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Effect of Air-gap Shape on the Thermal and Mechanical Features of Hollow Concrete Bricks

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بسم الله الرحمن الرحيم

(وَلَمَّا بَلَغَ أَشُدَّهُ وَاسْتَوَى آتَيْنَاهُ حُكْمًا وَعِلْمًا وَكَذَلِكَ نَجْزِي الْمُحْسِنِينَ) ﴿١٤﴾

سورة القصص- الآية ١٤

SUPERVISOR CERTIFICATION

This is to certify that the Bachelor of Engineering project titled: *Effect of Air-gap Shape on the Thermal and Mechanical Features of Hollow Concrete Bricks*, submitted by **Yousif Hamed, Abdulrezaq Aqeel** and **Muqtada Lafta**, in partial fulfillment of the requirements for the award of the degree of **Bachelor of Engineering in Mechanical Engineering** at the **University of Misan/ College of Engineering**, was carried out under my supervision during the academic year 2024-2025.

The contents of this project report, in full or in part, have not been submitted to any other institution or university for the award of any degree or diploma.

The project work has been carried out with diligence and sincerity, and the students have demonstrated a sound understanding of the engineering concepts involved in the project.

I hereby recommend the submission of this project for examination and consideration toward the award of the degree.

Date: 21 May 2025

Place: College of Engineering, University of Misan

Signature of the Supervisor:

إهداء

ما كانت هذه الخطى لتستقيم، ولا هذه الغاية لتُبلغ، لولا نَفَسٌ من رحمة الإله، ولُطفٌ خفي سار بين العثرات، فأحاطني بعنايته، وأمدّني بقوة من عنده، فله الحمد كما ينبغي لجلال وجهه وعظيم سلطانه.

إلى من كان للحق ميزانه، وللعلم بابه، ولسيف العدالة مضاءه؛ إلى من نقش في الذاكرة ملامح الشجاعة والفصاحة والنور، إلى أمير المؤمنين علي بن أبي طالب، أبعث ثمرة هذا الجهد، عربون محبة وولاء.

إلى شهداء الوطن، من صعدوا إلى السماء ليهبونا الحياة على الأرض، أولئك الذين سُطّرت أسماؤهم في سجلات الخلود، لهم في قلبي دعاء، وفي وجداني انحناءة إجلال.

إلى أبي وأمي، نبع العطاء ومصدر الإلهام، من علّماني كيف أقف، وكيف أكتب، وكيف أحلم. لولا صبرهما ودعاؤهما، ما كنت لما أنا عليه اليوم.

وإلى من غرسوا أول بذرة في حقول معرفتي، وبالأخص إلى روح معلمي الراحل الاستاذ (ناظم مزعل المرياني) الذي وإن غاب جسدًا، بقي أثره في عقلي ووجداني، له مني دعاء لا ينقطع، ووفاء لا يزول.

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(وَلَقَدْ آتَيْنَا لُقْمَانَ الْحِكْمَةَ أَنِ اشْكُرْ لِلَّهِ ۚ وَمَن يَشْكُرْ فَإِنَّمَا يَشْكُرُ لِنَفْسِهِ ۖ وَمَن كَفَرَ فَإِنَّ اللَّهَ غَنِيٌّ حَمِيد)

(لقمان: 12)

وقال رسوله الكريم (ص): "من لم يشكر المخلوق، لم يشكر الخالق"

وها نحن نصل إلى ختام هذا الجهد العلمي، لا يسعنا إلا أن نعبر عن بالغ شكرنا وامتناننا لكل من مد لنا يد العون وأسهم في إنجاز هذا المشروع. ونخص بالذكر مشرفنا الفاضل الدكتور قدامه محمد قاسم الياسري، الذي كان لعنايته وتوجيهاته السديدة بالغ الأثر في إنجاح هذا العمل فقد بذل من وقته وجهده وصبره ما يستحق عليه كل الشكر والتقدير. جزاه الله عنا خير الجزاء، وبارك في علمه، وحفظه من كل مكروه.

Abstract

Improving the thermal performance of building materials is essential for reducing cooling loads in hot climates. This study presents an experimental investigation into how the shape of internal air-gaps and the use of recycled waste fills affect both the thermal and mechanical behavior of hollow concrete bricks. Bricks with square, rectangular, circular, and triangular cavities were fabricated, and tested each geometry and compared to specify the thermally-efficient shape in three orientations (East, South and West). Thermal indicators, including maximum temperature reduction, temperature gradient decrement factor and time delay, were analyzed and discussed. Eventually, a compressive strength test was conducted to evaluate the mechanical behaviour of modified bricks.

