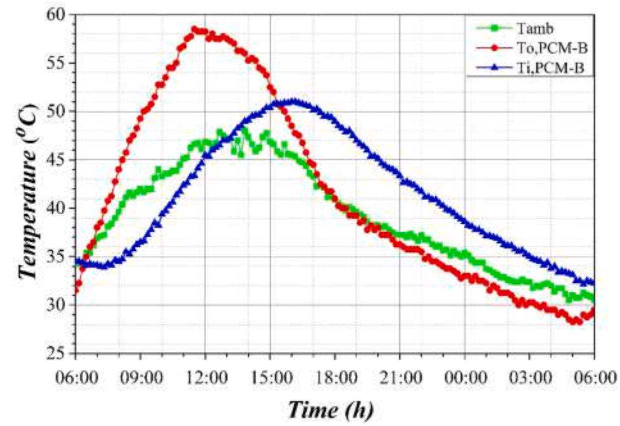

Fig. 7. Timely inner and outer surface temperature of PCM-B.

Fig. 8 shows the thermal behaviour of the PCM/SD-B when the containers of PCMs and sawdust are arranged in a two-line configuration. The outer surface of bricks begins to absorb heat from the sun, and the PCM line begins to melt as the temperature increases above the transition point, releasing the excess heat of the surface temperature. The second line of sawdust containers works to trap heat conducted towards the inner surface of the PCM/SD-B. According to the measurements, the maximum outer surface temperature of PCM/SD-B at 12:30 was 58.25 °C when the ambient temperature was marked around 46.8 °C, while the inner surface temperature was 51.6 °C at 16:00. The inner surface temperature of PCM/SD-B was increasing slightly due to the PCM freezing phenomenon. Then, the inner surface temperature was rising more than the outer surface, following the same trend of PCM-B, due to the heat released uncontrollably from the PCM containers after sunset. Even at 18:00, the inner surface temperature was higher than the outer surface by >2 °C, due to the high stored amount of heat in the PCM containers and lack of ventilation. It can be remarked that both PCMs and sawdust worked as a heat storage and insulation during peak time, slowing down heat transfer from the outer surface that is exposed to direct heat towards the inner surface. Thus, both PCM-B and PCM/SD-B give somewhat similar behaviour after 15:30 due to the PCM freezing

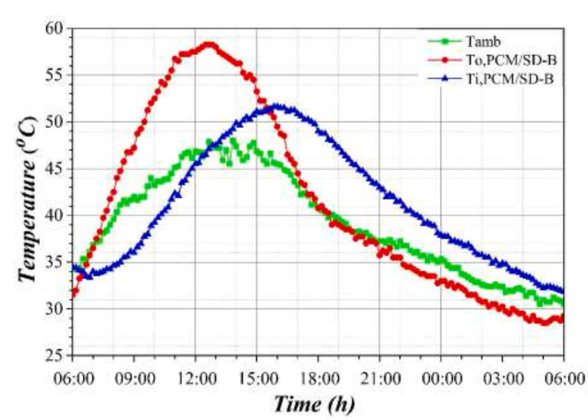

Fig. 8. Timely inner and outer surface temperature of PCM/SD-B.

phase (releasing heat), with superior behaviour for PCM-B over the PCM/SD-B.

Fig. 9 visualises the thermal behaviour of the outer surfaces of the tested bricks at different times. The thermal photos of bricks indicated that the outer surface temperature had fairly the same thermal behaviour from the early morning at 6:00 until 18:00, with slight raising or lowering in the temperatures at 9:00. At this time, the temperature is expected to pass towards the inner surface edge with a specific thermal resistance from bricks at various potentials. The reference brick count on the thermal resistance of concrete raw materials, while the other bricks have a better resistance due to the low thermal conductivity of the SD and PCM. However, the PCM-B and PCM/SD at this time designated a higher outer surface temperature than the other bricks, indicating more heat to be resisted and stored in the PCM containers, trapping the heat in the outer surfaces. At noon, the thermal behaviour is relatively the same for all bricks, except for PCM-B, which displayed a high outer surface temperature. This may contribute to the high resistance potential of PCM containers during peak time, which tries to drag the heat transfer towards the inner edge. This is obvious in Fig. 7, which indicates a lower surface temperature of PCM-B than the others. However, this thermal behaviour was negatively changed in both PCM-B and PCM/SD-B in the late afternoon due to the freezing phase. This is obvious in the thermal photos at 17:00, which show higher outer surface temperatures of B-B and SD-B than those of PCM-B and PCM/SD-B.

