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Case study

Effect of encapsulation area on the thermal performance of PCM incorporated concrete bricks: A case study under Iraq summer conditions

Qudama Al-Yasiri [a,b,c,*], Márta Szabó [b]

[a] *Doctoral School of Mechanical Engineering, Hungarian University of Agriculture and Life Sciences, Páter K. u. 1, Gödöllő, H-2100, Hungary*
[b] *Department of Building Engineering and Energetics, Institute of Technology, Hungarian University of Agriculture and Life Sciences, Páter K. u. 1, Gödöllő, H-2100, Hungary*
[c] *Department of Mechanical Engineering, Faculty of Engineering, University of Misan, Al Amarah City, Maysan Province, 62001, Iraq*

A R T I C L E I N F O

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Thermal performance
Conductive heat transfer
Heat reduction

A B S T R A C T

In this paper, the thermal performance of phase change material (PCM) incorporated concrete bricks is studied experimentally. Four concrete bricks (three with macroencapsulated PCM and one without PCM represented the reference) are fabricated, and their thermal performance is tested under hot climate conditions. The study considered the effect of PCM encapsulation heat transfer area on brick's thermal performance at the same PCM quantity. PCM bricks included three different PCM capsule arrangements in which the first brick involved one bulky capsule (Brick-B, 4*4*10 cm^3), the second brick had two capsules (Brick-C, 4*4*5 cm^3), and the third brick involved five PCM capsules (Brick-D, 4*4*2 cm^3). The peak temperature reduction (PTR), the conductive heat transfer reduction (HTRc), and the time delay (TD) were presented and calculated, taking into account the inner and outer brick surface temperatures of PCM bricks compared with the reference brick. Results showed that concrete bricks' thermal performance could be remarkably improved using PCM even under maximum outdoor temperatures. Moreover, the best thermal performance is reported for Brick-D, in which the maximum PTR, HTRc, and TD are reached 156.5 %, ~61 %, and ~133 %, respectively, compared with the reference brick under maximum outdoor temperatures.

1. Introduction

Buildings are the major consumer of energy worldwide. Most of the building energy is used for space heating and cooling to provide suitable human thermal comfort. It was reported that the energy spent for space heating and cooling in buildings reached as high as 61 % and 40 % of total residential and commercial building demand [1]. Moreover, the building envelope is responsible for 50 % of direct heating and cooling loads and responsible for 36 % of building final global energy use [2]. Numerous technical solutions have been introduced and investigated to minimise such a high percentage of thermal load, applying different passive and active techniques [3–6]. Amongst recent ones, the incorporation of phase change materials (PCMs) with building envelope elements provided a remarkable enhancement in building efficiency considering energy-saving and thermal comfort [7–9]. PCMs can work as thermal

* Corresponding author at: Doctoral School of Mechanical Engineering, Hungarian University of Agriculture and Life Sciences, Páter K. u. 1, Gödöllő, H-2100, Hungary.
E-mail address: qudamaalyasiri@uomisan.edu.iq (Q. Al-Yasiri).

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Nomenclature

Abbreviations

ATR	Average inner temperature reduction [°C]
HTRc	Conductive heat transfer reduction [%]
PCM	Phase change material
PTR	Peak inner temperature reduction [%]
TD	Time delay [min]

Symbols

A	Area [m^2]
k	Thermal Conductivity [W/m K]
x	Brick thickness [m, mm]
Q	Conductive heat transfer [W]
$Q_{reference}$	Conductive heat transfer of the reference brick [W]
Q_{PCM}	Conductive heat transfer of the PCM bricks [W]
SR	Solar radiation [W/m^2]
T_i	Inner brick surface temperature [°C]
$T_{i,av}$	Average inner brick surface temperature [°C]
T_o	Average outer brick surface temperature [°C]
$\tau_{Ti,max}$	The time at the maximum brick inner surface temperature [min]
$\tau_{To,max}$	The time at the maximum brick outer surface temperature [min]

energy storage in the building envelope by controlling the heat energy during phase transition and work as heat barrier (insulator) or supplier.

Building walls are the primary source of heating/cooling loads in buildings due to their large area compared to other building elements. Therefore, many studies have considered the possible advancements for this essential element [10,11]. Several studies have discussed integrating PCMs with walls as a separated layer that may suffer from leakage and economic concerns due to large walls area [12–14]. Besides, other studies have investigated the PCM incorporation into bricks as they represent the building walls' main construction element [15–19].