The results indicated that circular air-shape deliver the best thermal insulation, achieving a maximum temperature reduction by up to 10.1 °C. When these circular cavities were packed with plastic waste, it was observed a further improvement in this indicator by 12.2 °C and a thermal time delay approaching 180 min. The circular-gap bricks retained a compressive strength of 3.65 MPa on average, comparable to that of other specimens. These findings underscore the benefit of optimizing air-gap geometry, especially circular shapes, to yield hollow bricks that meet structural demands while significantly enhancing thermal resistance in hot-climate applications.

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Nomenclature

Abbreviation	Definition
AHU	Air Handling Unit
ASTM	American Society for Testing and Materials
CMU	Concrete Masonry Unit
DF	Decrement Factor
ESP	Eggshell Powder
FEM	Finite Element Modeling
GFC	Geopolymer Foam Concrete
IEA	International Energy Agency
MEP	Micro-encapsulated PCM
MTR	Maximum Temperature Reduction
OPC	Ordinary Portland Cement
PCM	Phase Change Material
SDA	Sawdust Ash
TG	Temperature Gradient
WWR	Window-to-Wall Ratio

Symbols

Symbol	Definition	Unit
T_i	Average interior surface temperature	°C
T_o	Average exterior surface temperature	°C
$T_{o,max}$	Maximum exterior surface temperature	°C
$T_{i,max}$	Maximum interior surface temperature	°C
$T_{o,min}$	Minimum exterior surface temperature	°C
$T_{i,min}$	Minimum interior surface temperature	°C
T_{amb}	Ambient temperature	°C
L	Brick's thickness	cm
U	U-value (Overall heat transfer coefficient)	W/m^2K
R	R-value (Thermal resistance)	$m^2 \cdot K/W$
Q	Heat flow rate	W

Chapter 1: Introduction

1.1 Introduction

As human society continues to evolve, 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 69% of this portion is used for cooling and heating [2, 3]. To address this issue, developing innovative technologies and solutions is essential to reduce energy consumption in buildings. Building envelope plays a crucial role 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. Walls act as thermal barriers, helping to maintain indoor temperatures by reducing heat loss in winter and minimizing heat gain in summer. The choice of construction materials significantly impacts a building's thermal performance, durability, and environmental footprint.

Concrete is the most widely used building material, composed of cement, aggregates, sand, water, and various additives tailored to achieve specific properties. [4]. It requires significant natural resources, while also emitting a large amount of carbon dioxide [5] and other greenhouse gases during the production of ordinary Portland cement, sand, and coarse aggregates. In order to overcome these issues, the building industry is shifting its focus toward sustainable green concrete made from alternative or recycled waste materials. Incorporating recycled waste materials can help mitigate aggregate shortages at construction sites while also minimizing the environmental impact associated with aggregate mining and disposal [6].

Hollow bricks have become increasingly popular in the construction industry over the past decades. Growing demands for better thermal insulation in building materials, driven by national standards in Europe, have led manufacturers to shift away from traditional solid bricks. Instead, hollow bricks with various internal cavity designs have largely replaced solid bricks and now dominate the market. However, unlike solid bricks, whose thermal conductivity can be measured using standard methods, the intricate structure of hollow bricks presents challenges for conventional testing techniques [7].

1.2 Research scope

This project focusses on the development and evaluation of concrete bricks with various air-gaps, thermally and mechanically. The study aims to shed light on alternative methods to develop concrete bricks/blocks to be used efficiently under the hot weather conditions. The scope of this project includes:

- **Material selection and mix ratio**: Developed bricks were fabricated using local raw materials (Portland cement, crushed gravel and sand). The raw materials were mixed with 1:2:2 mix ratio for the cement:gravel:sand, where other mix ratios influencing on the thermal and mechanical properties.
- **Study location**: The developed bricks were tested under the hot weather conditions of Al Amarah City, Southern Iraq. This location has long sunshine hours and high solar radiation.
- **Waste materials and compactness**: The used waste materials were collected randomly and used as fills with no specific procedure. The thermal and physical characteristics of waste materials and their compactness inside cavities have a notable effect on the thermal behaviour of bricks.

