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Thermal performance of concrete bricks based phase change material encapsulated by various aluminium containers: An experimental study under Iraqi hot climate conditions

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ABSTRACT

This study presents the experimental results of concrete bricks based macroencapsulated phase change material (PCM) in different capsule designs (circular, square and rectangular cross-sections). Eight concrete bricks (including a reference brick without PCM) are fabricated, and their thermal performance is tested under hot summer conditions of Al Amarah city, Iraq. The study considered several indicators such as the interior maximum temperature reduction (MTR), decrement factor (DF) and time lag (TL) to compared among tested bricks in addition to the thermal behaviour during melting and solidification of PCM. Results indicated that all PCM based bricks are performed better than the reference brick in which the maximum interior temperature is shaved and shifted. Moreover, the best thermal performance is reported for bricks of large PCM capsules number. Amongst others, the brick-based square cross-section PCM capsules showed the best thermal contribution where the average MTR of 1.88°C, average DF of 0.901 and average TL of 42.5 min were obtained compared with the reference brick. The study concluded that PCM capsules' heat transfer area is the main parameter that controls PCM's thermal behaviour as long as all PCM capsules have the same PCM quantity and position. Therefore, excessive encapsulation area might influence the thermal performance of concrete brick and should be specified for the efficient use of PCM storage capacity.

1. Introduction

Building sector shares about 40% of the total energy consumption worldwide. This share will increase due to the increment of energy consumption for space heating and cooling by 12% and 37%, respectively, in 2050 [1]. The most significant percentage of building energy can be saved through the building envelope. In this regard, it has been reported that building construction and operations accounted for 36% of the final global energy used in buildings and 39% of the energy-related CO_2 emissions in 2018 [2]. Therefore, serious actions have to be taken to limit this consumption by implementing various renewable technologies and systems. Amongst booming technologies, incorporating phase change material (PCM) is a fast-growing technology in the building industry that has been implemented to improve thermal performance and energy-saving [3–6].

Due to their high area, exterior walls represent the main drawback when considering the heat transfer exchange rate within the building envelope and can be improved remarkably by applying PCMs [7,8]. PCM incorporated bricks have been studied as an efficient passive solution to improve building walls' energy efficiency [9,10]. As bricks are the primary construction material of walls worldwide, PCM can remarkably increase their storage capacity, especially for thin walls (the popular pattern in hot climates) [11].

Researchers have been studied the contribution to the energy saving of PCM based bricks and reported exciting findings. Among others, Aketouane et al. [12] numerically studied PCM's thermal performance incorporated hollow bricks under six regions in Morocco. Main findings showed that the PCM could remarkably reduce the heat flux peak values. Moreover, PCM of 27°C melting temperature can save the building's energy in the Saharan climate and oceanic climate by up to 25% and 40%, respectively. Tunçbilek et al. [13] studied PCM's thermal behaviour incorporated conventional bricks and its contribution to

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energy-saving on a seasonal and annual basis under the Marmara region's climate conditions, Turkey. In their study, different PCM melting temperatures were studied (18°C – 26°C) with different quantities and positions concerning the interior and exterior environments. Numerical results showed that filling brick gaps near the interior environment resulted in better energy conservation and the optimal PCM performance depends highly on the season. However, the best thermal performance was reported for PCM of 18°C melting temperature. Furthermore, the heating and cooling loads were reduced by 17.6% and 13.2%, which provided adequate thermal comfort. Alawadhi et al. [14] have numerically studied the thermal performance of PCM bricks (based cylindrical holes filled with PCM) compared with standard bricks in terms of heat flux reduction. They considered different parameters such as PCM type (n-Octadecane, n-Eicosane and P116 of melting temperature 27°C, 37°C, and 47°C, respectively), PCM quantity and the best position for the holes inside bricks. Numerical results showed that n-Eicosane showed the best thermal effectiveness, and increasing PCM quantity resulted in better performance. Moreover, the central position is the best for PCM thermal performance and brick mechanical strength. The highest heat flux reduction reached 17.55% when n-Eicosane filled three holes at the centre position. Castell et al. [15] experimentally studied five cubicles based different options of bricks macro-encapsulated PCMs (SP-25 A-8 and RT-27 of respectively 26°C and 28°C melting temperatures) under climatic conditions of Puigverd de Lleida, Spain. Results showed that the peak temperature and electricity consumption was reduced by up to 1°C and 15%, which resulted in lower CO_2 emissions by 1-1.5 kg/year/m^2.

Saxena et al. [16] experimentally examined two PCMs (n-Eicosane and OM35) incorporated bricks under hot weather of Delhi, India as a passive strategy to reduce the brick interior surface temperature and heat transfer flow. Calculated results reported a temperature reduction by 5-6°C across PCM bricks and reduced 8% and 12% of heat transfer for n-Eicosane and OM35 bricks, respectively. Under the same conditions, Saxena et al. [17] have studied the thermal behaviour of single and dual macroencapsulated PCM layers (1-1.3 cm thickness) embedded inside bricks. Findings showed that peak temperature reduced by up to 6°C and 9.5°C along with a heat transfer reduction of 40% and 60% for single and dual PCM bricks compared with the conventional bricks. Wang et al. [18] experimentally investigated a new type of PCM bricks based on expanded graphite and paraffin (paraffin 70% by weight) used for wall constructions. Their study considered the PCM wall's thermal performance compared to a conventional wall under different climate conditions. Under summer conditions, results showed that the PCM brick reduced the maximum interior wall surface temperature by 0.2°C and resulted in a cooling load reduction of 24.32% and a time lag of 1-2 h compared with the conventional wall performance.

In this paper, the thermal performance of PCM incorporated concrete bricks was experimentally studied over four consecutive days under actual hot summer conditions of Al Amarah city (Latitude: 31.84° & Longitude: 47.14°), Iraq. Paraffin wax of high melting temperature (∼44°C) was used as a thermal energy storage medium, macro-encapsulated with the same quantities inside different aluminium capsules and incorporated inside concrete bricks. Eight concrete bricks (including the reference brick) were tested, and their thermal performance was evaluated in terms of the reduced interior temperature, decrement factor and time lag. Furthermore, the thermal performance of bricks during the melting and solidification phases was assessed. The thermal performance of bricks based diverse options of capsules (circular, square and rectangular) was evaluated and compared. This work performed useful information regarding the best option for PCM based bricks for wall applications.