3.3. Evaluation of thermal performance of developed bricks

Reducing the heat transfer rate from the outside to the inside surfaces indicates the thermal performance of bricks to be used for energy-efficient buildings. Besides, stabilising and shifting temperature throughout the peak time is also essential to evaluate the building elements under various advancements. This work presents the energy advancement of modified bricks concerning the reduction of inner surface temperature, declining temperature fluctuations and extending the temperature time lag.

The inner surface temperature reduction between the modified bricks with respect to the bare brick is shown in Fig. 10. As could be observed in the figure, SD-B showed higher temperature reduction than the PCM-B and PCM/SD-B till 9:00, and after 18:00 till the next day. This shows the role of low thermal conductivity materials (like SD) in low temperature levels. However, this behaviour has changed at higher temperatures in which the PCM start to be more active than SD when the temperature exceeds the mark of 40 °C- 44 °C. During peak time between 12:00 and 15:00, the PCM-B and PCM/SD-B displayed superior performance compared to the SD-B. The inner surface reduction of the

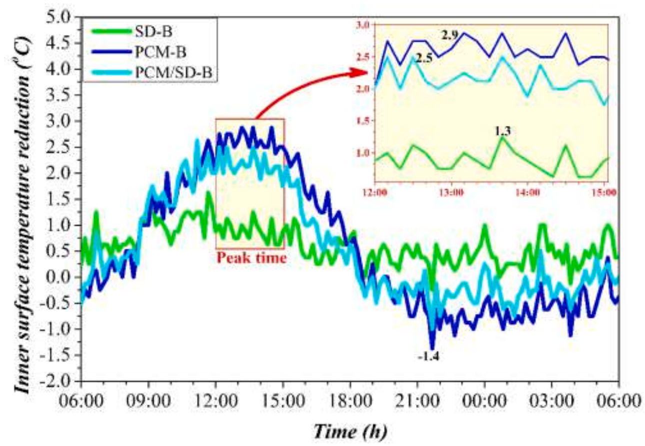

Fig. 10. Inner surface temperature difference of experimental bricks.

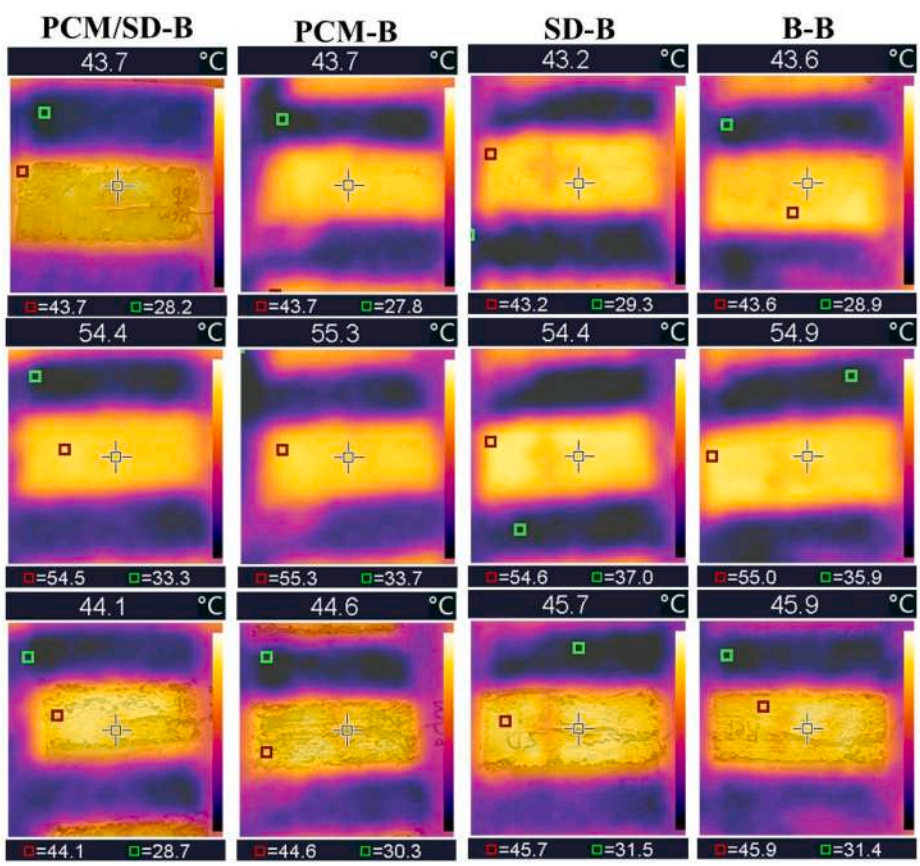

Fig. 9. Thermal photos of experimental bricks at different times.