1.3 Objectives

1. Design and fabricate concrete bricks of different air-gap shapes (namely, square, rectangular, circular, and triangular).
2. Study the thermal insulation behavior of the developed bricks considering their ability to minimize and delay the temperature.
3. Explore the insulation effect of different waste materials for the best thermally-performed brick type. The suggested waste materials are namely sawdust, cork and waste plastic.
4. Conduct a mechanical compression test for the developed bricks to show their mechanical behavior along with their thermal performance.

Chapter 2: Literature Studies

2.1 Overview of building energy

In recent years, the thermal requirements of buildings have become increasingly important to reduce energy consumption and ensure indoor thermal comfort. As a result, the construction industry has focused on developing high-performance buildings that minimize energy use while maintaining occupant comfort. In many regions, buildings consume significant amounts of energy for heating and cooling, leading to a growing need for energy-efficient [2]. Given that heating and cooling systems account for a large proportion of building energy use, improving energy efficiency in this area presents a major opportunity for reducing overall consumption. One approach to enhancing efficiency is the selection of appropriate construction materials that improve insulation and thermal performance.

2.2 Building elements and their influence on indoor environment

The design and composition of building elements in essential in determining indoor environmental quality and energy performance. Elements such as walls, roofs, floors, windows, and doors significantly affect heat transfer, ventilation, daylighting, and acoustics within a building. Proper selection and integration of these components contribute to improved thermal comfort, energy efficiency, and overall occupant well-being. Understanding the interactions between building elements and their influence on indoor conditions is essential for optimizing building performance and reducing energy demand.

2.2.1 **Walls**

The role of walls as a fundamental building element extends far beyond mere aesthetics; they are crucial in shaping the overall energy performance and consumption of buildings. As the primary interface between the interior environment and the external climate, walls significantly influence how buildings interact with their surroundings. They serve multiple functions, including providing structural support, insulation, and protection from the elements, while also contributing to the thermal comfort and energy efficiency of a space.

In an era where sustainability and energy conservation are paramount, understanding the impact of wall design and materials on energy consumption has become increasingly important. The choice of materials, thickness, insulation properties, and even the configuration of windows within walls can dramatically affect a building's heating and cooling demands. For instance, well-insulated walls can minimize heat loss in winter and reduce heat gain in summer, leading to lower energy costs and a reduced carbon footprint.

Moreover, advancements in building technologies have introduced innovative wall systems that not only enhance energy efficiency but also promote occupant well-being. Features such as living walls—vertical gardens that improve air quality and provide natural insulation—are gaining popularity as both aesthetic enhancements and functional elements that contribute to energy savings [8].

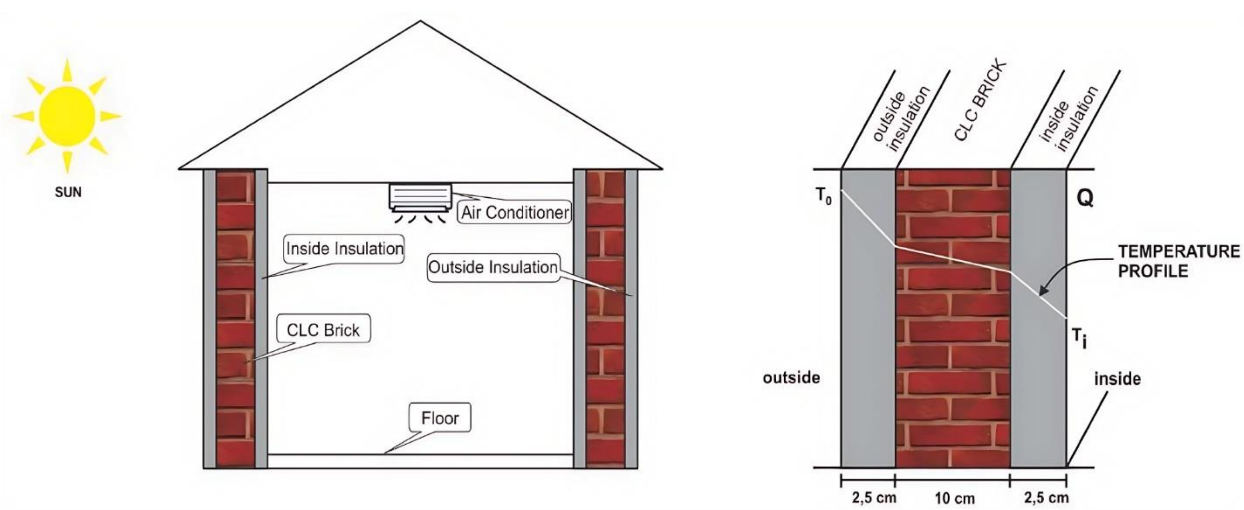

Figure 2.1 Building Description and Wall design.