Several studies in the literature have reported the incorporation of PCMs in the constructive bricks with different approaches. Amongst the recent, Mahdaoui et al. [20] numerically investigated the effect of PCM capsules on the heat transfer reduction and temperature fluctuation reduction when incorporated into hollow bricks under Moroccan climate conditions. They discussed different PCM quantities, namely 6 %, 10 %, 16 % and 20 % of the brick volume. The results showed that the thermal performance of brick was improved as the PCM quantity increased. Moreover, the best results were obtained for the bricks of 16 % and 20 % PCM that showed similar performance and reduced the indoor temperature to thermal comfort levels. Jia et al. [21] numerically compared the effect of thermal insulation material and PCM on hollow bricks thermal performance. The main findings indicated that the thermal insulation material could increase the brick thermal resistance, whereas the PCM increased the thermal inertia. Besides, they concluded that both thermal insulation material and PCM could significantly improve the thermal performance of brick and shift the peak load. Erlbeck et al. [22] studied the performance of concrete blocks based on different PCM capsule packages (namely, plate-shaped, cylindrical, cuboid and spherical packages) having different quantities. The main findings indicated that plate-shaped capsules have the best heat transfer behaviour during melting and solidification phases. Mukram and Daniel [23] experimentally tested two cement blocks, one with PCM and the other without PCM. They aimed to study the inner temperature and cooling load reduction under laboratory-controlled conditions. The results indicated that the maximum ambient temperature was reduced by up to 5 °C and the cooling load decreased by 11.88 % for the PCM cement block compared with the block without PCM. Tunçbilek et al. [24] numerically investigated the best performance of hollow bricks based PCM under climate conditions of Marmara region, Turkey, on a seasonal and annual basis. They discussed the best PCM melting temperature, PCM quantity and position compared with the conventional bricks with air gaps. Results revealed that the best PCM melting temperature was dependant on the season in which the annual thermal demand was reduced by 17.6 % at the best case. Sexana et al. [25] experimentally tested two PCM types, macroencapsulated using rectangular containers under hot weather conditions of Delhi, India. They proposed two PCM arrangements, single and dual, to investigate heat transfer and temperature reduction. The results showed that the brick inner surface temperature was decreased by 4.5 °C–7 °C, and the heat transfer was reduced by 40 % and 60 % using single and dual arrangements, respectively.

In this paper, an experimental study was performed to investigate the thermal performance of concrete bricks involving PCM capsules under Iraq's hot weather conditions. Four concrete bricks (three with a macroencapsulated PCM and one without PCM) were fabricated, and their thermal performance was tested in terms of peak temperature reduction, conductive heat transfer reduction and time delay of heat. The main parameter considered in this work is the effect of encapsulation heat transfer area to compare PCM bricks against the brick without PCM. This investigation scope has limited attention in the literature according to the best knowledge of the authors. The current work also aims to introduce a new type of concrete bricks that rely on a locally available PCM with suitable encapsulation arrangements that contribute significantly to the thermal engineering science of buildings.

2. Materials and methods

2.1. Experimental set-up

In the current work, four concrete bricks (including a reference one) were designed, fabricated and experienced under hot weather conditions of Al Amarah city ((Latitude: 31.84 ° & Longitude: 47.14 °), Iraq. This brick type is mainly used to construct the building walls and fences in the residential and governmental buildings in the country. Despite the good mechanical properties and competitive cost of concrete bricks, they suffer from poor thermal performance compared with the other bricks in the country, making it the worst construction option [26]. The constructed bricks are termed as Brick-A (reference brick), Brick-B, Brick-C and Brick-D for the PCM concrete bricks, as indicated in Fig. 1. The tested bricks were placed in a properly designed high-density cork frame (80 mm thickness), made of Isofoam products (straibor boards) that were produced by Gulf insulating material Co., the leading company in Iraq and Middle East [27]. These cork boards are locally used for roofing and flatting works thanks to their high insulation ability ($k = 0.033-0.39\ W/m^2.K$) [28], which ensures high insulation quality in the experiment. The frame was shielded further using a fibreglass blanket T_o increase thermal insulation further. Tested bricks were positioned in the frame, and thermal insulation foam was used between the brick edges and the frame to seal and prevent air leakage.