PCM-B reached a maximum of 2.9 °C during peak time, achieving a preference over the SD-B by 1.6 °C. During the PCM melting phase, the heat absorbed by the brick's outer surface was stored as latent energy without a significant temperature increase in the modified brick, which eventually decreased the inner surface temperature. However, employing PCM and SD in the bricks (PCM/SD-B) showed a lower thermal trend, in which the inner surface temperature was reduced by a maximum of 2.5 °C. This mark shows that replacing three PCM containers with three SD containers has lowered the inner surface temperature reduction by 1.2 °C, emphasising the role of PCM in such harsh climate conditions. Therefore, it can be remarked that although the improved thermal insulation of sawdust, the PCM-B exhibit better thermal performance than PCM/SD-B. However, inclusion of sawdust could reduce the thermal mass of the brick due to its lightweight with a low density, which reduces its ability to store latent heat, while the PCMs need a sufficient thermal mass around for heat absorbing and releasing. Thereby, the PCM-B achieved better thermal performance due to the unimpeded heat transfer, the benefit of the full potential of PCM containers and the thermal mass of PCM-B is preserved.

After sunset, the SD-B showed the best thermal insulation behaviour over the PCM-B and PCM/SD-B. This expected behaviour is attributed to the high thermal energy storage of PCM containers, which start releasing massive stored heat when the outdoor ambient temperature declines. This indicates the negative side of PCM when integrated passively in building constructions. Moreover, the figure showed that the SD-B had a better behaviour than the B-B during the night period since the storage capacity of sawdust is much less than that of concrete.

As mentioned previously, the decrement factor is significant to determine the ability of bricks as construction materials to mitigate the heat transfer from the outer surface to the inner surface and dampen the temperature fluctuations. Therefore, a lower value of the decrement factor indicates better performance of bricks, emphasising the importance of thermal inertia over thermal insulation in this concept. In this regard, Fig. 11 demonstrates the decrement factor calculated for all tested bricks. As could be observed, the higher the PCM involved in the brick, the lower the decrement factor. Consequently, the PCM-B showed a lower decrement factor, followed by the PCM/SD-B, compared to the SD-B and B-B. The B-B showed a lower decrement factor by 9.3 %, 4.7 % and 1.9 % compared to the PCM-B, PCM/SD-B, and SD-B, respectively. In view of that, adding sawdust to the concrete brick helps reduce the temperature fluctuations throughout the day, while incorporating the PCM has minimised the temperature further. This outcome confirms the effectiveness of PCM to stabilise the temperature of the construction element at a level around the PCM melting temperature.

The inner surface temperature of a brick is significantly influenced by the thermal response time, temperature stability and quantity of heat transferred from the outside to the inside. Consequently, the time lag is essential to quantify the heat transfer delay from the outer surface of bricks exposed to the heat source to the inner surface of bricks, shifting the peak load time to the off-load period. Since the construction material's thermal conductivity is important in this matter, integrating the SD and PCM would remarkably influence the time lag. Fig. 12 designates the time lag of the reference and modified bricks, considering the time of peak temperature on the outer and inner surfaces of each test brick. As illustrated, the B-B achieved a 180-minute time lag, while the modified bricks with SD, PCM and PCM/SD achieved 210, 250 and 220 min, respectively. Equivalently, the time lag of the SD-B, PCM-B and PCM/SD-B was extended over the B-B by 30, 70 and 40 min, signifying a modification by 6.37 %, 7.25 % and 6.62 %, respectively. These outcomes indicate a better thermal resistance of PCM-integrated bricks over the insulation-based bricks. This indicates the superior behaviour of the PCM over the sawdust to resist the heat flow towards the inner surface of the brick. However, the PCM freezing phase still represents a challenge to produce high-performance building elements in passive applications.

