



Research paper

Experimental analysis on the effect of cavity shape on the thermal and mechanical performance of hollow concrete bricks

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ABSTRACT

Improving the concrete elements' thermal performance is essential to minimise cooling loads in hot regions. However, this could be achieved using different insulation types, which are costly in most cases. This study presents an experimental investigation into how the shape of internal air cavities could influence the thermal and mechanical behaviour of hollow concrete bricks. Therefore, bricks with square, rectangular, circular, and triangular cavities were fabricated and tested, thermally and mechanically, to specify the optimal shape at three orientations (east, south and west). Thermal indicators, including the reduction in maximum surface temperature, decrement factor and temperature gradient, were analysed and deliberated. Eventually, a compressive strength test was conducted to evaluate the mechanical behaviour of the developed bricks. The research results indicated that the brick with circular cavities delivered the best thermal insulation, achieving a maximum temperature reduction by up to 10.1 °C at high ambient temperatures. Besides, this cavity shape attained compressive strength of 3.65 MPa on average, representing 9 %–20 % higher mechanical properties than those of other cavities. These findings underscore the dual benefit of optimising air cavity geometry towards the circular shape to advance the thermal and mechanical features of concrete bricks. In addition, the research supports the production of hollow bricks that meet structural demands while significantly enhancing thermal resistance in hot climate applications.

1. Introduction

As human society continues to grow, the demand for better indoor living environments has steadily increased. This has led to a significant rise in building energy consumption over the past decade to sustain normal operations. Currently, buildings account for 30 % of global final energy consumption and 26 % of global energy-related emissions [1]. In Iraq, the residential building sector consumes 48 % of the total energy generated, and around 69 % of this portion is spent to meet the cooling and heating requirements [2]. Therefore, developing innovative technologies and solutions is essential to reducing energy consumption in buildings. Building envelope is a key in regulating thermal energy, as it serves as a barrier between indoor and outdoor conditions. Consequently, each component of the envelope must be carefully designed with both mechanical and thermal considerations. One of the most

critical components of the building envelope is the wall, playing a fundamental role in regulating heat transfer and overall energy efficiency.

Constructive bricks, especially concrete bricks, are widely used due to their low cost and good mechanical properties. However, considering their subpar thermal performance, their use in hot climates is constrained. Thus, it is essential to maintain the mechanical characteristics of bricks while promoting their thermal properties. Over the past years, a variety of procedures have been utilised to improve bricks' thermal performance by combining waste materials [3], insulators [4], nanomaterials [5], and phase change materials [6]. Since it may boost mechanical and thermal characteristics while fostering sustainability, the utilisation of waste materials in brick production has drawn a lot of attention [7]. To assess the thermal and mechanical performance of concrete mixtures, including bricks, several studies have investigated

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various waste materials, including rice husk [8], crumb rubber [9], sawdust ash [10], palm fronds [11], hemp fibre-reinforced polymers [12], pumice powder [13], and other agro-wastes [14]. For instance, Mahapatra et al. [8] examined the possibility of using rice husk in cement mortar in place of sand. According to the study, increasing the rice husk quantity into bricks has reduced compressive strength while greatly improving the thermal insulation. The thermal conductivity decreased by 12 % when rice husk was substituted for 7 % of the sand. Additionally, the study found a linear correlation between the cement mortar's volumetric heat capacity and dynamic thermal performance. Kantasiri et al. [9] investigated the use of leftover crumb rubber in concrete for applications involving thermal insulation. The study found that adding crumb rubber reduced the unit weight by 1598–1746 kg m⁻³ and the compressive strength by 7.45–31.26 MPa using the Taguchi method for optimisation. Nonetheless, the material's thermal conductivity was greatly enhanced, rising from 0.51 to 0.67 W/m·K, making it an effective choice for energy-efficient buildings. Ahmed et al. [15] investigated incorporating biomass waste—more especially, pomegranate peel waste into fired clay bricks. In comparison to traditional bricks, the ideal mixture, which contained 15 % pomegranate peel waste, fired at 900 °C, showed reduced thermal conductivity. As a result, CO₂ emissions lowered from 7.50 % to 24.50 % and energy consumption diminished from 17.55 % to 33.13 %. Furthermore, economic analysis demonstrated the cost-effectiveness of energy savings, with payback periods ranging from 1.88 to 10.74 years. Nagapan et al. [16] explored the thermal and mechanical advancements of integrating spent Mushroom substrate as potential fine aggregates in cement bricks with 5 % - 25 % ratio. The study revealed that increasing spent Mushroom substrate ratio could improve the thermal insulation performance of bricks, while declining their mechanical properties. In general, the thermal conductivity of modified bricks could be minimised by 41.6%–84.9% compared with the standard cement brick. Furthermore, the mechanical performance analysis indicated that the modified bricks with spent Mushroom substrate at 15 % ratio could be utilised for non-loading wall partitions, while 5 % could meet the compressive strength standards of load-bearing walls. Saingam et al. [17] employed waste glass with ratios ranging from 0 % to 100 % and electronic waste fibres at 5 %, 10 %, and 15 % as a potential replacement material for aggregates. Study findings indicated that the specimen's compressive strength declined as the incorporated waste materials increased, reaching a 30 % decline at 100 % substitution. However, the study revealed that integrating electronic waste fibres at 5 % has improved the compressive strength, even over the control case. In addition, the findings showed that the thermal insulation of modified specimens was diminished, thanks to the incorporation of electronic waste fibres, decreasing the thermal conductivity from 1.97 W/m·K to 1.39 W/m·K at a 100 % replacement ratio. Al-Tamimi et al. [18] utilised finite element modelling to create a new geometry for hollow concrete blocks in addition to the inclusion of thermal insulators. Perlite, rubber, and polyethylene were explored as insulating materials, satisfying ASTM C129 requirements, compared to the local concrete blocks. Study findings showed that the thermal conductivity of newly designed hollow blocks has reduced by as much as 40 %. Besides, including thermal insulation materials could maximise the thermal insulation of blocks as high as 71 % over the traditional concrete blocks. Shah et al. [19] explored the influence of cavity size and adding mineral wool thermal insulation on the thermal enhancement of hollow concrete blocks. According to the research findings, larger air cavities for blocks have a positive impact to minimise heat transfer than smaller ones, lowering the temperature by 20.3 °C in severe hot environments. Besides, filling cavities with mineral wool could maximise the temperature difference between block's surfaces by as much as 40.9 %, indicating thermal and economical advantages.

In order to improve thermal storage capacity and energy efficiency in buildings, the incorporation of phase change materials (PCMs) into bricks and masonry units has been thoroughly investigated [20–22]. Numerous researchers have looked into various PCM incorporation

methods, showing increases in thermal mass, control over indoor temperature, and energy savings. Canim et al. [23] studied how to improve the thermal performance of pumice blocks by incorporating paraffin-based PCM. The study examined the improvements in latent heat properties, specific heat capacity, and thermal conductivity. Results showed up to a 6 % improvement in thermal conductivity and a 75 % increase in specific heat capacity. Energy simulations indicated that these PCM-enhanced blocks could provide a 2 %- 7 % energy efficiency improvement in hot-humid climates, along with a 30 % increase in wall time delay and a 1.5 °C reduction in peak indoor temperatures. Mukram and Daniel [24] developed a novel cement brick filled with micro-encapsulated PCM for thermal energy storage in building walls. Their analysis revealed that shifting PCM placement within the brick significantly affected heat flux reduction. The optimal configuration resulted in a 32 % reduction in heat gain and a 1.2 °C decrease in indoor temperatures, highlighting the effectiveness of PCM for passive cooling applications. Zhang et al. [25] examined the integration of PCMs and thermal insulation materials in concrete masonry unit walls. The study explored different wall patterns and PCM placements under various thermal conditions. Study results revealed that the PCM has enhanced the wall's thermal inertia, reduced thermal bridging effects, and improved the stationary and transient thermal performance. Taj et al. [26] investigated the incorporation of eutectic PCM (palmitic and lauric acid) into clay bricks experimentally. Their results showed a 32 % decrease in thermal amplitude, a 150-minute heat transfer time lag, and a 4 °C- 5.5 °C decrease in indoor temperatures. Additionally, the PCM bricks reduced heat flux by 25 % to 30 %, which made them very useful for passive thermal regulation.