2.2. Fabricating of PCM bricks

The concrete bricks investigated in this work were constructed with a 23 cm length, 12 cm width and 7 cm depth. Three PCM concrete bricks were fabricated with immersed PCM capsules during the moulding process. The PCM capsules were made from an aluminium bar (1 mm thickness) with a square cross-section area. The bar was cut into three different size groups, as shown in Table 1 and Fig. 2. Every PCM brick held the same PCM quantity (~145 g) to maintain a fair comparison among PCM bricks compared to the reference brick. PCM capsules were placed centrally and symmetrically inside each PCM concrete brick to ensure good thermal behaviour and maintained brick strength.

The PCM used to prepare PCM capsules is a locally available paraffin wax extracted during the Iraqi oil dewaxing process in the petroleum refineries. This PCM type has many desired properties such as good thermophysical properties (Table 2), stability under many thermal cycles, environmentally friendly and compatibility with aluminium containers [29,30].

The concrete was prepared using the mixing ratio 1:1.5:3 (cement/sand/gravel), the popular low-density concrete blocks in the country [28,32]. The paraffin was melted and poured inside the aluminium capsules till solidified and capped using an aluminium cover (1 mm thickness). Finally, PCM capsules were immersed carefully inside the concrete and left to dry naturally. Fig. 3 shows the procedure followed to prepare the PCM capsules and concrete bricks.

2.3. Measurement devices

A data logger based multi-channel Arduino (type Mega 2560) and T-type thermocouples were used to measure the outer and inner brick surface temperatures. Two thermocouples (sensors) were used for each brick, one placed on the outer brick surface and the other were centered in the inner surface (see Fig. 1). It is worth mentioning that inner sensors were inserted through tiny holes made in the

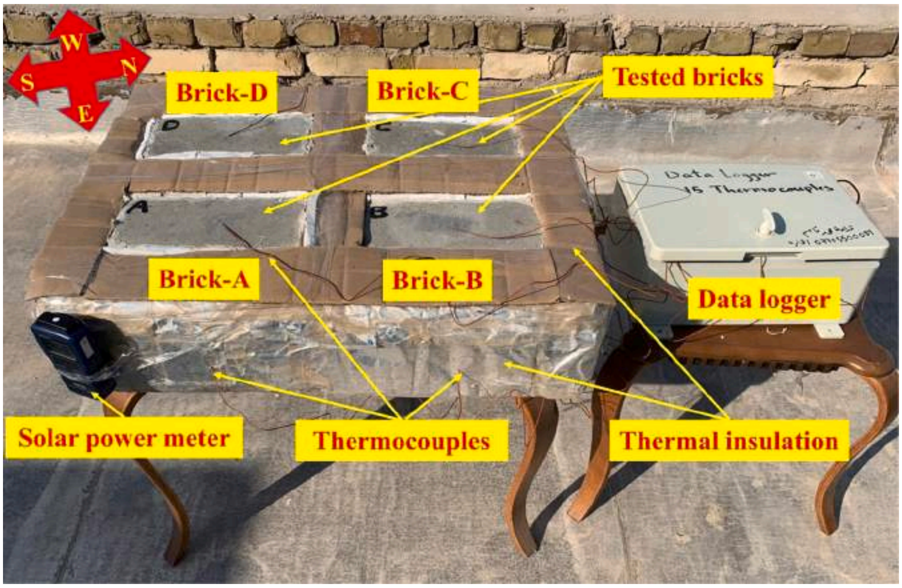

Fig. 1. Experimental set-up.

Table 1
Dimensions and specifications of PCM concrete bricks.

Brick sample	Capsule dimensions (cm)	No. of capsules	Encapsulation heat transfer area (cm^2)
Brick-A	–	–	–
Brick-B	4*4*10	1	192
Brick-C	4*4*5	2	224
Brick-D	4*4*2	5	320