2. Materials and methods

2.1. Description of the experimental set-up

Eight concrete bricks were fabricated and tested under summer hot climate conditions of Al Amarah city, Iraq. The bricks were made from concrete as they have the worst thermal performance compared to local brick types and result in high cooling loads [19]. They have been mixed with a ratio of 1:1.5:3 (cement/sand/gravel), the popular mixing ratio of concrete bricks in the country of Iraq [20,21]. The bricks were fabricated with the dimensions length, width and depth of 23, 12 and 7 cm to control PCM capsules' position and maintain a suitable experimental set-up. The first brick sample is the reference brick (A), and the other seven samples were made with PCM capsules of different shapes and sizes (named as B, C, D, E, F, G and H). Experimental rooms were made from high-density cork (80 mm thickness) and covered with a fibreglass blanket to provide more insulation. Each brick was placed in a separate room, and two thermocouples were installed on both sides to measure the temperature difference during the experiment period, as shown in Fig. 1. During installation, bricks were sealed using high-quality insulation foam to ensure no air leakage between the interior and exterior environments and guarantees that heat passes only through the bricks.

2.2. Preparation of PCM bricks

Seven PCM bricks were fabricated with PCM capsules of different shapes and sizes. The capsules were made from locally available aluminium (1 mm thickness) of circular, square and rectangular cross-section area. Aluminium sections were cut into different shapes and sized carefully to hold the same quantity of PCM (approximately 144-148 g), providing a fair comparison among tested samples. Likewise, capsules' design also considered the concrete brick size to produce symmetric bricks with maintained mechanical strength. The main design characteristics of the capsules are detailed in Table 1.

Paraffin wax was used as a PCM in this work as it is locally available at a low price and has good thermal and physical properties that make it suitable for different thermal heat storage applications [22,23]. Paraffin's thermal properties, such as its sharp melting temperature, relatively high density, and heat of fusion, are reasonably good compared with other PCMs investigated in the building applications [24]. However, it has been reported that paraffin has a poor thermal conductivity in nature which affects its thermal performance during melting and solidification phases and limits its use in practical applications. Therefore, different techniques have been discussed to maintain this drawback successfully, such as the immersion of nanoparticles, using of metallic foam, incorporating expanded graphite, using of internal/external fins and the macroencapsulation using high conductivity containers [25–29].

It has been proven that paraffin can be used effectively as a thermal energy storage medium into bricks under high temperatures [30]. Moreover, it can effectively shift the thermal load and improve concrete bricks' inertial capability [31]. The main thermo-physical properties of used paraffin are listed in Table 2.

PCM capsules were prepared carefully following the procedure shown in Fig. 2. Paraffin was melted using a gas boiler, poured into capsules and then left to be solidified naturally. Later, PCM capsules were capped using suitable aluminium sheets (1 mm thickness) and sealed using thermal glue to prevent any possible leakage during the melting phase.

PCM capsules were distributed identically throughout PCM bricks to avoid asymmetry of brick thermal performance. Moreover, the capsules were placed centrally inside each PCM brick as it is the optimal position for PCM capsules incorporated bricks that results in the best thermal performance during melting and solidification [33], and to keep the mechanical strength of bricks, as shown in Fig. 3. The procedure followed to fabricate PCM bricks is shown in Fig. 4.

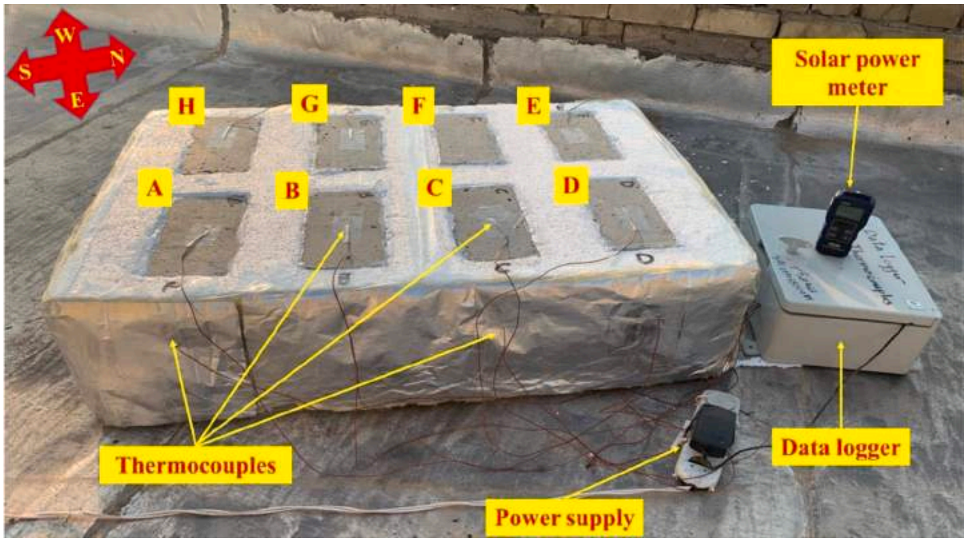

Fig. 1. Experimental set-up of the referenced and modified concrete bricks.

Table 1
Design characterisation of experimental brick samples.

Brick sample	Capsule cross-section area	Capsule dimensions (cm)	Number of capsules
A	Reference brick	——	——
B	Circular	Ø1.5*18	6
C	Square	4*4*10.25	1
D	Square	4*4*5	2
E	Square	4*4*2	5
F	Rectangular	4*2*7	3
G	Rectangular	4*2*5.125	4
H	Rectangular	4*2*3.5	6

Table 2
Thermo-physical properties of paraffin wax [32].