As could be observed from the above literature studies, most research efforts were conducted to improve the thermal insulation potential of bricks by incorporating low thermal conductivity materials into bricks and blocks. These studies are often considered thermal and mechanical performance analysis, overlooking the production cost and preparation complexity, which could be maintained by optimising the brick cavity itself. Therefore, this study aims to examine the influence of the air cavity shape of hollow concrete bricks on the thermal and mechanical characteristics under harsh weather conditions. This study aims to provide an alternative option to local construction methods by changing the air cavity from square shape to circular, triangular and rectangular configurations and evaluating their thermomechanical impact experimentally. The thermal insulation behaviour of fabricated bricks is investigated in view of their ability to minimise the maximum surface temperature and temperature fluctuations in various orientations. In addition, a mechanical compression test is implemented to indicate their mechanical characteristics in conjunction with their thermal performance. Accordingly, this study is believed to support the global goals towards sustainability by optimising brick thermal and mechanical performance at low cost and providing a realistic option for traditional construction methods.

2. Materials and methods

2.1. Preparation of test bricks and assembly of the experimental setup

The test bricks were fabricated using locally available cement, sand and aggregates following the instructions of the Iraqi blog for insulation and construction [27]. The concrete mixture was prepared by mixing cement, sand and coarse gravel with a 1:2:2 ratio by weight to obtain a 20 MPa compressive strength at 28 days. The chemical, physical and mechanical characteristics of raw materials used in the concrete mixture preparation are reported in [28]. Besides, the preparation procedure of concrete was conducted to meet the Iraqi standard IQS1077/1987 [29]. Custom molds were designed to produce concrete brick specimens with precisely controlled internal air gaps of various geometrical configurations. The molds were constructed using wood sheets treated with a water-resistant sealant to prevent moisture absorption during casting.

The mold was designed to produce a standard brick specimen with external dimensions of 230 mm $\times$ 120 mm $\times$ 70 mm (length $\times$ width $\times$ height), conforming to conventional brick dimensions. To create the internal air gaps, removable inserts made from wood were cut using various shaping procedures. Four distinct geometric shapes were selected for the air gaps, including Square cavities with 80 mm $\times$ 80 mm, Circular cavities with 90 mm diameter, Rectangular cavities 180 mm $\times$ 35 mm, and Triangular cavities with 160 mm $\times$ 80 mm. Fig. 1(a) and (b) demonstrate the proposed design of each brick and the experimental mold used to fabricate the bricks.

The molding process was conducted in an outdoor environment to utilise the natural air for brick solidification. Prior to molding, the inner surfaces of the molds were thoroughly cleaned and oiled to facilitate easy demolding without damaging the specimens. Throughout the molding process, particular attention was paid to maintaining the central position of the air gap inserts. Visual inspection was performed after vibration to verify that the inserts had not shifted from their intended positions. Additional concrete was added as needed to compensate for settlement during vibration, ensuring that the top surface of each specimen was level with the mold edges. For each geometric configuration (square, circular, triangular, and rectangular), a total of 16 specimens were molded (Fig. 1(c)) to allow for testing at different curing ages and to ensure statistical reliability of results when performing the mechanical test.

Following molding, the molds containing the fresh concrete specimens were covered to prevent moisture loss. The specimens were then left undisturbed for an initial setting period of 24 h. After this initial curing period, the specimens were carefully demolded. During demolding, special attention was paid to the extraction of the wooden inserts. A specialised extraction tool was designed to carefully remove the inserts without damaging the internal surfaces of the air gaps.

All specimens underwent visual inspection at various stages of preparation to ensure consistency and integrity. After demolding, each brick was checked for surface defects, proper geometry, and cleanliness of the internal air gaps. The inserts were carefully removed to avoid damaging the concrete, and the air gaps were inspected to confirm they were well-formed and free of residual material. Any specimens showing

cracks, deformations, or misaligned inserts were excluded from further testing. These inspections helped ensure that only defect-free specimens were used for evaluating the effects of air gap geometry on performance.

The test rig was constructed in situ using polyesterene (cork) blocks to hold experimental bricks. Cork blocks were marked and cut with four vertical cavities in the cork to snugly fit individual test specimens (bricks), as shown in Fig. 2(a). During brick installation, the probes of

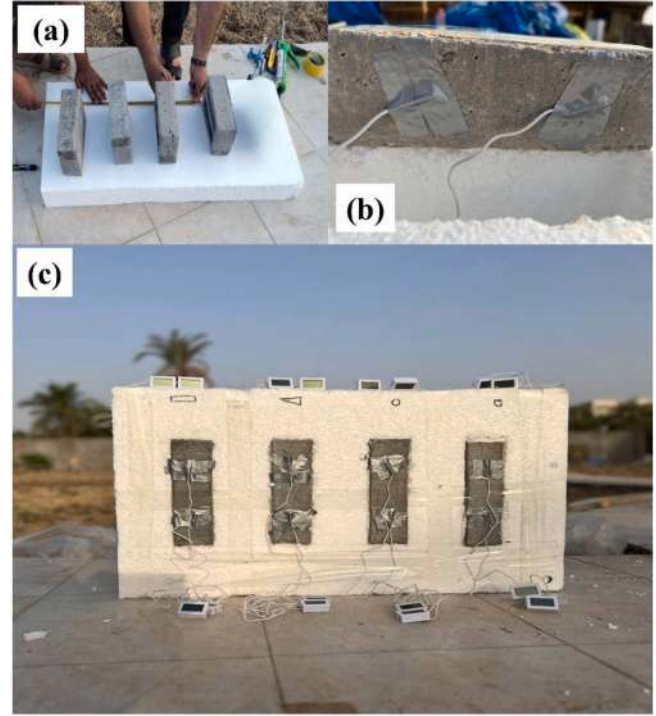


Fig. 2. (a) preparation of cork frame, (b) installation of temperature sensors, (c) test rig.

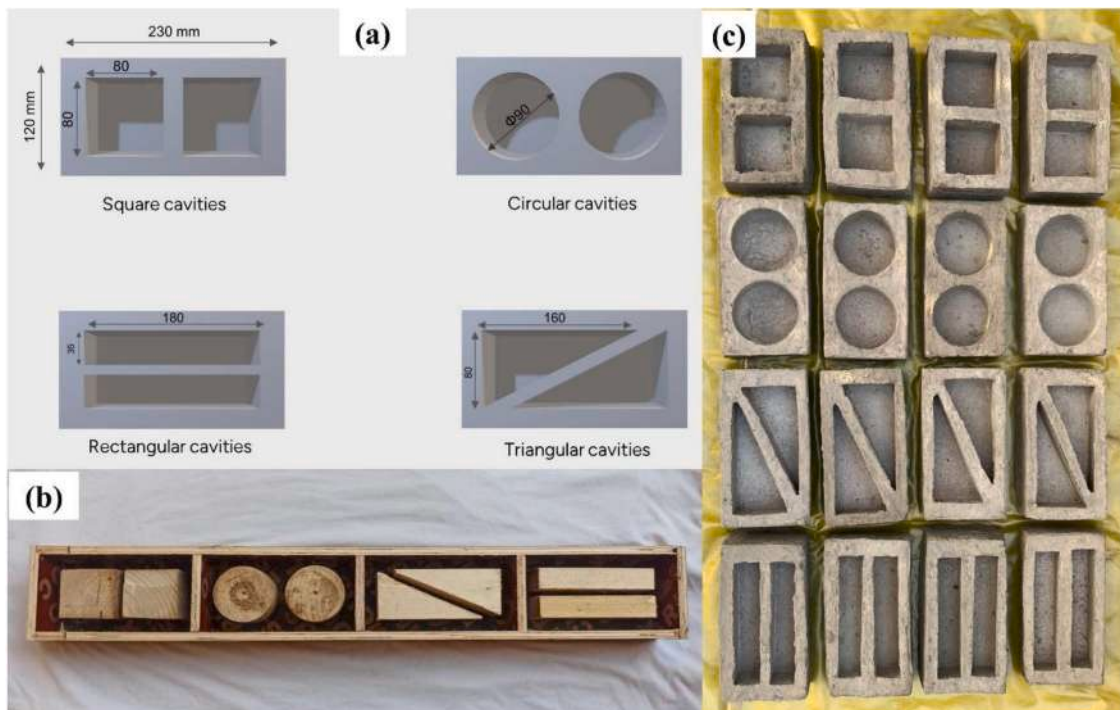


Fig. 1. (a) Design of proposed bricks, (b) top view of the mold, (c) final molded bricks.

two temperature sensors were attached to the inner surface of each test brick using multi duct tape to ensure accurate temperature recording (Fig. 2(b)). Each brick was inserted into its designated cavity in the cork enclosure, and the gaps between specimens and the cork block were sealed with silicone sealant to guarantee no air ventilation between the inner and exterior surfaces of the brick. Finally, two temperature sensors were affixed to the outer surface of each brick. The final test rig assembly is displayed in Fig. 2(c).