2.2.2 **Roofs**

Roofs are more than just protective coverings; they are critical determinants of a building's energy performance and overall sustainability. As the uppermost layer of a building envelope, roofs play a vital role in regulating indoor temperatures and shielding interiors from the external climate. The design, materials, and construction techniques employed in roofing systems directly influence the amount of energy required to heat and cool a building, making roofs key elements in achieving energy efficiency.

The roof's primary function is to protect the building's interior from environmental elements, such as solar radiation, rain, snow, and wind. However, the roof also dictates the degree to which a building absorbs or reflects solar heat, thereby impacting its cooling load in warmer months and its heating needs during colder periods. A well-designed roof can minimize heat gain in the summer, reducing the need for air conditioning, while also preventing heat loss in the winter, thus lowering heating costs [9].

Factors like roof shape, orientation, insulation, and surface reflectance significantly affect the building's energy consumption. For example, a roof with adequate insulation can act as a thermal barrier, preventing heat transfer between the interior and exterior environments. Similarly, the choice of roofing materials, such as reflective coatings or specialized shingles, can reduce solar heat absorption and improve energy efficiency.

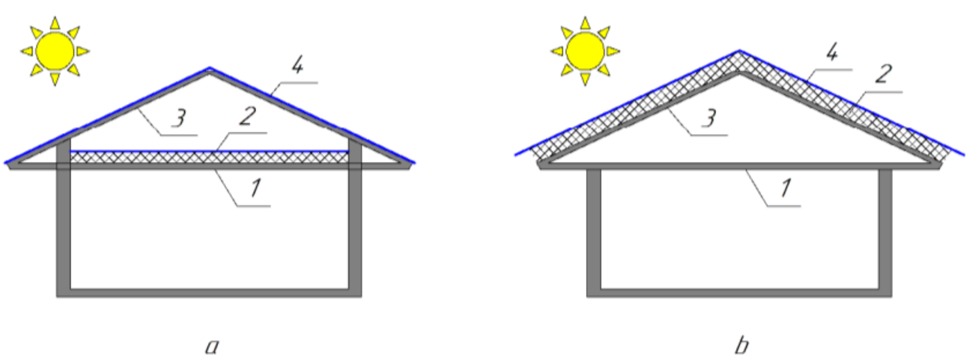

Figure 2.2 Different types of roofs: insulated roof (a). cold roof (b)

2.2.3 **Floors**

Floors are essential building elements that significantly impact a building's energy consumption and thermal properties. Buildings account for a large portion of global energy consumption and greenhouse gas emissions.

The type of flooring used affects energy consumption because some flooring provides better thermal insulation, which reduces the need for air conditioning and heating. Thermal resistance (R-value) indicates how well materials resist heat flow; the higher the R-value, the more energy-efficient the floor. Flooring comprises a significant portion of a building's surface area, so using uncontrolled flooring leads to higher power consumption.

Different floor shapes can also affect a building's energy consumption [10]. The influence of a building's depth ratio on energy consumption is greater than its width ratio [10]. Advances in energy efficiency are key to decoupling energy consumption from floor area growth [1]. The energy consumed per square meter in buildings needs to decline significantly to align with net-zero emission scenarios. Sustainable flooring systems can generate renewable energy when people interact with them, reducing reliance on fossil fuels [1].

2.2.4 **Windows**

Windows significantly affect a building's energy consumption and thermal properties [11]. The window-to-wall ratio (WWR), window frame materials, and glazing type all play crucial roles in energy efficiency [12].