Thermal/physical property	Value
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 (solid) 2.1 (liquid)

2.3. Instruments and measurement devices

A data logger based multi-channel Arduino (type Mega 2560) and thermocouples were used to measure the temperatures during the experiment period. The thermocouples (T-type of 0.2 mm) were placed on both sides of each brick. The data logger was programmed to record the temperatures every 10 minutes to indicate temperature fluctuation during the experiment days. The recorded temperatures were continuously saved into 4 GB storage memory. During experiment day-hours, the solar radiation was collected manually every 30 min using a solar power meter (Model SM206) with 10 W/m^2 accuracy and 0.1 W/m^2 resolution.

2.4. Evaluation of bricks' thermal performance

Several indicators have been introduced to indicate each PCM brick contribution compared with the reference brick. The indicators are dependent on the interior surface temperature (T_i) and the average exterior surface temperature of bricks (T_o). These indicators are the maximum temperature reduction, decrement factor, time lag, and bricks thermal behaviour during melting and solidification phases.

3. Results and discussion

The experiments lasted for four consecutive hot days in September, starting from 6:00 of 16.09.2020 till 6:00 of 20.09.2020. Typically, September among the hottest months in Iraq (including July and August), wherein the solar radiation and ambient temperature are the maxima throughout the year, as shown in Fig. 5.

T_i and T_o variation and solar radiation (SR) for PCM brick samples against reference brick are presented in Fig. 6 as a function of time. T_i was increasing in conjunction with the increase of T_o and reached the highest values with a time delay varied in each PCM brick compared with the reference brick. The bricks' temperature increased considerably as the SR increased and reached the highest of 1059, 1053, 1062 and 925 W/m^2 on the first, second, third and fourth day of the experiment. This is encountered with the highest T_o of 63.5°C, 63.67°C, 62.96°C and 59.3°C in the midday. T_o values were used to calculate the indicators presented in the last section instead of sol-air temperature (a term considering the ambient temperature and solar radiation) as they are more accurate when compared with the interior temperature of bricks (i.e., T_i).

As mentioned in Section 2.4, several indicators have been applied to compare among tested PCM bricks and specify PCM's contribution to each one. These indicators are as follows:

3.1. Maximum temperature reduction (MTR)

It has been reported that the reduction of interior surface temperature is one of the main benefits gained from incorporating PCM into building elements [35,36]. Such a reduction is essential to better thermal comfort as it directly influences the mean radian temperature and operative temperature [37]. Measurements of the current experiment showed that the maximum interior surface temperature during peak hours was reduced in all PCM bricks compared to the reference brick, as shown in Fig. 7. This reduction reflects the positive contribution of PCM into concrete bricks.

As designated in the figure, concrete bricks with many PCM capsules (i.e., B, E and H) showed the highest reduction in T_i than other PCM bricks, even though slight reduction. Expressly, E followed by H indicated was showed the best performance.

Quantitively, the best MTR can be simply calculated by considering the difference between the maximum T_i of reference brick and PCM

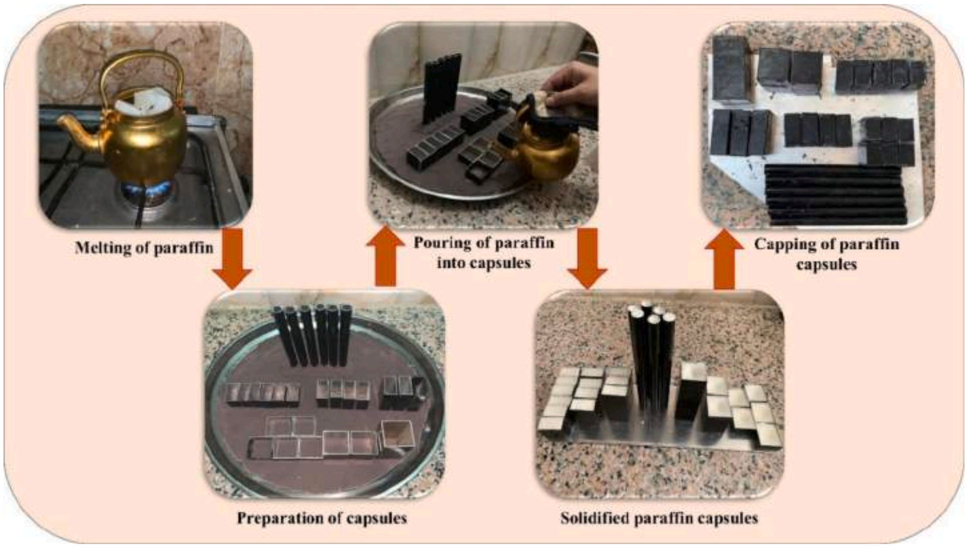

Fig. 2. Preparation of PCM capsules.

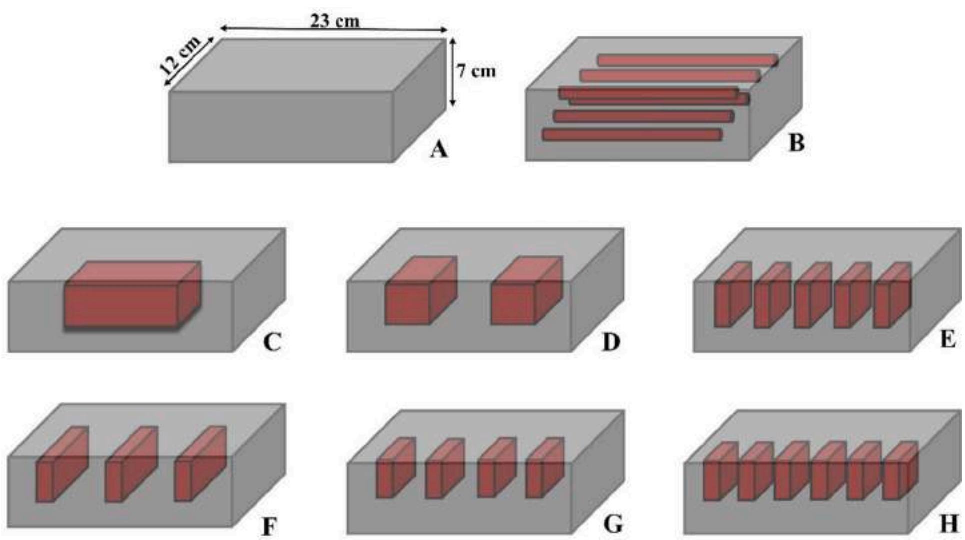

Fig. 3. Schematic for PCM capsules incorporated bricks.

brick, according to Eq. (1), as follows:

$$MTR = T_{i\ (reference\ brick)} - T_{i\ (PCM\ brick)} \tag{1}$$

According to the above equation, the results of MTR for each PCM brick are shown in Table 3.