2.2. Measurement devices and tools

The measurement setup was designed to capture the thermal behaviour of specimens under controlled environmental conditions. Four high-precision digital thermometers were deployed for each brick specimen to monitor temperature gradients across the brick. Two temperature sensors were fixed on the inner surface, and the other two on the outer surface. Besides, two sensors were hung near the rig to track the changing weather conditions. The average of each two temperature sensors was adopted to precisely show the variation on the outer, inner and ambient temperatures with a 30-minute time step. The temperature sensors had a temperature range of (−50 to 110 °C) with an accuracy of (±1 °C).

A portable digital anemometer was used to measure ambient air velocity near the specimen surfaces with a measuring range of air velocity of (0–45 m/s ± 3 %), enabling more accurate thermal modelling and performance assessment. Moreover, a solar power meter (of ±10 W m^{−2} accuracy, 0.1 W m^{−2} resolution and 1–3999 W m^{−2} range) was utilised to measure the incident solar radiation on the specimen surfaces. The meter was mounted at the same plane as the specimen surface exposed to the simulated solar radiation. This arrangement ensured that the measured irradiance values accurately represented the actual solar radiation incident on the test specimens. Both the anemometer and solar power meters were used in the three experimental days with a 30-minute time step. In addition, a high-resolution thermal imaging camera (accuracy of ±2 % ±2 °C tested @25 °C, and −20 °C – 600 °C measurement range) was employed to capture comprehensive surface temperature distributions on the outer surfaces of specimens in specified hours.

Compressive strength is one of the most important mechanical properties of masonry units, as it directly relates to their load-bearing capacity. In this study, compression testing was conducted to evaluate how different air-gap geometries influence the structural performance of hollow concrete bricks. The results provide essential data for comparing mechanical behaviour across brick designs. The test was carried out

Table 1
Specifications of measurement devices.

Measurement device	Number	Role/function	Photo of the device
Digital thermometer	18	Temperature measurement	
Digital anemometer	1	Wind speed measurement	
Solar power meter	1	Solar radiation measurement	
Thermal camera	1	Visualise the temperature distribution on the outer surface of bricks	
Compression machine	1	Compressive strength identification	

using a digital compression testing machine, which belongs to the Department of Civil Engineering- College of Engineering at the University of Misan. This device applies a steadily increasing compressive load through a hydraulic system, with real-time monitoring via a digital interface. The brick specimen is positioned between two steel plates and loaded until failure. The machine ensures precise and consistent measurements of maximum compressive strength, in accordance with relevant testing standards. Using this device, a total of 16 brick specimens (4 brick samples of each air-gap shape) were tested. Table 1 lists the characteristics of experimental devices.

2.3. Evaluation methods of bricks' thermal performance

The thermal performance of concrete bricks with various air gaps was assessed by collecting the temperature measurements for both the inner and outer surfaces of each brick. Later, key indicators were calculated from collected data to show how the developed bricks reduce the surface temperature. The analysed indicators in this work include the maximum temperature reduction, the decrement factor and temperature gradient reduction. All of these indicators are calculated considering the average surface temperature on the inner and outer surfaces of bricks. The average inner surface temperature (T_i) is the mean temperature measured on the inner surface of the brick, representing the heat transmitted into the building from outdoors. Similarly, the average outer surface temperature (T_o) is the mean temperature recorded on the outer surface of the brick exposed to solar radiation.

The maximum temperature reduction refers to the highest difference in temperature observed between the outer and inner surfaces of each concrete brick. It indicates the brick's ability to reduce heat transfer, in which higher values designate better thermal insulation performance. The maximum temperature reduction is calculated using Eq. (1).

$$\text{Maximum temperature reduction} = T_{o,max} - T_{i,max} \quad (1)$$

The decrement factor signifies the reduction in the brick's temperature fluctuations, based on the inner and outer surface temperatures. The decrement factor shows the ability of bricks to dampen the temperature thanks to their thermal resistance. Mathematically, the decrement factor is calculated using Eq. (2) [30].

$$\text{Decrement factor} = \frac{T_{i,max} - T_{i,min}}{T_{o,max} - T_{o,min}} \quad (2)$$

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

Eventually, the temperature gradient denotes the temperature reduction through the brick thickness. Mathematically, the temperature gradient (in °C/cm) is calculated by dividing the maximum temperature difference of each brick by the brick's thickness (i.e., 12 cm), according to Eq. (3):

$$\text{Temperature gradient} = \frac{T_{i,max} - T_{i,min}}{L} \quad (3)$$

3. Results and discussion

3.1. Study location

The experiments were conducted from 6:00 to 18:00 under hot climate conditions of Al Amarah city (Latitude: 31.84° and Longitude: 47.14°), southern Iraq, for three consecutive days in May 2025. This location is categorised by a hot summer with long sunshine hours and high solar radiation [31]. Fig. 3 displays a thermal photo of the study location.

The solar radiation and wind speed variation of the location under study during experiments are presented in Figs. 4 and 5, respectively. As could be noticed, the weather was cloudy during the experiment days, in which the solar radiation was fluctuating throughout the day. This

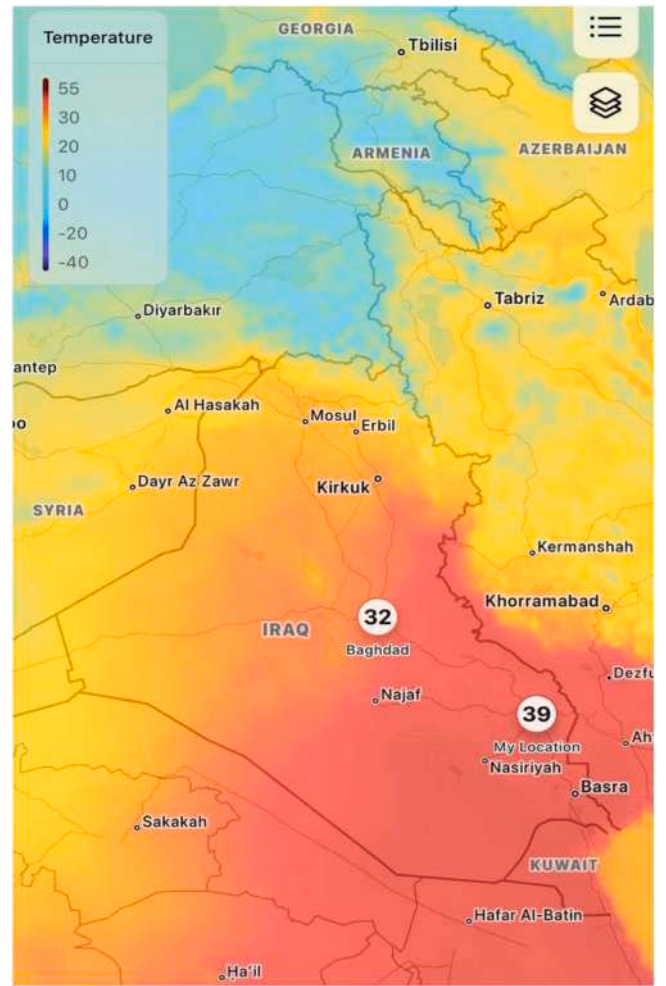


Fig. 3. Morning thermal photo of the study location on the first day of the experiment.

behaviour is common during transition months, such as May. The solar radiation was highest for the west orientation experiment, reaching a maximum of 1045 W m⁻² in the afternoon at 14:30. However, the south-facing orientation experiment reached its peak of 875 W m⁻² around midday, and the east-facing experimental day peaked at 669 W m⁻² in the late morning, at time around 10:30. Besides, the wind speed was varied between approximately 0 m s⁻¹ and 2.7 m s⁻¹ for the east, south and west orientations. These values indicate that the heat transfer is slightly influenced by the wind speed, which is necessary to show the thermal insulation performance of the tested bricks.