Optimizing window proportions can significantly reduce annual energy consumption. Research indicates that the optimal window percentage varies depending on the facade's orientation [12]:

- North side: 26%-33% window percentage
- South side: 21%-25% window percentage
- East side: 54%-57% window percentage
- West side: 58% window percentage

It's worth noting that large window areas can contribute to high energy consumption if not carefully considered [13]. In high-rise residential buildings, solar heat gain through windows can account for 45% of the total cooling load [13]. Thermally insulated windows are essential for energy efficiency in buildings. Smart windows can optimize energy use across various climates. The integration of artificial light with daylight, using dimming systems, can also affect energy consumption.

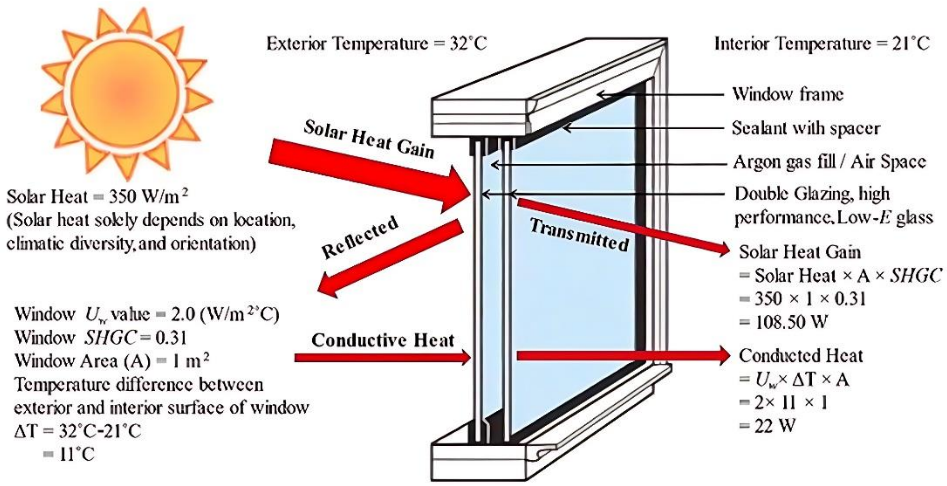

Figure 2.3 Schematic illustration of heat transfer mechanisms in an energy-efficient window

2.2.5 **Doors**

Doors are crucial for energy efficiency in buildings, affecting thermal comfort and energy consumption. Energy-efficient doors are designed to optimize insulation and prevent air leakage.

Several factors contribute to a door's energy efficiency:

- **Material**: Fiberglass and steel doors are generally more energy-efficient than wood doors due to their insulation properties. Solid wood doors offer some thermal resistance, but require proper finishing and maintenance.
- **Insulation**: Doors with a dense foam core provide excellent insulation1. Insulated cores in steel and fiberglass doors help maintain internal temperatures.
- **Installation**: Proper installation ensures a tight seal, preventing air leakage.

- **Type**: Impact-resistant doors and vinyl patio doors often include energy-efficient features like low-emissivity glass and insulated frames. High-speed doors can minimize thermal losses by reducing the time the door is open.

2.3 Thermal and mechanical developments of brick walls

The thermal and mechanical properties of brick walls are influenced by various factors, including the type of bricks used, the design of the wall, and environmental conditions.

2.3.1 **Thermal performance of brick walls**

The thermal performance of brick walls is crucial for energy efficiency in buildings. Recent research has focused on optimizing the thermal insulation properties of different types of bricks.

- **Thermal conductivity**: Studies have shown that the thermal conductivity of bricks varies significantly based on their composition. Here are the typical thermal conductivity values of different types of brick walls [14].

Table 2.1 Thermal conductivity values of different brick wall types

Brick Type	**Thermal Conductivity (W/mK)**
Common red bricks	0.6
Insulating bricks	0.15
Clay bricks	0.5-1.0
Lightweight coursing bricks	0.42-0.50
Medium-dense concrete bricks	0.51
Dense concrete bricks	1.33-1.63
Lightweight concrete bricks	0.19

- **Thermal resistance**: The thermal resistance (R-value) of brick walls is a critical measure for assessing their insulation effectiveness. Research indicates that R-values can be improved by selecting appropriate brick types and wall configurations. For example, a wall composed of horizontally hollow bricks can achieve an R-value of 0.5368 $m^2 \cdot K/W$, while vertically perforated bricks can reach up to 1.5470 $m^2 \cdot K/W$ [15].

- **Impact of mortar and insulation:** The presence of mortar joints can significantly affect the overall thermal performance. Studies suggest that using less conductive mortars or minimizing mortar joint areas can enhance the R-value by reducing thermal bridging effects [16].