The table above clearly indicated that the MTR of PCM bricks that involved many PCM capsules was the best. Similarly, bricks of bulky PCM capsules showed lower MTR and poorer thermal performance. The average MTR can be calculated for each PCM brick during all cycles to quantify the best PCM brick performance. The average MTR of B, C, D, E, F, G and H compared with A during all cycles was ~0.81°C, 0.50°C, ~0.81°C, ~1.88°C, ~0.31°C, 0.25°C, and ~1.19°C, respectively. These results show that the bricks of many PCM capsules (i.e., E and H) got the highest MTR compared with bricks with larger PCM capsules.

The T_i values were not limited to the peak hours only, but the same behaviour can be seen when considering the temperature range during all-day cycles, as shown in Fig. 8.

The main reason behind this disparity of MTR values is the overall heat exchange area of each PCM capsules. It can be noticed that E and H samples have a larger number of PCM capsules compared with the other samples (except for B). Therefore, the heat transfer area of them was enlarged, which maximised the rate of PCM melting. On the other hand, sample B also has a large number of PCM capsules. Accordingly, it has a huge heat transfer area compared with E, and H samples, which result in excessive heating might influence the PCM melting process. However, the B sample also showed good MTR than other PCM bricks that have bulk PCM capsules.

3.2. Decrement factor (DF)

DF stands for the decrement in the brick's peak temperature considering the interior and exterior surface temperatures (i.e., T_i and T_o). The DF calculated using Eq. (2) [38,39], as follows:

$$DF = \frac{T_{i,max} - T_{i,\ min}}{T_{o,max} - T_{o,\ min}} \tag{2}$$

where $T_{i,max}$, $T_{i,min}$, $T_{o,max}$ and $T_{o,min}$ are the maximum and minimum temperatures of the interior and exterior surfaces of the brick (°C), respectively.

Accordingly, the lower DF means lower cyclic fluctuations would

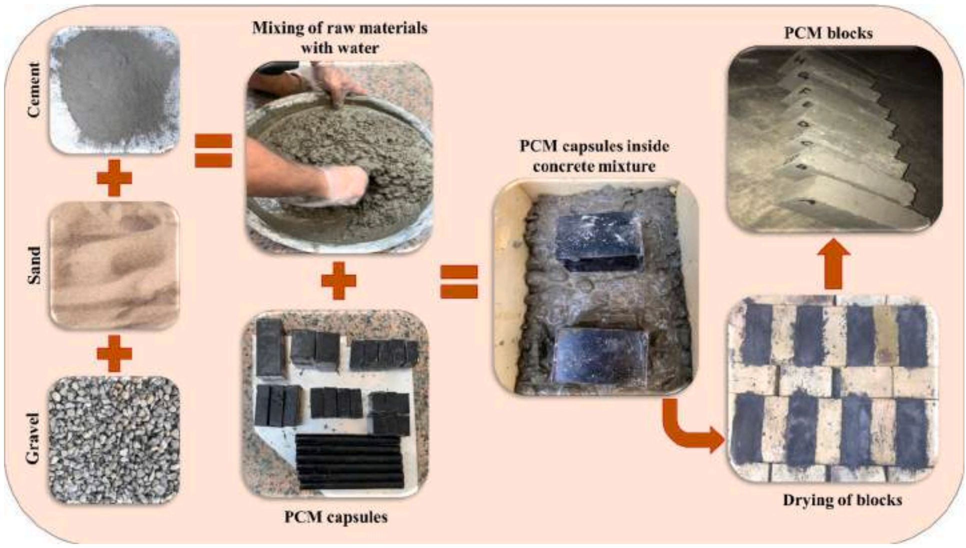

Fig. 4. Fabrication procedure of PCM concrete bricks.

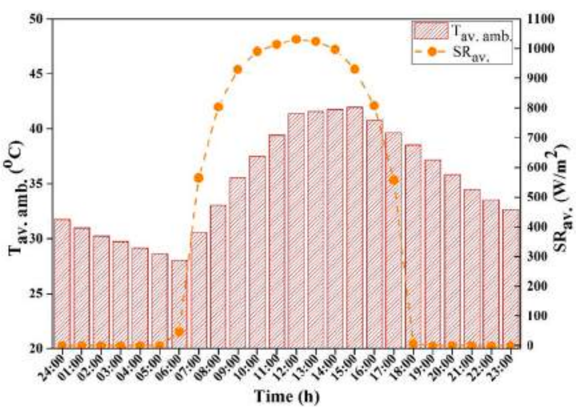

Fig. 5. Average hourly ambient temperature and solar radiation during September for the location under study [34].

occur in the interior surface temperature during the day-cycle as an advantage of PCM thermal storage utilisation. Fig. 9 shows the calculated DF for experimental brick samples for all cycles.

The figure clearly shows that the E sample has the lowest DF in all cycles, representing the best case. However, B and H samples also showed a good DF in comparison with other PCM brick samples. Bulk PCM capsules (i.e., sample C and F) designated high DF even higher than that of reference brick, meaning that the PCM was not melted or solidified completely, resulting in negative thermal behaviour. Therefore, the interior temperature fluctuations were not maintained during peak hours. The average DF of A, B, C, D, E, F, G and H was 0.908, 0.903, 0.932, 0.917, 0.901, 0.937, 0.923 and 0.910, respectively.