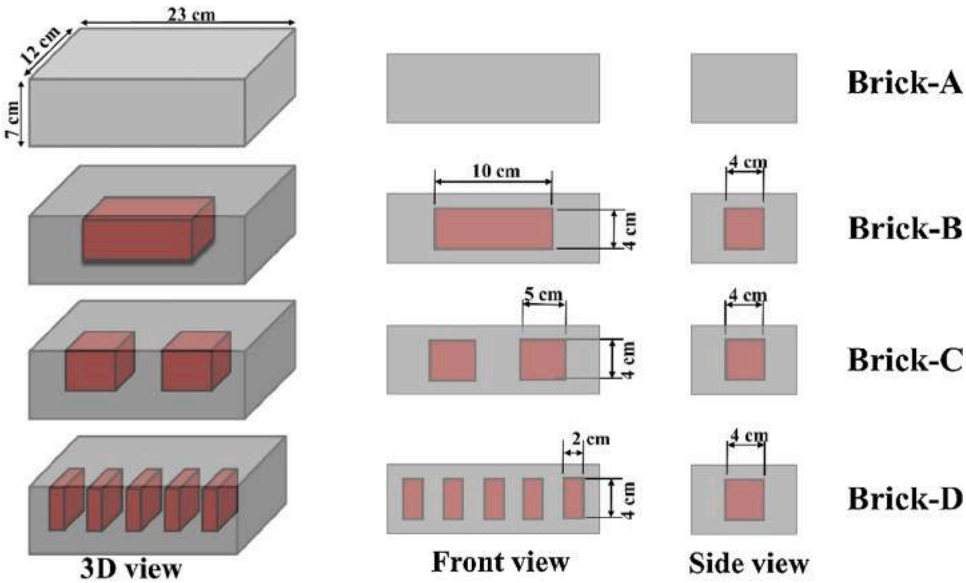

Fig. 2. Schematic of concrete bricks.

Table 2
Thermophysical properties of paraffin wax [31].

Thermal/physical property	Value/Property
Appearance	Whitish
Melting temperature (°C)	44
Thermal conductivity (W/m K)	0.21
Density (kg/m^3)	930 (solid) 830 (liquid)
Latent heat of fusion (kJ/kg)	190
Specific heat (kJ/kg K)	2.1

cork frame and insulation blanket and foamed to prevent air leakage. The outer sensors were averaged in the measurements and referred to as outer brick surface temperature (T_o), whereas the inner sensor was kept fixed for each brick (T_i).

The data logger has been programmed to measure the temperatures every 10 min to collect the temperature fluctuation throughout the day. The data logger provided a storage memory to save the measurements during the day and night continuously. Besides, the solar radiation (SR) during the day hours was measured manually every 30 min using a solar power meter. More specifications and error range for the used instruments are listed in Table 3.

2.4. Brick's thermal performance assessment

The thermal performance of tested bricks can be assessed using different methods. In this research, peak temperature reduction and conductive heat transfer reduction were presented and discussed. These methods can directly compare the tested PCM bricks and reference brick in terms of T_i and T_o.

2.4.1. Peak temperature reduction (PTR)

The reduction of brick's inner surface temperature due to incorporating PCM with the building envelope is the forefront benefit of the built environment [34]. The average reduction of T_i (ATR) for each brick calculated by considering the difference between T_o and

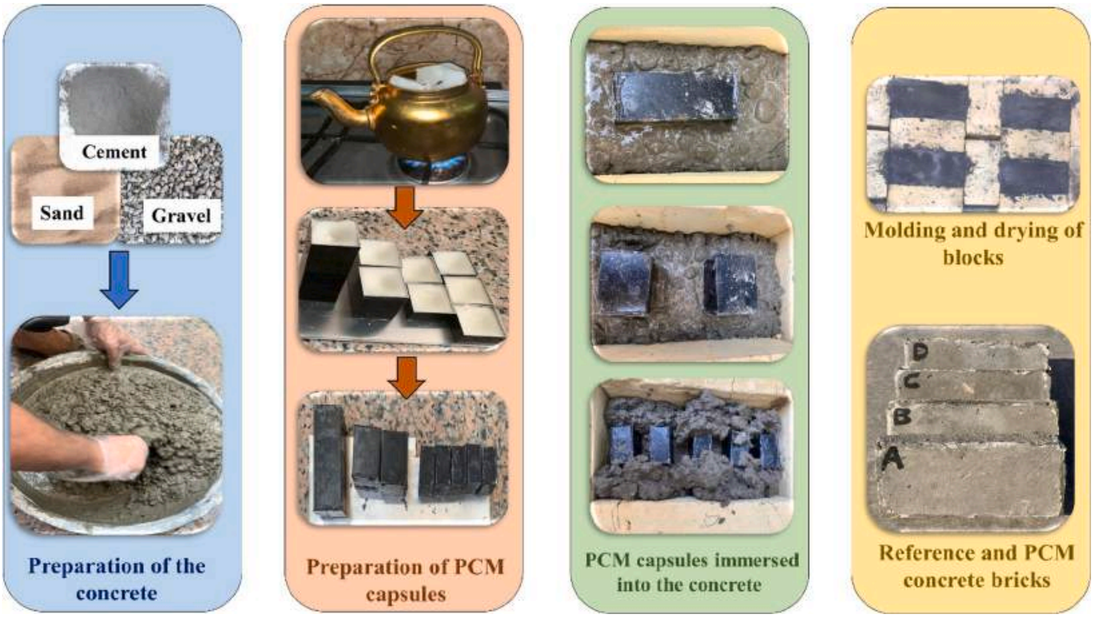

Fig. 3. Preparation of PCM concrete bricks.