2.3.2 Mechanical behavior of brick walls

The mechanical properties of brick walls are equally important for ensuring structural stability under various loads.

- **Compressive strength:** Brick walls exhibit high compressive strength, which is typically much greater than their tensile strength. The average compressive strength for common bricks ranges from 32.6 MPa, with a coefficient of variation indicating some variability in performance across different batches [16].
- **Tensile strength:** The tensile strength of brick walls is significantly lower than compressive strength, often leading to failure under tensile loads. Studies indicate that the tensile strength can be as low as 10% of the compressive strength [17].
- **Elastic modulus**: The elastic modulus of masonry is influenced by the type of bricks and mortar used. It typically falls between 700 and 1200 times the compressive strength of the masonry prism. This ratio helps in estimating how much a wall will deform under load.
- **Poisson's ratio:** The Poisson's ratio for brick masonry is generally around 0.19, indicating how much a material deforms laterally when subjected to axial stress [18].

2.3.3 Enhancements in thermal and mechanical properties

Enhancements in the thermal and mechanical properties of brick walls are essential for improving energy efficiency and structural integrity in modern construction. Recent studies have focused on various methods, materials, and designs to optimize these properties

Thermal enhancement

Enhancements in the thermal performance of brick walls are essential for improving energy efficiency and comfort in buildings. Various methods have been identified to optimize the thermal properties of brick materials and wall assemblies.

1. **Material composition**

The use of different clay mixtures and firing conditions can significantly enhance the thermal performance of bricks. Higher firing temperatures and longer durations result in denser bricks with improved thermal conductivity. For instance, horizontally hollow bricks made from specific clay mixtures exhibit thermal conductivities as low as 0.1536 W/m·K, leading to better insulation properties [15].

2. **Brick geometry**

The geometry of brick perforations plays a crucial role in thermal performance. Redesigned perforated ceramic bricks have shown a 20% decrease in U-values, indicating improved thermal resistance. This redesign has been implemented in manufacturing practices in regions like Chile, where it has resulted in substantial energy savings for residential buildings [19].

3. **Composite materials**

Innovative composite blocks that combine solid and hollow sections with insulating layers (e.g., extruded polystyrene) have been developed. These blocks demonstrate superior thermal properties compared to traditional hollow core blocks, effectively reducing heat transfer through walls [16].

Mechanical enhancements

Enhancements in the mechanical properties of brick walls are vital for improving their structural integrity and performance under various loading conditions. Recent research has identified several methods to achieve these enhancements.

1. **Structural design**

The mechanical behavior of brick walls can be improved through optimized design configurations that distribute loads more evenly across the structure. For example, using lighter materials or adjusting the geometry of bricks can enhance strength-to-weight ratios and tensile strain capacities [20].

2. **Mortar selection**

The choice of mortar also impacts the mechanical properties of brick walls. Using less conductive mortars or reducing the area of mortar joints can minimize thermal bridging effects while maintaining structural integrity.

3. **Advanced manufacturing techniques**

Innovations in manufacturing processes, such as creating bricks with specific void configurations or composite materials, lead to enhanced mechanical strength and durability without significantly increasing weight or cost [20].

Developments in the thermal and mechanical properties of brick walls are essential for modern construction practices that prioritize energy efficiency and sustainability. Ongoing research into material composition, wall design, and innovative construction methods will be key to enhancing the performance of brick walls in future building projects.

2.4 Summary of literature studies

Numerous studies aim to enhance the thermal insulation of bricks to minimize building cooling loads. Researchers investigate various approaches, such as incorporating insulating materials, waste materials, and phase change materials, to improve the thermal and mechanical properties of brick walls.

2.4.1 The implementation of waste materials

The use of waste materials in brick manufacturing has gained significant attention due to its potential to enhance thermal and mechanical properties while promoting sustainability. Several studies have explored different waste materials, such as rice husk, crumb rubber, sawdust ash, eggshell powder, and biomass waste, to evaluate their impact on brick performance.

- **Rice husk as a partial sand replacement**

Mahapatra et al. [21] investigated the use of rice husk as a partial replacement for sand in cement mortar. The study found that increasing the rice husk content led to a decrease in compressive strength but significantly improved thermal insulation. A 7% replacement of sand with rice husk resulted in a 12% reduction in thermal conductivity. Additionally, the water absorption of the material increased, affecting its overall durability. The study also established a linear relationship between the dynamic thermal performance and volumetric heat capacity of the cement mortar.