3.3. Time lag (TL)

TL defined as the period of shifting peak load to off-load. Therefore, it can be calculated as the difference between the time at maximum interior surface temperature ($T_{i,max}$) and the time at maximum average outer surface temperature ($T_{o,max}$), according to Eq. (3) [40,41], as follows:

$$TL = \tau_{T_{i,max}} - \tau_{T_{o,max}} \tag{3}$$

where $\tau_{Ti,max}$ and $\tau_{To,max}$ are the time at the maximum interior and exterior surface temperatures of the roof, respectively.

Fig. 10 shows the TL of all brick samples during the peak hours. The results fluctuated even for the same brick type over the days of the experiment. In general, all PCM concrete bricks showed longer TL than the reference concrete brick by 30 min at least. This advantage is attributed to PCM's ability to restrict the heat flowing from the exterior towards the interior surface during the melting phase, which shaved and shifted the heat flux.

The average TL can be presented to make a fair comparison among the PCM brick samples and point out the best TL during all days of the experiment. Compared with the reference brick, TL obtained from each PCM brick was varied between 20-50 min. The average TL obtained from PCM bricks compared with the reference brick during all cycles is shown in Fig. 11. Average TL was calculated by taking the average of four days for each PCM brick sample extracted the average of TL for the reference brick, according to Eq. (4), as follows:

$$TL_{average} = TL_{average,\ PCM\ brick} - TL_{average,\ reference\ brick} \tag{4}$$

Among PCM brick samples, E and H samples showed the highest average TL by about 42.5 min during the experiment more than the reference brick, indicating efficient utilisation of PCM incorporation. D, F and G also indicated a good TL of 40 min compared with the brick of bulk PCM (i.e., C) that reported 37.5 min time delay. Surprisingly, the B brick sample showed the lowest TL, compared to other PCM samples, by 35 min more than A. The reason might be attributed to the considerable heat transfer area of PCM capsules of the B sample, which resulted in fast PCM melting and kept the brick heated for a longer time. Hence, the brick cannot restrict the flow of heat towards the interior environment as it reached a full melting state.

3.4. Brick thermal behaviour during melting and solidification phases

PCM thermal behaviour is varied during heat charging and discharging phases, influencing the PCM brick interior temperature accordingly. A comparison among PCM bricks can be made against the reference brick during peak and off-peak hours of the first-day cycle to investigate the thermal performance.

Specifically, in this study, the rate of heat charging and discharging depends highly on the heat transfer area of PCM capsules as long as we deal with the same PCM quantity and position of capsules [42]. This parameter (i.e., heat transfer area) influences the rate of heat flows towards PCM capsules during day's hours and out of them during off-peak hours at night. The heat transfer area of PCM capsules in each PCM concrete brick is indicated in Fig.12.

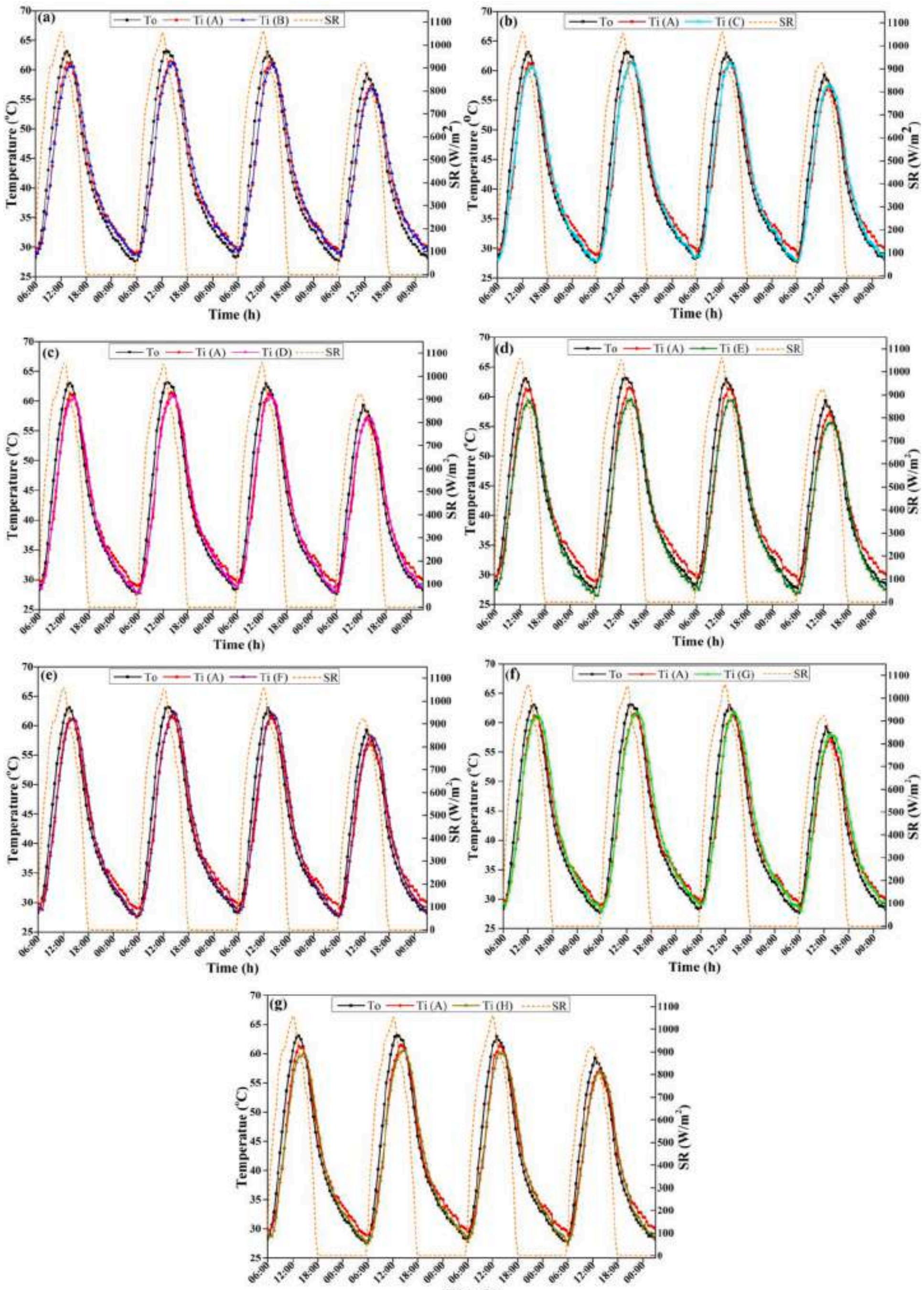

Fig. 6. Temperature profile for (a) A vs. B, (b) A vs. C, (c) A vs. D, (d) A vs. E, (e) A vs. F, (f) A vs. G, (g) A vs. H.