4. Conclusion

This research investigated the thermal behaviour of concrete bricks integrated with sawdust (SD) and phase change material (PCM) as a sole or combined, tested under a hot location for one experimental day. The SD and PCM were macroencapsulated into plastic containers and examined for a full thermal cycle, considering their role to minimise and shift peak temperature. Three concrete bricks involved with SD, PCM, and PCM/SD were developed and examined against a fourth brick involved with empty containers as a reference. The thermal behaviour and energy contribution of the developed bricks were assessed considering the temperature shrinkage between the outer and inner surface temperatures and time lagging. The outcomes demonstrated that all modified bricks showed better hourly thermal behaviour than the reference brick during peak time. However, the PCM-integrated bricks showed better behaviour than the SD in all studied indicators. However, the PCM displayed negative thermal behaviour in the off-peak time during the PCM freezing phase, influencing the brick performance negatively. Quantitatively, the brick integrated with PCM containers displayed the best thermal behaviour, in which the inner surface temperature was reduced by a maximum of 2.9 °C and shifted by up to 70 min over the reference brick. Besides, the brick integrated PCM and SD showed moderate thermal behaviour, showing maximum temperature reduction, temperature fluctuation damping and time lag extension by 2.5 °C, 4.7 % and 6.62 %, respectively, compared to the reference brick. The PCM-based brick designated negative behaviour during the PCM freezing phase, influencing the inner surface temperature during nighttime.

Although the results achieved in the current research are remarkable

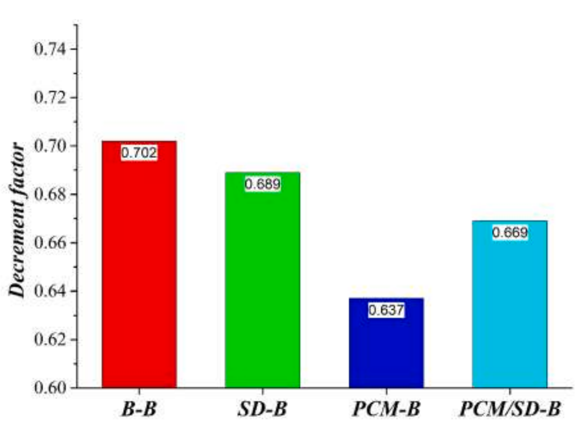

Fig. 11. Decrement factor of bricks.

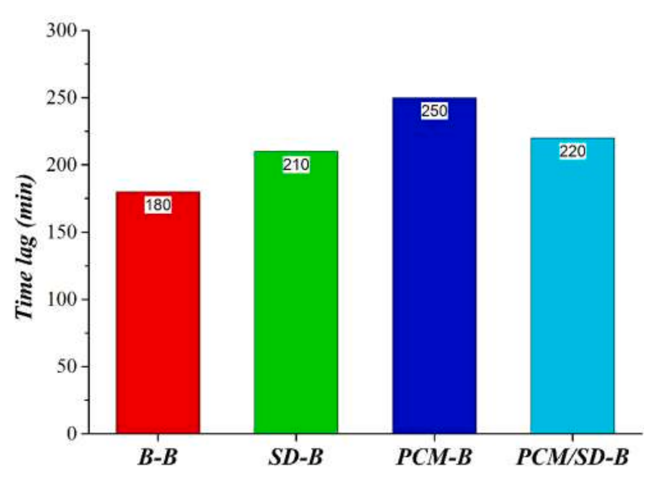

Fig. 12. Time lag of bricks.

for one day, further investigations for a longer time are still needed to confirm to highlight the effectiveness of PCM at different solar radiation rates. For instance, a proper night ventilation mechanism could be adopted to minimise the negative behaviour of the PCM during the freezing phase. In addition, the PCM and sawdust could be integrated homogeneously within the modified brick directly with a careful incorporation methodology to perceive their safety and mechanical characteristics. Besides, the findings of this research could be further adopted to construct scaled rooms and quantify the decline in indoor room temperature and thermal comfort potential of the suggested bricks. This could present a realistic behaviour of PCM and SD towards applicability and commercialising this green technology to develop energy-efficient building envelopes.

CRediT authorship contribution statement

Qudama Al-Yasiri: Writing – original draft, Resources, Investigation, Formal analysis, Data curation, Conceptualization, Methodology, Writing – review & editing. **Mohammed Alktranee:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization, Methodology. **Hayder Al-Lami:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Márta Szabó:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization. **Péter Bencs:** Writing – review & editing, Supervision, Formal analysis, 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.

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Data availability

Data will be made available on request.

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