3.2. Analysis of brick surface temperature

Figs. 6–8 show the surface temperature variation of the tested bricks along with the ambient temperature in various orientations. This figure shows the ambient, outer and inner surface temperatures in each study day. In Fig. 6, the outer surface temperatures for the east orientation were increased from approximately 25 °C at 06:00 to a peak of around 49.5 °C near 13:00, before gradually decreasing. All tested bricks showed similar variation trends with a slight temperature difference. However, the circular cavity shape generally exhibited marginally higher temperatures throughout the day, especially around the peak. This may indicate better thermal behaviour of this brick type, resulting from a good thermal resistance to keep the temperature high on the outside surface. From the other side, the triangular-shaped brick displayed lower outer surface temperature, especially after 11:30. This

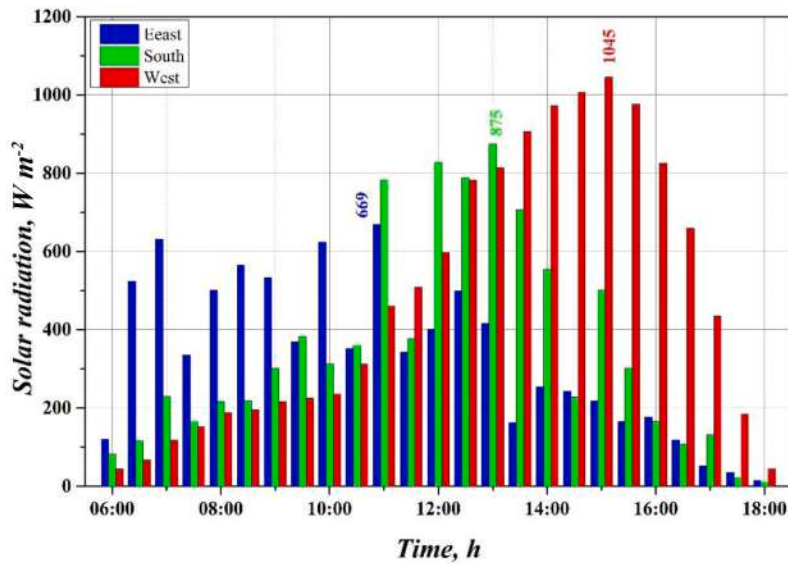


Fig. 4. Solar radiation during experiments.

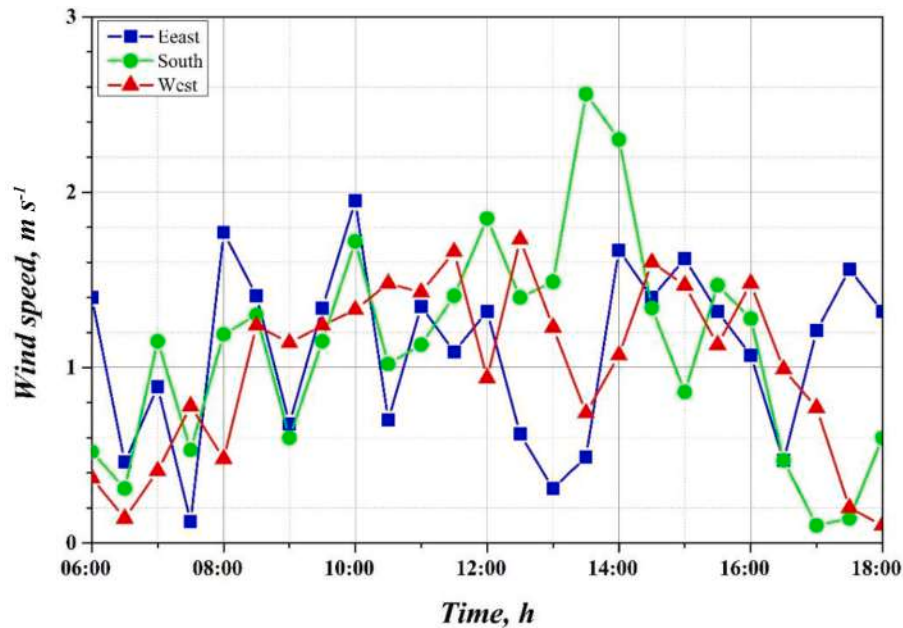


Fig. 5. Wind speed variation during experiments.

behaviour may demonstrate poor thermal resistance for this brick type since more heat was allowed to pass through it towards the indoor surface.

Fig. 6 also shows that the inner surface temperatures rose from approximately 23 °C–24 °C at 06:00 to a maximum of around 45 °C–46 °C between 15:00 and 16:00 when oriented towards the east. The circular and square cavity-shaped bricks consistently maintained low inner surface temperatures compared to the other shapes, mostly during peak hours. Nonetheless, the brick with triangular cavities indicated the poorest thermal behaviour, showing poor thermal insulation compared with all other bricks. The bricks with rectangular shapes indicated moderate thermal performance between the circular and triangular shaped bricks, with similar temperature behaviour of square cavities in the early hours.

Referring to Fig. 7, which displays the temperature variation of bricks when directed towards the south orientation, it could be observed

that all bricks showed the same behaviour with higher outer surface temperature values for the circular cavity-based brick. The figure shows increased outer surface temperature from approximately 24 °C at 06:00 to a peak of around 49 °C near 13:00, before gradually decreasing till the late afternoon. The triangular cavity shapes generally exhibited lower outdoor temperatures than others, similar to their behaviour in the east orientation.

The inner surface temperatures for the south-facing bricks showed an increase from around 22 °C–23 °C in the early morning (at 06:00) to a peak of approximately 42 °C–43 °C in the late afternoon (around 15:00–16:00). During the period of highest temperatures, the bricks with circular cavities, followed by the square cavities, demonstrated better thermal performance by maintaining slightly lower inner surface temperatures. This behaviour proves superior thermal insulation potential for the circular cavities compared to the other shapes.

Fig. 8 displays the outer and inner surface temperatures for the west

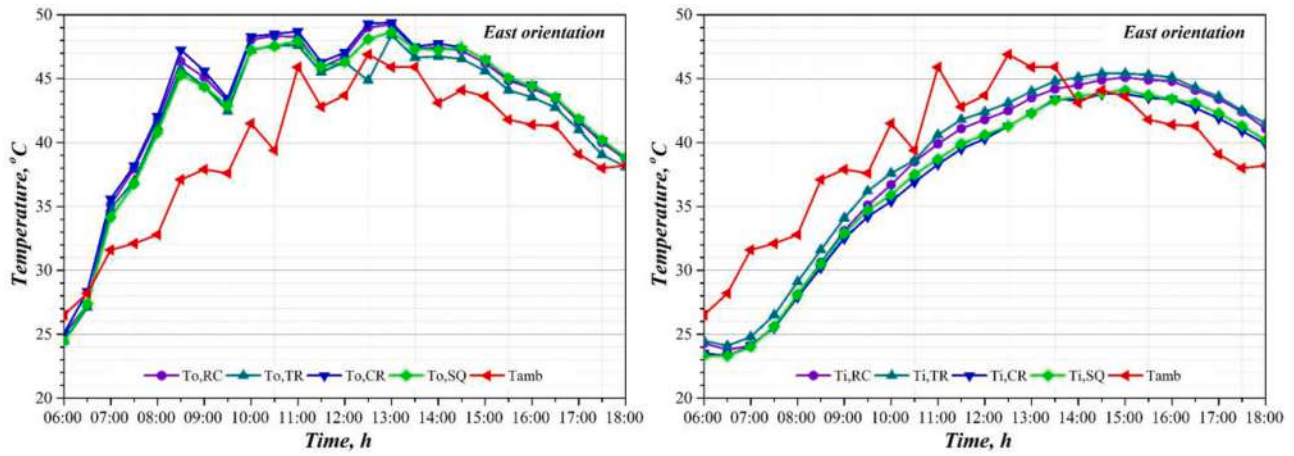


Fig. 6. Outer and inner surface temperature variation of bricks under the east orientation.