All bricks showed nearly equal interior temperature during the early hours of the day in which the melting phase did not take place yet, and all PCM bricks behaved like reference bricks. The interior temperature decreased for PCM bricks compared with the reference brick around 10:00, wherein the heat passing through the bricks was reached the melting temperature of PCM (i.e., 44°C). Here, the melting phase of PCM was started, and heat has been stored in PCM capsules. The capsule heat transfer area influences the rate of heat stored in each PCM capsule due to the increased heat exchange interface. In other words, the rate of PCM melting and solidification will be fast as the encapsulation heat transfer area increased. For that, PCM bricks of large heat transfer areas have stored more heat faster than those of a small area as a result of completed PCM melting. Therefore, it is clear that sample E performed better than the bricks of the square cross-section area shown in Fig.13-a, and sample H showed the best performance compared with the bricks of rectangular cross-section area (Fig.13-b). A comparison can be made among the PCM bricks with the highest heat transfer area (i.e., B, E and H) against the reference brick, as shown in Fig.13-c. In this regard, it was evident that all PCM bricks have better thermal performance than the reference brick during peak hours. Furthermore, brick E has the lowest T_i during all hours compared with B and H bricks. Simultaneously, B brick showed poorer thermal performance than E and H bricks, although it has a larger heat transfer area. It is logical as the heat transfer area speed up the time to reach full PCM melting, and thus, capsules cannot store more heat and behave as the reference brick.

In the solidification phase, the bricks' thermal behaviour was reversed. The reference brick performed better than PCM bricks as the ambient temperature gets low, but this behaviour was limited. As

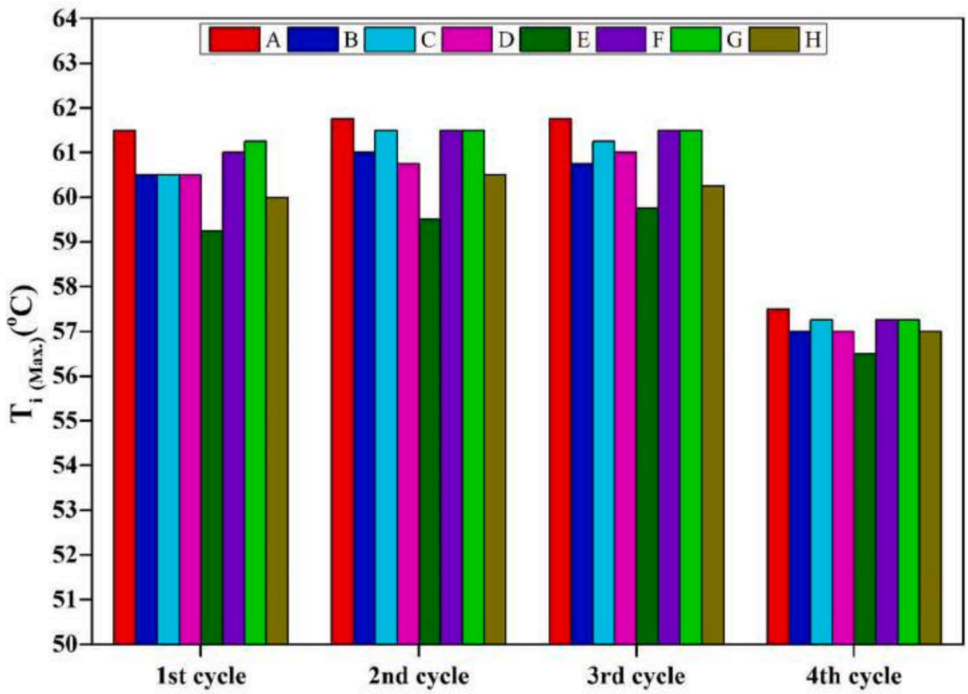

Fig. 7. Maximum T_i of tested concrete bricks at peak hours.

Table 3
MTR for PCM bricks during peak hours.

No. of cycle	MTR (°C)						
	B	C	D	E	F	G	H
1st	1	1	1	2.25	0.5	0.25	1.5
2nd	0.75	0.25	1	2.25	0.25	0.25	1.25
3rd	1	0.5	0.75	2	0.25	0.25	1.5
4th	0.5	0.25	0.5	1	0.25	0.25	0.5

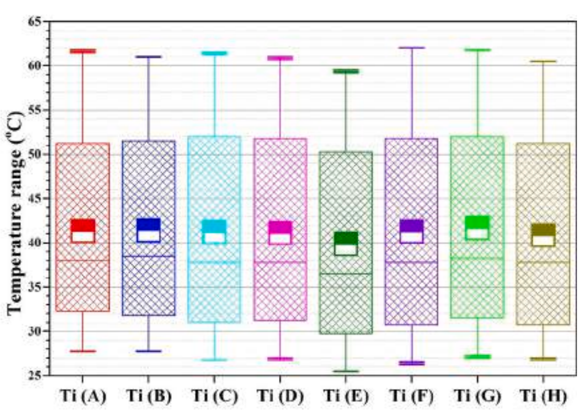

Fig. 8. Range of T_i for tested bricks for all cycles.