Table 3
Specification and measurement errors of the instruments [33].

Instrument	Model	Range	Resolution	Accuracy
Thermocouples T-type (0.2 mm)	TEMPSENS	−270 °C to 370 °C	–	+/−0.5 °C
Solar power meter	SM206	0.1∼399.9 W/m^2	0.1 W/m^2	±10 W/m^2

T_i of bricks during maximum outdoor temperature hours (namely from 11:00 to 15:00), in each day cycle according to Eq. (1), as follows:

$$ATR_{Brick} = T_o - T_{i,av.} \tag{1}$$

where $T_{i,av.}$ is the average inner temperature of bricks during maximum outdoor temperature hours (°C). Eq. (1) is used to calculate the PTR to compare among PCM bricks considering ATR of the PCM and reference bricks, according to Eq. (2), as follows:

$$PTR = \frac{ATR_{PCM} - ATR_{reference}}{ATR_{reference}} \times 100\% \tag{2}$$

2.4.2. Conductive heat transfer reduction (HTRc)

The conductive heat transfer (Q) through the tested bricks is calculated according to Fourier's formula by considering the inner and outer surface temperatures (i.e., $T_{i,av.}$ and T_o) for steady-state, one-dimensional heat flow (Eq. (3)), as follows:

$$Q = \frac{T_o - T_{i,av.}}{(x/kA)} \tag{3}$$

where x is the thickness of tested concrete brick (m), k is the thermal conductivity of concrete bricks (W/m °C), and A is the surface area of brick perpendicular to the flow of heat (m^2). In this work, k is assumed to be equal for all bricks (1.4 W/m °C, [28]) to simplify the calculation procedure.

HTRc in the PCM brick compared with the reference brick is calculated considering Q of PCM and reference bricks according to Eq. (4), as follows:

$$HTRc = \frac{Q_{reference} - Q_{PCM}}{Q_{reference}} \times 100\% \tag{4}$$

2.4.3. Time delay (TD)

The time difference between the maximum temperature of the inner and outer surfaces of brick is called TD. This delay attributes to the thermal resistance of brick against the flow of heat. In this case, TD is calculated by applying Eq. (5) [35], as follows:

$$TD = \tau_{T_{i,max}} - \tau_{T_{o,max}} \quad (5)$$

where $\tau_{Ti,max}$ and $\tau_{To,max}$ are respectively the time at the brick's maximum inner and outer surface temperatures.

3. Results and discussion

This experimental work was lasted for three consecutive hot days of September 2020, starting from 6:00 of 21-23.09.2020. This month is among the hottest in the country, characterised by high ambient temperature and SR. Fig. 4 shows the weather conditions of September in Iraq for the location under study. The days of experiments were selected carefully in advance, forecasted to have almost the same temperature rising and clear sky conditions.

The incident SR and temperature variation in each half-hour were recorded continuously, as presented in Fig. 5. As expected, the higher SR was recorded in midday hours around noon and decreased dramatically in the late afternoon. Accordingly, the outer brick surface temperature (i.e., T_o) increased as the SR increase. However, an apparent time lag is noticed between the highest SR and T_o.

Similarly, T_i increased with a time delay as T_o increased and reached lower values for PCM bricks than the reference brick. The highest T_o recorded in the experiment was 63.125 °C, 63.188 °C and 63.23 °C, respectively, in the first, second and third experimental days. These values were encountered with the highest SR of 1197, 1204 and 1207 W/m^2, respectively, around midday.

In general, T_i values for PCM bricks (i.e., Brick-B, Brick-C and Brick-D) were lower than those of reference brick (Brick-A) during sunshine hours and relatively adverse behaviour during the night period. PCM bricks were had lower T_i values than reference brick temperature during the maximum outdoor temperature period, as presented for one day in Fig. 6. This behaviour shows the role of PCM capsules in minimising the flow of heat when subjected to high outdoor temperatures.