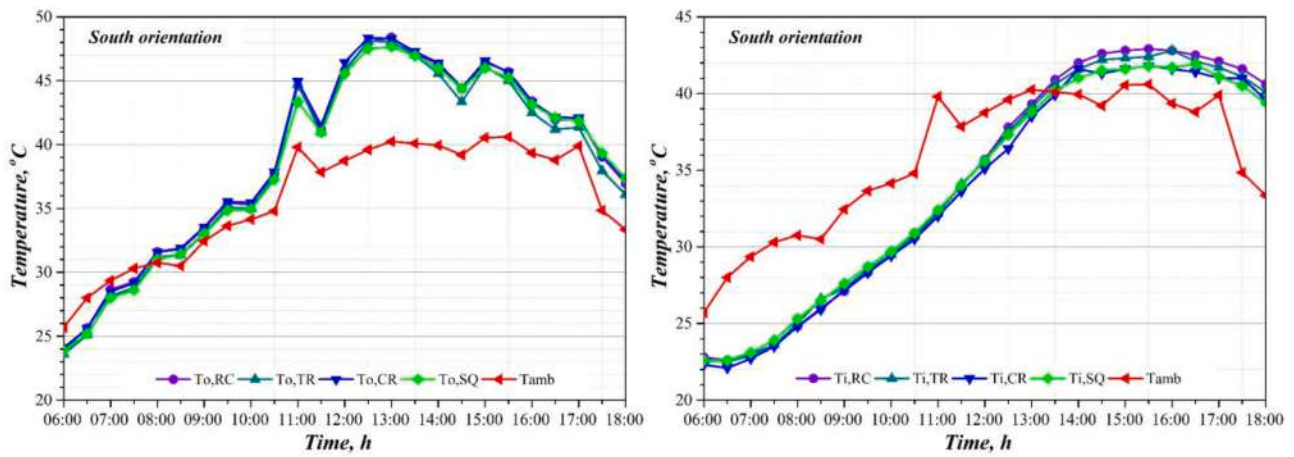


Fig. 7. Outer and inner surface temperature variation of bricks under the south orientation.

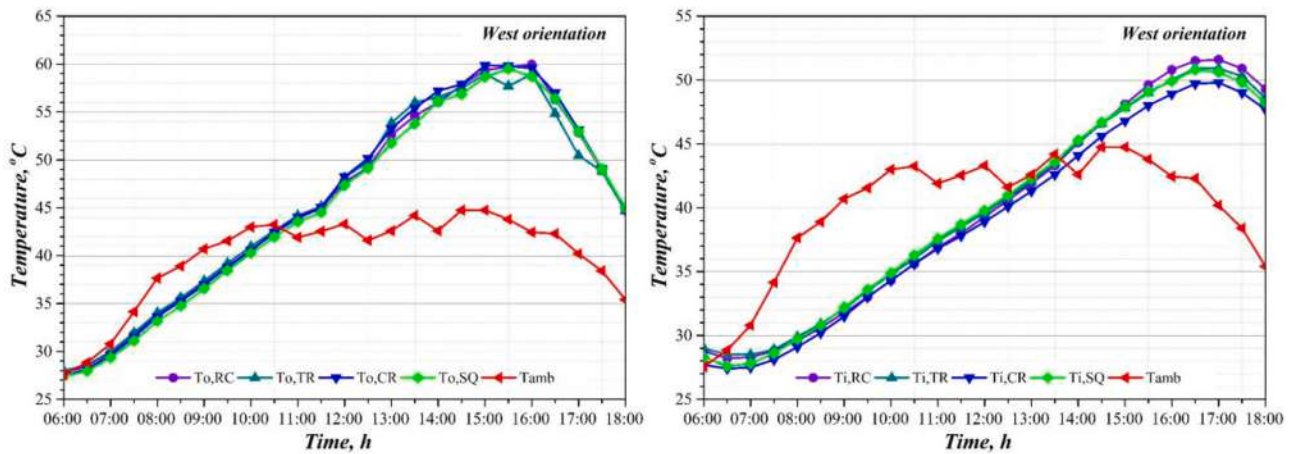


Fig. 8. Outer and inner surface temperature variation of bricks under the west orientation.

orientation case. As could be observed from the left-side figure, the outer surface temperature of the tested bricks was increased from approximately 27.5 °C at 06:00 to a peak of around 60 °C near 16:00. This temperature range was the highest compared to the east and south orientation cases since the weather was clear with high solar radiation. The circular, rectangular, and square cavity shapes generally reached the highest temperatures around the peak, with the triangular shape

being slightly lower during the peak period. The behaviour of the triangular cavities was the same for all studied cases, indicating the poor thermal insulation of this brick type.

The west-oriented bricks presented in Fig. 8 demonstrate that the inner surface temperatures started at approximately 27 °C– 28 °C at 06:00 and rose to a maximum value between 16:00 and 17:00. During this peak period, the circular cavity design confirmed superior thermal

insulation, maintaining an inner surface temperature around 49.5 °C- 50 °C. In contrast, the rectangular, triangular, and square cavities resulted in higher inner surface temperatures, reaching approximately 51 °C- 52 °C. These values indicate that the circular cavity was more effective at mitigating heat gain on the inner surface at all orientations.

Convincingly, it could be reported that the bricks with high outdoor surface temperatures performed better than those with low surface temperatures, as could be visualised in Fig. 9. This could be interpreted as the cavities with best performance resist the heat transfer from outdoor towards the indoor surface, keeping the outer surface temperature high. Besides, the inner surface temperature of cavities with rounded edges (i.e. circular cavities) showed significant thermal insulation, while the cavities with sharp edges (i.e., triangular cavities) showed poor performance. The main reason for such performance may be attributed to the fact that the sharp corners act as thermal bridges, which accelerate heat transfer from the solid-to-solid part of bricks [32]. Conversely, rounder edges afford uniform heat transfer with no thermal bridges, which promotes the natural convective heat transfer more than sharp corners.

3.3. Analysis of the thermal effectiveness of bricks' cavities

As mentioned earlier, the thermal behaviour of bricks with different air gaps was evaluated in terms of the maximum temperature reduction, decrement factor and temperature gradient. Fig. 10 displays the maximum temperature reduction of bricks across all three orientations, in which the circular cavity design consistently provided the highest reduction, achieving 5.1 °C, 6.3 °C, and a notable 10.1 °C for the east, south and west orientations, respectively. Comparatively, the brick with circular cavities has minimised the inner surface temperature by about 16 %, 28 % and 34 % over the square, triangular and rectangular cavities in the east orientation.

This achievement proves that the circular cavity is most effective at reducing the peak temperature transfer from the outer to the inner surface. Besides, the higher the outside ambient temperature, the better the reduction confirmed, as could be observed in the west-orientation case. This obviously means that the circular cavities have resisted the heat flow towards the interior edge of the brick, while lower thermal

resistance was confirmed from the other shapes. This behaviour is attributed to the uniform thermal distribution of heat transfer in the rounded edges compared to the sharp edges [33]. Besides, the sharp edges of the square, triangular and rectangular cavities have stagnation areas, influencing the heat transfer of bricks. In other words, the heat dissipation inside circular cavities is uniform and spread evenly inside the brick, avoiding the so-called localised hot spots [34]. These spots are common in sharp corners of square, rectangular and triangular cavities, which concentrate the heat, resulting in non-uniform heat behaviour and maximising surface temperature. Eventually, the natural convection inside circular cavities is more stable than that of other cavities, which allows heat to be dissipated around the cavity before reaching the indoor surface of the brick.