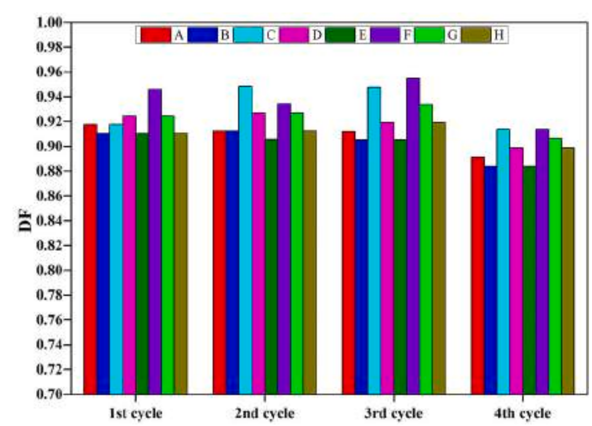

Fig. 9. DF of brick samples at peak hours.

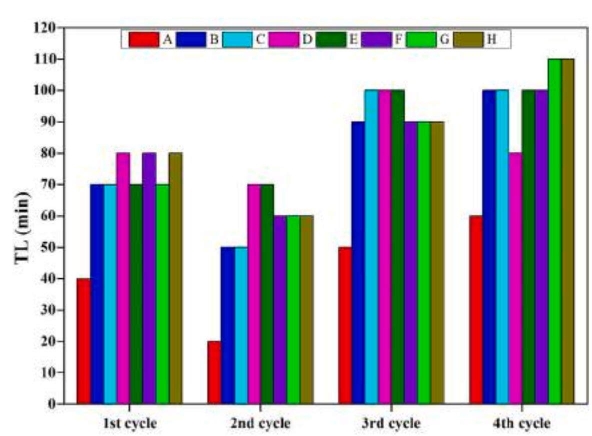

Fig. 10. TL of brick samples at peak hours.

indicated in Fig.14-a, reference brick was performed better than PCM bricks of square cross-sectional capsules until around 21:00 in the late evening. Later, the temperature of PCM bricks performed better till the end of the cycle. Likewise, PCM bricks of rectangular cross-section capsules also showed a reversed thermal performance compared with the reference brick till around 21:00 - 22:00, as indicated in Fig.14-b. In both cases (i.e., Fig.14-a and b), bricks of a higher number of capsules (i.e., E and H) were performed better than bulky PCM bricks due to their immense heat transfer area, which accelerated the time of PCM solidification. Fig. 14-c compares PCM bricks of a large number of PCM

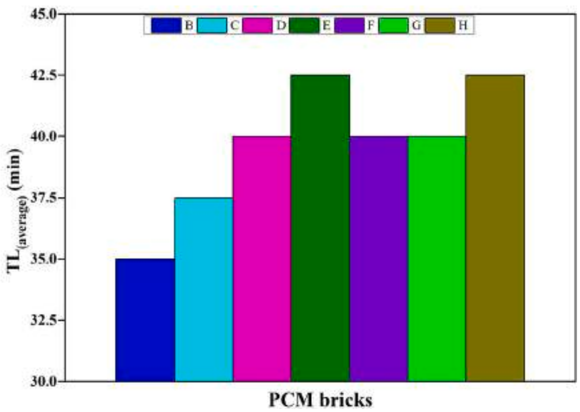

Fig. 11. Average TL of PCM bricks.

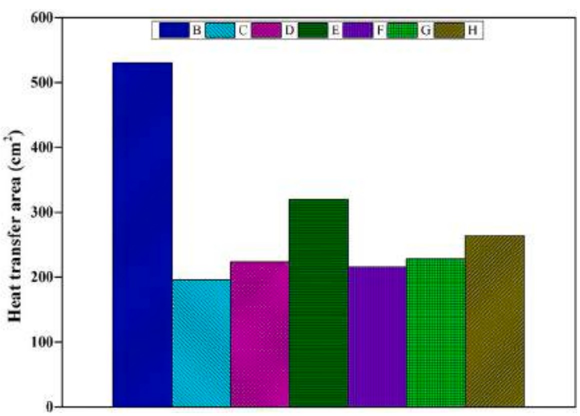

Fig. 12. Overall heat transfer area of PCM capsules in each PCM brick.

capsules (i.e., B, E and H) which indicates that E was reported with the best thermal behaviour all over the time compared with B and H samples. Moreover, the H sample showed better performance than the B sample in comparison with the A sample.

All in all, the results of tested PCM concrete bricks considering all the above indicators are tabulated in Table 4.

4. Conclusions

In this paper, the thermal performance of PCM capsules incorporated concrete bricks was studied experimentally under Iraq's actual summer conditions. Different shapes and sizes of aluminium PCM capsules were placed centrally inside seven concrete bricks, and their thermal performance was compared with a concrete brick without PCM. The thermal behaviour of bricks was discussed in terms of MTR, DF, and TL. Furthermore, an assessment during melting and solidification phases was made. The main conclusions that can be drawn from the study are summarised as follows:

- In general, PCM-based concrete bricks have a positive thermal behaviour compared to the reference brick without PCM.
- Concrete bricks of many PCM capsules lowered the interior temperature more than those based bulky PCM capsules thanks to the high PCM heat transfer area. In this regard, the average MTR of sample E and H reached ~1.88°C and ~1.19°C, respectively, compared with sample A. However, the excessive increase of the PCM heat transfer area may negatively impact the interior temperature due to reaching a fast complete PCM melting and keeping PCM in a melting state for a long time. This is obviously designated in sample B, resulting in an average MTR of ~0.81°C only compared with the reference brick.
- Bricks with many PCM capsules (i.e., B, E and H) resulted in better DF than bricks of bulk PCM capsules. The average DF of sample B, E and H are calculated as 0.908, 0.901 and 0.910 compared with sample A. Besides, the average TL of these bricks also was long (by about 42.5 min) except for the B, which showed an average TL of only 35 min, influenced by the considerable heat transfer area.