- **Crumb rubber as a lightweight aggregate**

Kantasiri et al. [22] explored the incorporation of waste crumb rubber in concrete for thermal insulation applications. Using the Taguchi method for optimization, the study revealed that incorporating crumb rubber led to a decrease in unit weight (1598–1746 kg/m^3) and a reduction in compressive strength (7.45–31.26 MPa). However, the thermal conductivity was significantly improved, ranging from 0.51 to 0.67 W/mK, making the material a viable option for energy-efficient construction.

- **Geopolymer foam concrete with sawdust ash and eggshell powder**

Abdellatief et al. [23] examined the effects of sawdust ash (SDA) and eggshell powder (ESP) on geopolymer foam concrete (GFC). The results indicated that replacing up to 10% of the precursors with ESP and 5% with SDA enhanced compressive strength by 16.54% and 4.45%, respectively. Additionally, these mixtures improved thermal properties, with thermal conductivity values of 1.237 W/(mK) for ESP-based GFC and 1.167 W/(mK) for SDA-based GFC. The materials also showed superior thermal diffusivity and specific heat, contributing to improved insulation performance.

- **Biomass waste in clay bricks**

Ahmed et al. [24] studied the inclusion of biomass waste, specifically pomegranate peel waste, in fired clay bricks. The optimal mixture, with 15% pomegranate peel waste fired at 900°C, exhibited lower thermal conductivity compared to conventional bricks. This resulted in energy consumption reductions of 17.55% to 33.13% and CO2 emission reductions of 7.50% to 24.50%. Additionally, economic analysis showed that the payback period for energy savings ranged from 1.88 to 10.74 years, indicating cost-effectiveness.

2.4.2 **Incorporation of phase change materials**

The integration of Phase Change Materials (PCMs) into bricks and masonry units has been explored extensively to enhance thermal performance and energy efficiency in buildings. Several researchers have investigated different PCM incorporation techniques, demonstrating improvements in thermal mass, indoor temperature regulation, and energy savings.

- **PCM-Enhanced pumice blocks**

Canım et al. [25] investigated the integration of paraffin-based PCM into pumice blocks to enhance their thermal performance. The study measured thermal conductivity, specific heat capacity, and latent heat properties. 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.

- **Micro-PCM in cement bricks**

Mukram et al. [26] developed a novel cement brick filled with micro-encapsulated PCM (MEP29) 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.

- **Concrete masonry units with PCM and insulation**

Zhang et al. [27] examined the integration of PCMs and thermal insulation materials in concrete masonry unit (CMU) walls. The study explored different wall patterns and PCM placements under various thermal conditions. Findings showed that PCM-enhanced walls provided improved thermal inertia, reduced thermal bridging effects, and enhanced both stationary and transient thermal performance.

- **Eutectic PCM in clay bricks**

Taj et al. [28] conducted an experimental study on eutectic PCM (Lauric acid and Palmitic acid) incorporated into clay bricks. Their findings demonstrated a 4–5.5°C reduction in indoor temperatures, a 32% reduction in thermal amplitude, and a heat transfer time lag of 150 minutes. The PCM bricks also achieved a 25–30% reduction in heat flux, making them highly effective for passive thermal regulation.

2.4.3 **Other thermal insulation strategies**

In addition to waste materials and phase change materials, researchers have explored other innovative thermal insulation strategies to enhance the energy efficiency of building materials. These approaches focus on optimizing the geometry of construction units, incorporating advanced insulation materials, and improving thermal conductivity to reduce heat transfer. By refining masonry designs and embedding specialized insulating elements, these methods contribute to lower energy consumption and improved thermal comfort in buildings. Below, we summarize key findings from recent studies on these alternative thermal insulation techniques.

Al-Tamimi et al. [29] developed a novel geometry for hollow concrete blocks using finite element modeling (FEM), achieving a 40% reduction in thermal conductivity. By incorporating perlite, rubber, and polyethylene as insulation materials, their masonry blocks significantly improved thermal resistance, meeting ASTM standards for non-load-bearing walls.