The decrement factor, as earlier stated, designates the effectiveness of tested bricks to minimise the temperature fluctuations. Fig. 11 indicates the decrement factor of bricks at various orientations. The circular cavity design consistently exhibited the lowest decrement factor at all orientations. For the east orientation, the brick with circular cavities had a decrement factor of approximately 0.37. However, for south and west orientations, the decrement factor of the brick with circular cavities was around 0.21 and 0.14, respectively, showing better performance than the bricks with other cavities. These findings demonstrate that the circular cavity is superior in reducing the amplitude of temperature swings from the outside to the inside compared with the other cavity shapes. This is because the temperature is slowly swinging in the rounded cavities due to less surface area with large cavity volume, which reduces the heat loss to the surroundings. Besides, the circular cavities have a uniform thermal distribution of heat entering from the outdoor edge towards the indoor, resulting in more stable heat flow throughout the brick and reducing the temperature swing eventually. This provides uniform resistance for air to trap heat flow and prevent heat concentration that could occur in cavities with sharp corners.

Fig. 11 also shows that the decrement factor for the brick with circular cavities was remarkable under high ambient temperatures, as indicated in the west case. Specifically, the circular cavity has reduced the temperature swing by about 8 %, 15 %, and 28 % compared with the rectangular, triangular and square cavities, respectively, while it was reduced by only 2.7 %, 2.4 % and 7.6 % in the east orientation case. This

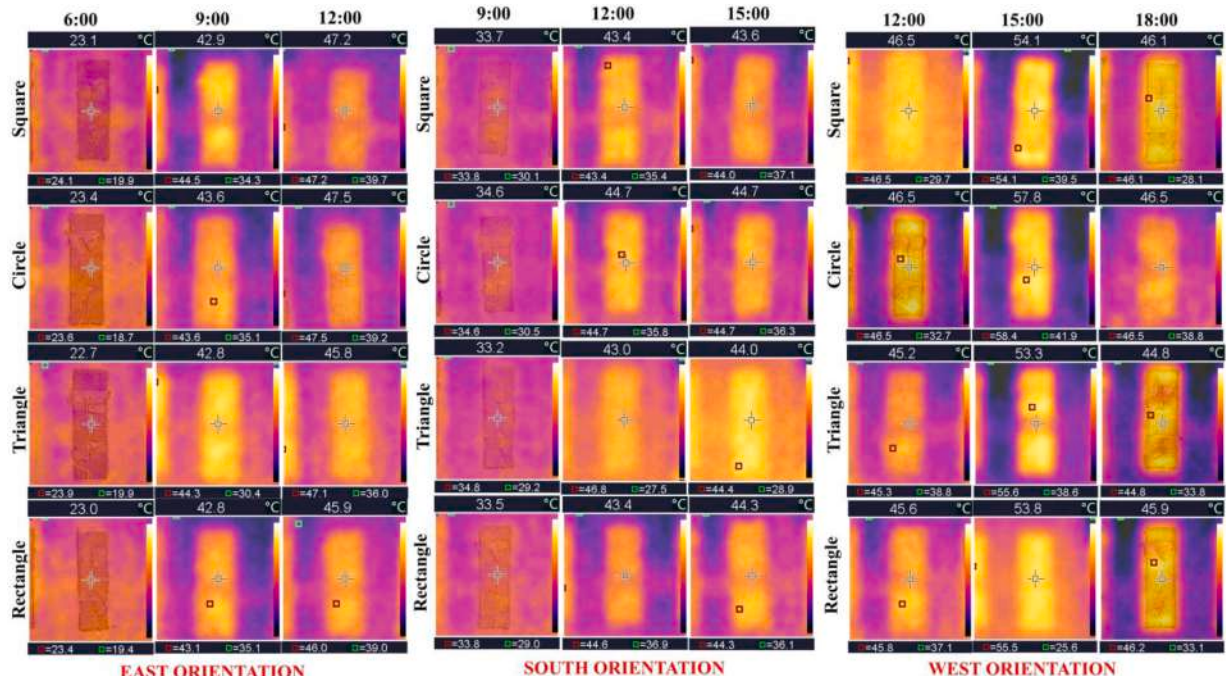


Fig. 9. Thermal photos of the outer surface temperatures.

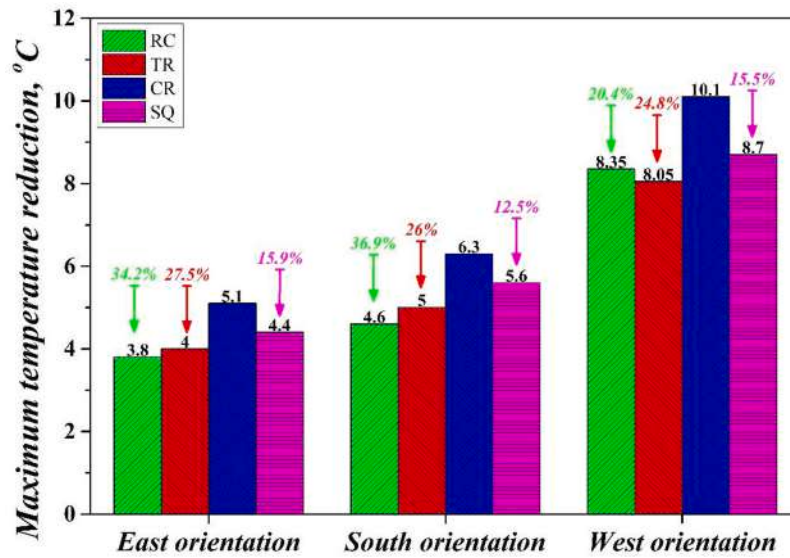


Fig. 10. Maximum temperature reduction of tested bricks at various orientations.

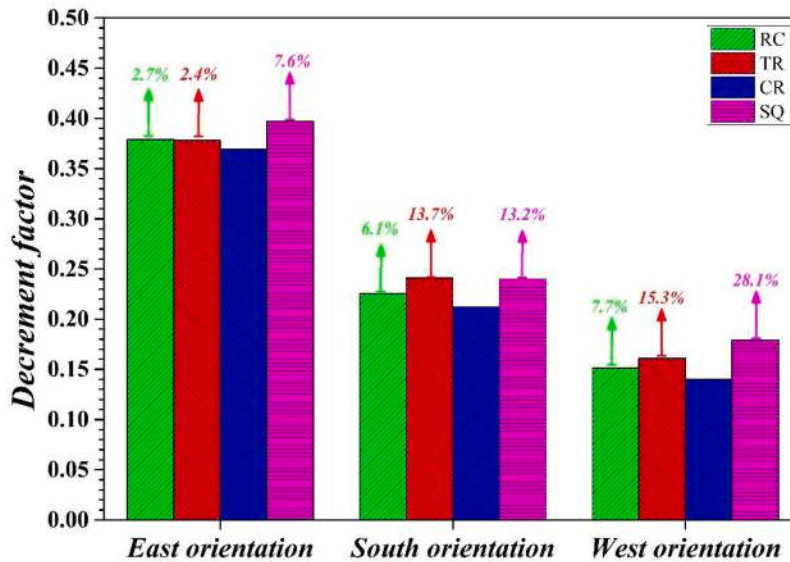


Fig. 11. Decrement factor of test bricks at various orientations.

could be attributed to the fact that the heat transfer is flowing quickly at high ambient temperatures, allowing better performance for the circular cavities than the other ones. Besides, the brick's thermal resistance copes with the heat transfer at low temperature cases, which makes the bricks have a relatively similar decrement factor.

The temperature gradient of test bricks is illustrated in Fig. 12. Consistently across all three orientations, the brick designed with circular cavities has achieved the highest temperature gradient. For the east orientation case, the circular cavities showed a temperature gradient of $0.42\text{ }^{\circ}\text{C}/\text{cm}$, while it was $0.53\text{ }^{\circ}\text{C}/\text{cm}$ for the South orientation, and $0.84\text{ }^{\circ}\text{C}/\text{cm}$ for the west orientation. The high temperature gradient in the brick with circular cavities compared with other bricks indicates better thermal insulation of the brick towards heat flow. This could be attributed to the uniform heat convection distribution inside rounded edges compared with the sharp ones, which reduces temperature jumps. On the contrary, sharp edges of square, rectangular and triangular cavities create air pockets with high temperature concentrations, resulting in steep gradients and reducing the thermal insulation potential of bricks. However, the brick with square cavities has followed

with a good temperature gradient, indicating favourable thermal insulation performance due to the large cavity thickness in the width direction. Convincingly, the brick with circular cavity configuration provides the most effective thermal barrier, leading to a steeper temperature drop across the brick's thickness.