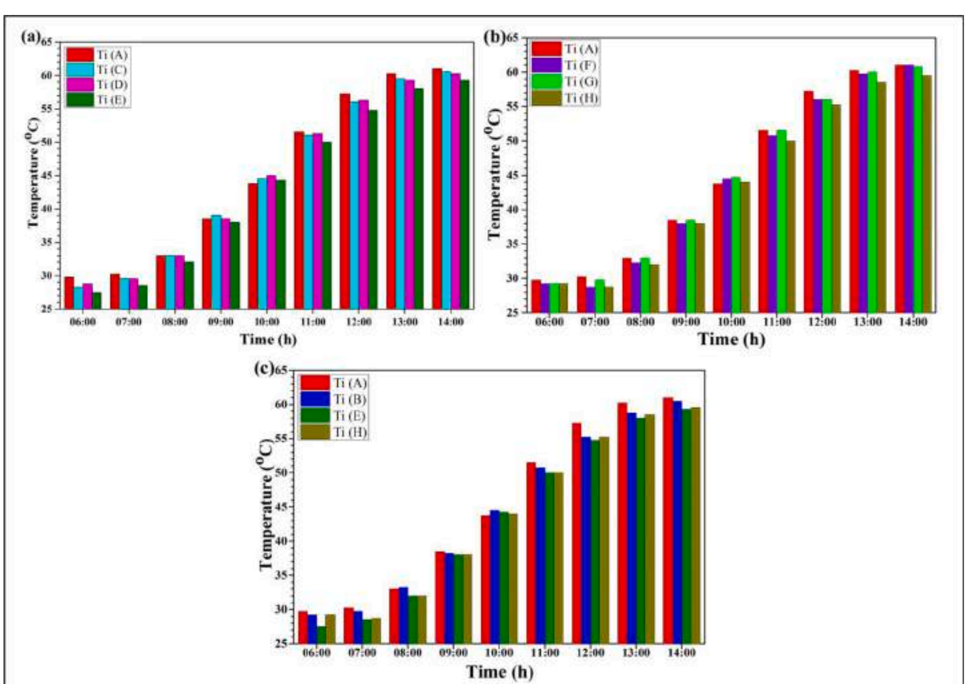

Fig. 13. Hourly Ti during the peak period in the first cycle for (a) A vs C, D and E, (b) A vs F, G and H, (c) A vs B, E and H.

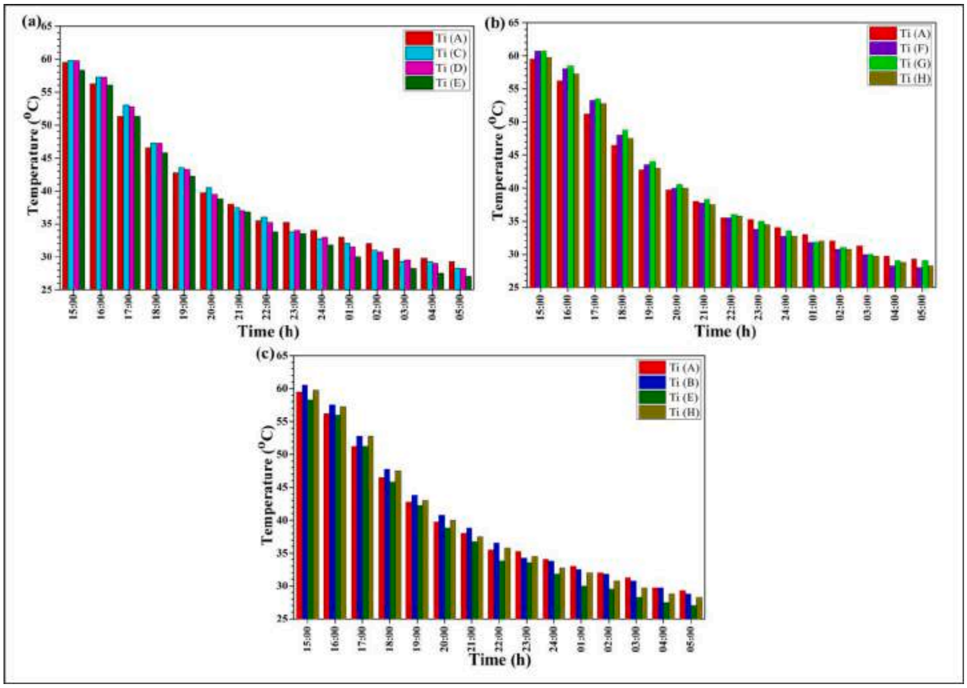

Fig. 14. Hourly Ti during the off-peak period in the first cycle for (a) A vs C, D and E, (b) A vs F, G and H, (c) A vs B, E and H [34].

Table 4
Summary of the experiment results.

Brick sample	Overall heat transfer area (cm^2)	Average MTR (°C)	Average DF	Average TL (min)
B	529.9	0.8	0.903	35
C	196	0.5	0.932	37.5
D	224	0.8	0.917	40
E	320	1.9	0.901	42.5
F	216	0.3	0.937	40
G	228	0.3	0.923	40
H	264	1.2	0.910	42.5

- In conclusion, the best thermal behaviour was reported for the E sample (square cross-section PCM capsules). The maximum interior temperature was reduced averagely by about 1.88°C compared to the reference brick (i.e., A). The best average DF of 0.901 and TL of 42.5 min was obtained for the E sample, which are the best results of tested PCM samples.
- During melting and solidification phases, the E sample showed the best thermal performance compared with other PCM and reference bricks. This behaviour attributed to the immense heat transfer area of E capsules, which accelerated the time to reach complete melting and solidification for PCM and efficiently utilised its storage capacity. However, considering PCM quantity, a large heat transfer area may influence the thermal behaviour due to excessive heating of brick for a long time, such as the B sample case. Therefore, studying the optimal heat transfer area is necessary for better utilisation of PCM thermal storage capacity.

CRediT authorship contribution statement

Qudama Al-Yasiri: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **Márta Szabó:** Conceptualization, Formal analysis, Investigation, Writing - review & editing, Supervision, Funding acquisition.

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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