Night cooling is essential for passive applications as it influences the effectiveness of PCM when fully or partially discharges the heat from the encapsulated PCM. Considering the period 20:00 up to 6:00 in Fig. 5, it is obvious that Brick-D had the lowest T_i compared with the other PCM bricks, proving the positive effect of a large encapsulation area during the discharging time. Surprisingly, Brick-B and Brick-C almost had the same influence at this period, mainly because they have relatively equal encapsulation heat transfer areas (indicated in Table 1).

Variation of T_i for Brick-D was the best of PCM bricks behaviour followed by Brick-C. Besides, Brick-D showed the worst thermal performance among PCM bricks and was sometimes relatively similar to the behaviour of reference brick. The main reason for that may attribute to the immense heat transfer area of encapsulation for Brick-D compared with other PCM bricks. This large area provides more heat to be stored in the PCM during maximum outdoor temperature hours due to the high thermal conductivity of encapsulation material (i.e., aluminium). Similarly, a large heat transfer encapsulation area can positively affect the discharging of heat during off-peak hours (night period). This can be noticed in the behaviour of T_i during the late-night period in Fig. 5.

The calculations of ATR and PTR during maximum outdoor temperature hours are presented in Fig. 7.

As designated in the figure, all PCM bricks showed better temperature reduction than the reference brick. Generally, the brick that has more PCM capsules showed better thermal performance (i.e., $ATR_{Brick-D} >> ATR_{Brick-C} > ATR_{Brick-B}$). This is mainly attributed to the increased heat transfer area, making the PCM melt totally during harsh weather conditions. The high melting temperature of the used PCM required more heat transfer area provided by the encapsulation container to store more heat flowing from outside towards inside. Besides, PCM poor thermal conductivity could affect heat charging and discharge, which results in poor thermal performance for bulky PCM. Fig. 7 also indicate that Brick-B has PTR exceeded 150 % in all day cycles, reflecting a superior thermal performance for this PCM brick compared with the reference one. Moreover, Brick-C also showed a good PTR in the first and second cycles with lower performance for Brick-B.

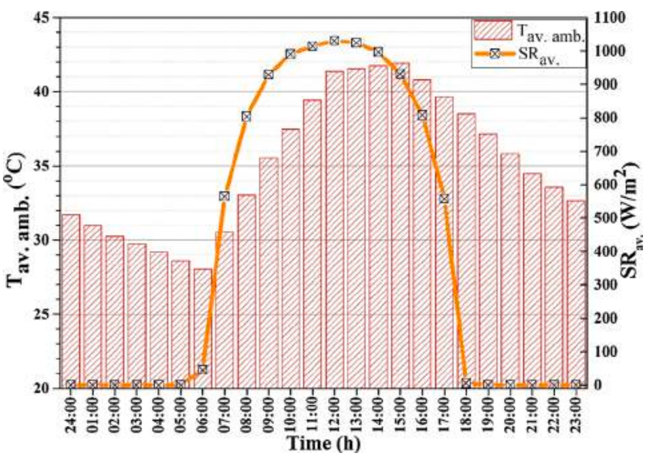

Fig. 4. Average ambient temperature and solar radiation of the location of the experiment during September 2019 [36].

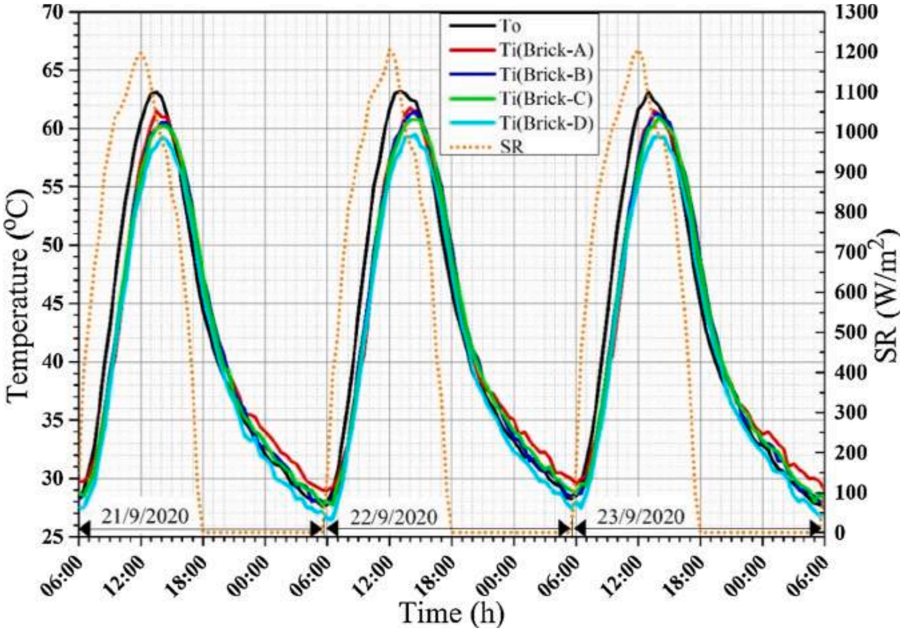

Fig. 5. T_o, T_i and SR variation during experimental days.