3.4. Mechanical performance of bricks

The mechanical test of the developed bricks was conducted using a compression test machine. Four brick samples for each air-gap shape were crushed to specify the maximum load of each brick. Fig. 13 shows the maximum load of crushed samples.

The mechanical test (Fig. 14) indicates that the circular air-gap brick exhibited the highest average compressive strength, achieving approximately 3.65 MPa , while the bricks' rectangular, triangular and square shapes showed 3.34 , 2.82 and 3.04 MPa on average. This performance was notably better than the other designs, in which the brick of circular cavities was stronger than the rectangular, triangular, and square ones by approximately 9.3% , 29.4% , and 20.1% , respectively. This could be

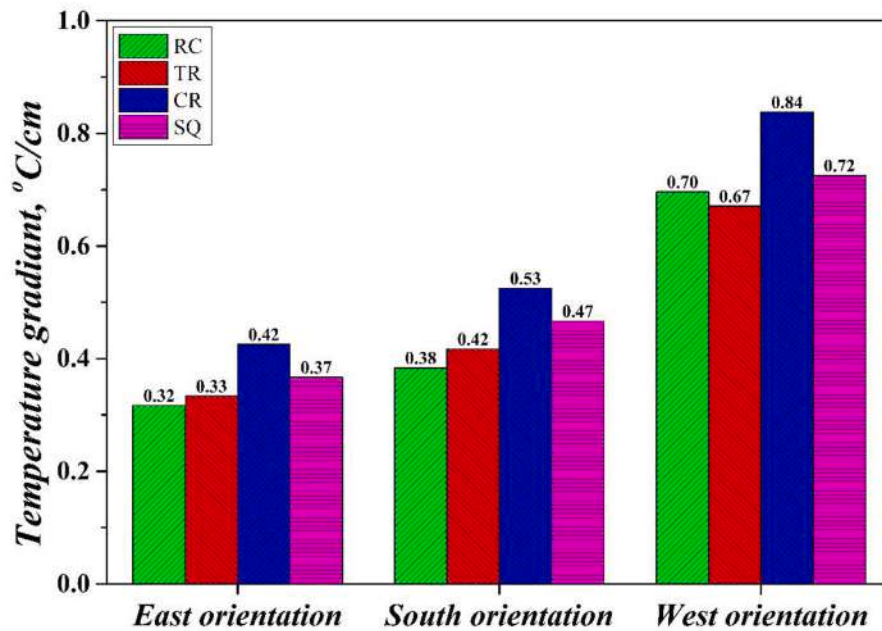


Fig. 12. Temperature gradient of bricks at various orientations.

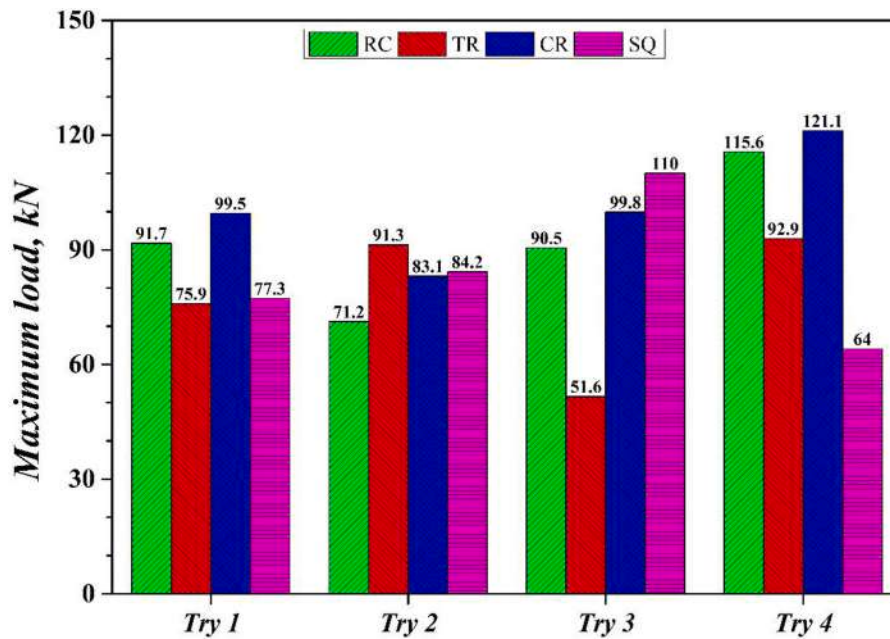


Fig. 13. Maximum load of tested bricks.

attributed to the lower mechanical stress concentration on the circular holes, compared with the sharp edges. In other words, circular cavities provide uniform stress distribution during loading, allowing smooth flow around the cavities. On the contrary, sharp edges of square, rectangular and triangular cavities allow stress concentration in the edges, making points of weakness to start the failure. In addition, rounded cavities prevent natural crack initiation, which is common in sharp edges, which expedites the brick's failure under compression. From the thickness point of view, the circular cavities have thicker concrete compared to the other bricks, maintaining better material support around the cavities.

3.5. Comparison of research results with literature studies

Some research efforts have been made to investigate the thermal and mechanical advancements of bricks/blocks with different air cavity shapes. For instance, Kočí et al. [35] conducted a numerical study to show the best thermally-performed brick integrated with one air cavity of different shapes and orientations (Fig. 15). Five different air cavities, namely with square, triangle and circular shapes, with the same air cavity to brick ratio of 0.35, were subjected to a constant heat flux source. Study findings showed that the conductive heat transfer through bricks was reduced by up to 12.1 %. Explicitly, the brick with the opposite triangle shape was the most thermally efficient among other configurations, indicating thermal conductivity by 0.223 W/m·K, while the circle-shaped brick was thermally poor due to high conductive heat



Fig. 14. Test bricks before and after the compressive strength test.

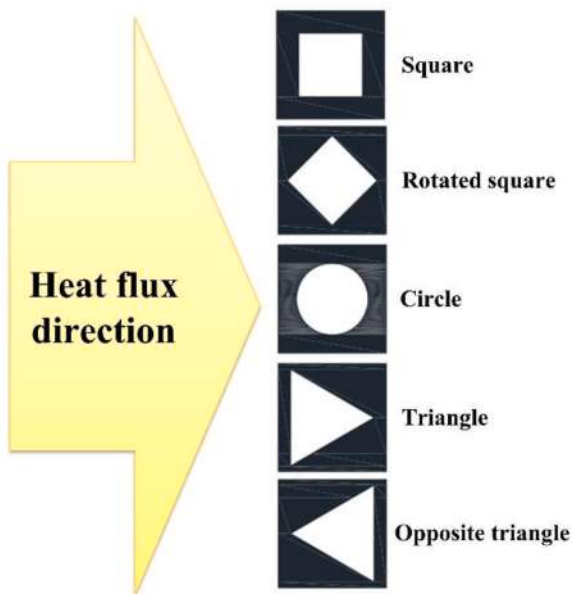


Fig. 15. Brick shapes developed by Kočí et al. [35] (reprinted by authors).

transfer reaching 0.236 W/m.K.

Following the same numerical approach, Sassine et al. [36] investigated the thermal and mechanical performance of 10 concrete blocks ($40 \times 20 \times 10$ cm) with square, rectangular and circular cavities. The developed blocks were provided with 1–9 air cavities of different arrangements, as illustrated in Fig. 16. Study findings showed that block model (3) exhibited the best thermal performance among other models, showing thermal resistance difference by 40 %- 60 % compared to them. In addition, the mechanical analysis showed that the block model (5) was the best due to high lateral mechanical resistance. However, the study revealed that block models (6), (7) and (10) are best considering both thermal and mechanical characteristics, which are essential in the construction industry.

Al-Tamimi et al. [37] verified a numerical study for 24 concrete blocks, modelled with $40 \times 20 \times 20$ cm dimensions and confirmed

under the weather conditions of Dhahran city, Saudi Arabia. The studied blocks included 2–8 air cavities of square, rectangular and circular shapes, in which blocks had a hollow ratio ranging from 0 % to 52.5 %, as illustrated in Fig. 17. Results showed that increasing the hollow ratio decreased the heat transfer across the blocks due to augmented convective heat transfer effect over the conductive heat transfer. Besides, blocks with 51 % hollow ratio (i.e., H-2, H-5 and H-10) displayed the highest inner surface temperature reduction by 7.18 °C. Conversely, the block with 28.3 % hollow ratio (i.e., H-3) designated the lowest temperature reduction by about 5.42 °C. For blocks with similar hollow ratios, the results showed that rectangular shapes had better thermal performance than those with circular and square shapes.

As can be noticed in the above literature studies, there is no common agreement regarding the optimal cavity shape for bricks/blocks to attain the best thermal and mechanical performance. Some of them reported that the rectangular shape is advantageous, while others showed that the rectangular shape is thermally efficient, with the poorest performance for the circular shape. Therefore, the results reported in the current work are more realistic since they were founded on an experimental basis, unlike numerical studies, which have certain results in most cases. Precisely, numerical studies were mostly conducted under steady-state boundary conditions, which are significantly different from the fluctuating environmental conditions in experimental work [38]. Therefore, both thermal and mechanical performances of hollow bricks with optimised cavity shapes are necessarily conducted experimentally to consider the overall influence of environmental conditions [39]. Explicitly, the influence of humidity, air speed and direction is mostly overlooked in numerical studies, resulting in unrealistic findings compared to the experimental examinations.

4. Conclusions and recommendations

4.1. Conclusions

This work performs a comparative analysis of the thermal and mechanical performance of concrete bricks with square, triangular, circular and rectangular cavities having the same volume. The bricks were fabricated and tested towards the east, south and west orientations considering the reduction in the surface temperature, decrement factor and temperature gradient. In addition, a compressive strength analysis

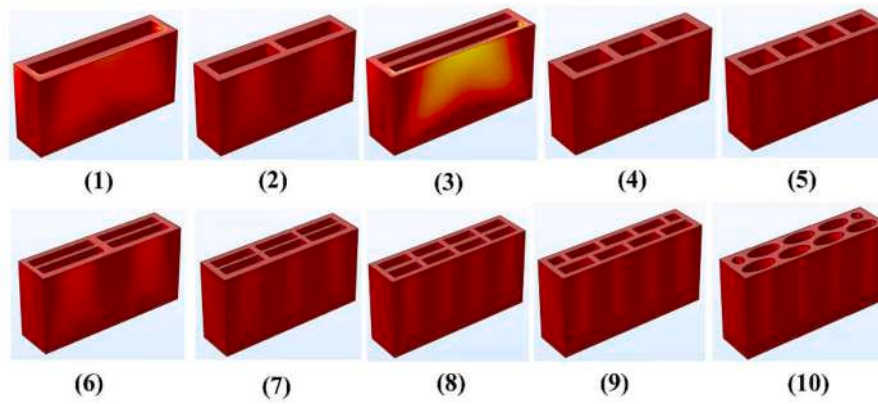


Fig. 16. Block configurations investigated by Sassine et al. [36] (reprinted by authors).

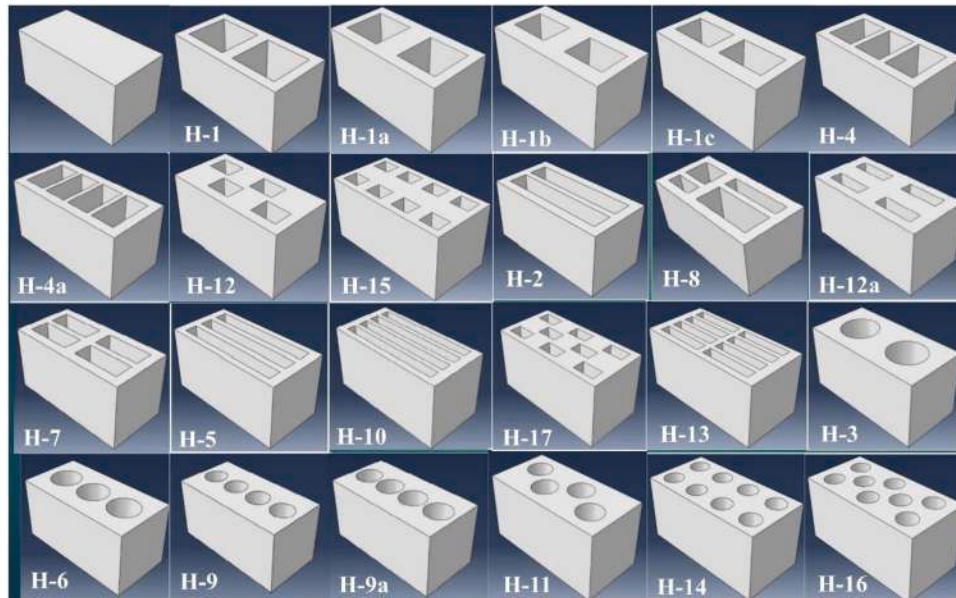


Fig. 17. Block models studied by Al-Tamimi et al. [37] (reprinted by authors).

was conducted for four samples of each brick type using a special compression machine. Amongst other bricks, the brick with circular air cavities showed the best thermal performance over the rectangular, triangular and square shapes in all orientations, especially at high ambient temperature. Quantitatively, the maximum temperature reduction for this brick reached a mark of 10.1 °C in the west orientation. Correspondingly, the decrement factor and temperature gradient attained a mark of 0.14 and 0.84 °C/cm, respectively, at the same orientation.

The brick with circular air cavities has achieved the best mechanical test, showing a better mechanical compressive strength by about 9 %, 29 %, and 20 %, over the rectangular, triangular, and square cavities-based bricks, respectively. The findings attained in the current research confirmed that the circular cavities could minimise the thermal and mechanical stresses of concrete, allowing for the production of efficient concrete bricks for wall constructions.

4.2. Recommendations and insights for future studies

Regardless of study limitations and scope, some recommendations could be suggested for the future, aiming to draw a solid path for new incomers to enrich this research field. Some of these recommendations are as follows:

- Different concrete mixing ratios could be experimented with to improve the mechanical strength of modified bricks. This could cause a decline in the mechanical properties of developed bricks due to high-volume air gaps.
- Same air gaps with smaller volume could be tested in comparison with the big ones studied in this research. The thermal and mechanical tests should be considered in this regard.
- Developing complex cavity geometries using 3D printing concrete machines is suggested to offer flexible models and optimise the thermal insulation of bricks easily. However, this approach is typically costly, as well as dealing with special raw materials [40].
- Incorporating waste materials, such as rubber, plastic and polystyrene wastes, could be studied to optimise the thermal insulation potential of bricks as well as the brick weight. This research direction could contribute to mitigating the plastic waste that raises environmental concerns. However, declined mechanical strength and fire risk aspects should be considered in such studies due to the ductility and flammability potential of plastics.
- Some aspects regarding bricks' durability, workability, load-bearing, sound damping and fire safety could be highlighted and analysed along with the thermo-mechanical features [41]. These aspects could afford a complete picture for the developed technology towards eco-friendly, cost-effective and feasible construction products.

- Environmental implications and lifecycle assessment could be explored on an annual basis for real-sized building walls to assess the long-term performance and potential advantages of optimised bricks. This approach could be conducted utilising some advanced simulation tools such as EnergyPlus and Ansys Fluent software.

CRediT authorship contribution statement

Qudama Al-Yasiri: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammed Alktrane:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yousif Hamed:** Investigation, Formal analysis, Data curation. **Abdulrezaq Aqeel:** Investigation, Formal analysis, Data curation. **Muqtada Lafta:** Investigation, Formal analysis, Data curation. **Péter Bencs:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Marta Szabo:** Writing – review & editing, Supervision, 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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