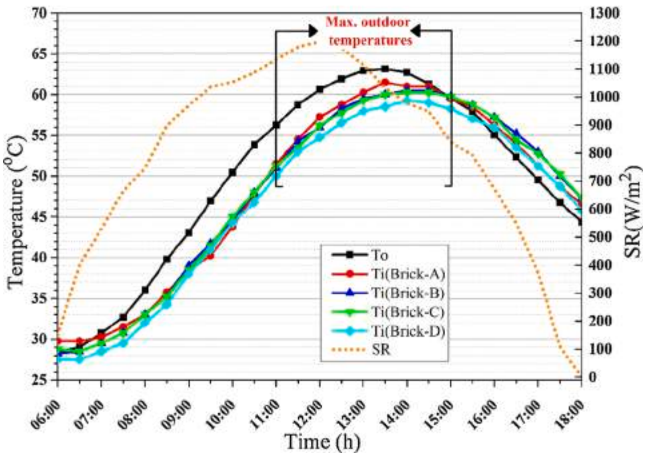

Fig. 6. Temperature variation of bricks during sunshine hours in 21/9/2020.

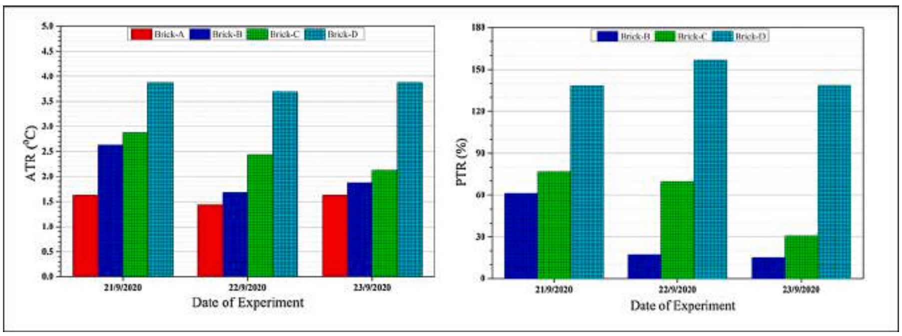

Fig. 7. ATR (left) and PTR (right) of concrete bricks during maximum outdoor temperatures.

Fig. 8 shows the calculation results of HTRc for PCM bricks. As expected, the best thermal performance was reported for Brick-D followed by Brick-C and then Brick-B because Q values were dependent mainly on the average T_i during maximum outdoor temperature hours (Eq. (4)). The best HTRc for Brick-D was calculated as ~58 %, ~61 % and ~58 % in the first, second and third cycle compared with the reference brick.

Brick-B that has a bulky PCM capsule showed the worst performance in all cycles. This may indicate that the PCM was not melted entirely during maximum outdoor temperature hours, and the heat transferred through the brick coming from outside more than the other PCM bricks. Likewise, Brick-C indicated moderate thermal behaviour compared with Brick-B and Brick-D. It is worth mentioning that the size and position of the PCM capsule(s) affect the HTRc. For instance, the PCM capsule in Brick-B has covered a limited brick area (i.e., 40 cm^2 out of 276 cm^2), meaning that the other brick area acted as a pure reference brick and influenced the T_i. Although PCM bricks showed remarkable enhancements compared with the reference one, this thermal behaviour is limited to the experimental work period and encountered conditions. In other words, the HTRc of PCM bricks varies during working cycles throughout the year depending on the level of heat that would restrict, which is mainly influenced by the weather conditions (SR, ambient temperature, wind speed, etc.).

Fig. 9 shows the calculation results of TD for bricks during the maximum inner and outer surface temperatures. As observed from the figure, PCM bricks generally have a better thermal response than the reference brick. This is mainly attributed to the activation of PCM in each brick, partially or entirely. TD in the reference brick was ranged between 30−40 min against 40−50 min, 50−60 min and 70−80 min in Brick-B, Brick-C and Brick-D, respectively.

Brick-D showed the best TD in all experimental days compared to Brick-B and Brick-C, meaning that the heat transferred from outside towards inside was shaved (according to Fig. 7) and shifted considerably. These results show that the PCM in Brick-D was utilised efficiently due to the large encapsulation area that accelerated the melting time and guaranteed more heat to be stored in each PCM capsule.

4. Conclusions

The present study investigated the effect of PCM encapsulation heat transfer area on the thermal performance of concrete bricks experimentally. A PCM of high melting temperature (~44 °C) was encapsulated using different-sized aluminium capsules, having the same square cross-section area and PCM quantity, immersed passively in concrete bricks and tested under hot summer conditions of Iraq. The thermal performance in terms of PTR, HTRc and TD was considered to compare tested PCM bricks against a reference one. It was found that the PCM of high melting temperature can significantly improve the thermal performance of concrete bricks under maximum outdoor temperatures. Moreover, the overall encapsulation area plays a predominant role in increasing the heat transfer to/from the PCM and improve charging and discharging. Hence, the larger the encapsulation area, the higher the temperature and heat transfer reduction, and the longer the heat time delayed. The best PTR and HTRc were calculated for Brick-D as 156.5 % and ~61 % mainly because it had a large capsules heat transfer area (320 cm^2) compared with Brick-A, followed by Brick-C and Brick-B (224 and 192 cm^2, respectively). Moreover, the best TD was obtained for Brick-D with a 70−80 min range compared with 30−40 min for the reference brick (i.e., Brick-A), equal to about 133 % increment in the peak time-shifting.

5. Limitations and future work

This work has discussed the influence of PCM encapsulation area on the thermal performance of concrete bricks under severe hot summer conditions in Iraq. The results presented are limited to the location and period of experimentation. However, the same findings are expected during the other severe hot months (June, July, August and September). The outcomes depend highly on the changeable

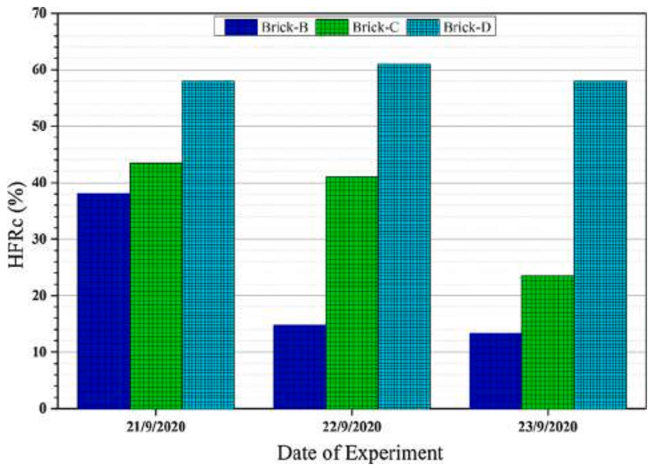

Fig. 8. HTRc of PCM bricks compared with the reference brick.

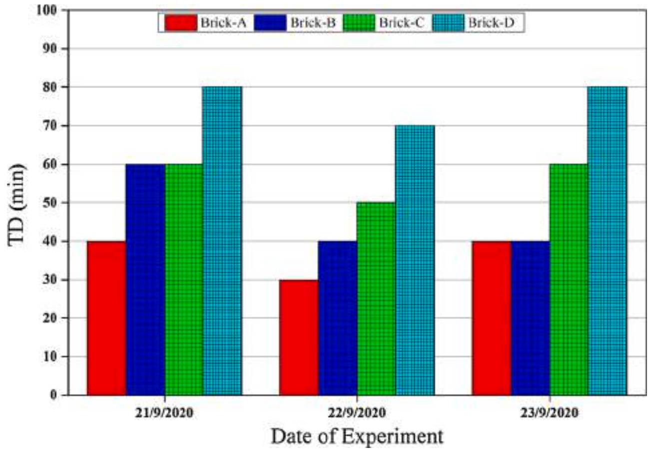

Fig. 9. TD for PCM and reference bricks.

weather conditions in the other months, especially when the ambient temperature drop below 44 °C.

The results presented in this work will be used for future experimental studies to investigate the contribution of passive PCM incorporation within building envelope elements (roof and walls). This is part of an experimental series conducted under the exact location and weather conditions to specify the best case for PCM position, thickness and brick thermal performance.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

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