Shah et al. [30] investigated the use of mineral wool insulation in hollow concrete blocks. Their study found that larger insulated blocks resisted heat transfer more effectively than smaller ones, with a temperature reduction of over 20°C under extreme conditions. The results were validated through experimental and numerical (FEM) analysis.

While Makrygiannis et al. [31] examined how brick geometry and thermal coefficients influence insulation performance. Their findings suggested that hollow bricks with optimized geometries and air pockets exhibited lower thermal conductivity, improving overall energy efficiency and thermal comfort.

In conclusion, research makes it clear that the materials used in construction play a huge role in improving energy efficiency. Choosing innovative options—like recycled waste products and phase change materials—can significantly cut down on energy use and reduce environmental impact over a building's lifetime. Prioritizing good insulation and thermal mass helps create spaces that stay comfortable naturally, reducing the need for heating and cooling systems. As the industry moves forward, adopting these sustainable practices will be key to building a greener future and tackling climate change.

Chapter 3: Materials and Methods

3.1 Introduction

Concrete is one of the most widely used construction materials globally due to its durability, availability, and cost-effectiveness. However, as the demand for energy-efficient and sustainable building materials increases, traditional concrete bricks face challenges in meeting modern thermal performance standards. One promising approach to enhance the thermal efficiency of concrete bricks is the incorporation of air gaps, which act as thermal insulators by reducing heat transfer through conduction. At the same time, it is crucial to ensure that these modifications do not significantly compromise the mechanical properties of the bricks, such as compressive strength and load-bearing capacity.

This study aims to investigate the effects of air gaps on the thermal and mechanical properties of concrete bricks. By systematically varying air gap configurations and evaluating their impact, this research seeks to provide a deeper understanding of how these modifications influence key performance metrics such as thermal conductivity, compressive strength, and overall structural stability. Furthermore, this study aligns with global sustainability goals by exploring innovative ways to improve energy efficiency in construction materials while maintaining their functional reliability.

3.2 Experimental setup and procedure

3.2.1 **Materials selection and characterization**

The experimental investigation was conducted using carefully selected materials to ensure consistency and reliability throughout the study. Ordinary Portland Cement Type I conforming to ASTM C150 standards was utilized as the primary binding agent. Prior to use, the cement was stored in a dry environment with controlled humidity (<60% Relative Humidity) to prevent premature hydration and clumping. River sand with a fine modulus was selected as the fine aggregate component. The sand was washed thoroughly to remove any organic impurities and clay particles that could potentially compromise the integrity of the concrete mix. Following washing, the sand was air-dried to achieve a saturated surface-dry condition, ensuring consistent water absorption during the mixing process.

3.2.2 **Mold design and fabrication**

Custom molds were designed 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 × 120 mm × 70 mm (length × width × 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:

1. **Square**: 80 mm × 80 mm cross-section
2. **Rectangular**: 180 mm × 35 mm cross-section
3. **Triangular**: Right angle triangle with 160 × 80 A and B sides
4. **Circular**: 90 mm Diameter

Figure 3.1 Mold used for molding process.

3.2.3 **Mix preparation**

The concrete mixture was prepared following a rigorous protocol to ensure consistency across all specimens. The mix design maintained a constant ratio of cement:sand:gravel = 1:2:2 by weight, targeted to achieve a characteristic compressive strength of 20 MPa at 28 days. Aggregates were prepared to saturated surface-dry (SSD) condition to ensure accurate water content control in the fresh concrete mix.

3.2.4 **Specimen molding procedure**

The molding process was conducted outdoors environment maintained at 23 ± 2°C. Prior to molding, the interior 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, rectangular, triangular, and circular), a total of 16 specimens were cast to allow for testing at different curing ages and to ensure statistical reliability of results.

3.2.5 **Curing procedure**

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 hours. After this initial curing period, the specimens were carefully demolded.

During demolding, special attention was paid to the extraction of the wooden inserts. A specialized extraction tool was designed to carefully remove the inserts without damaging the internal surfaces of the air gaps.

3.2.6 **Specimen inspection**

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.

3.2.7 **Assembly of the bricks' setup**

The assembly setup can be summed as:

- **Insulating enclosure preparation:** Marked and cut five vertical cavities in the cork block to snugly fit individual test specimens. As shown in figure (3.2).

Figure 3.2: Installation of test bricks inside cork frame.

- **Sensor placement:** Attached two temperature sensors probe to the external surface of each masonry block using duct tape. As shown in figure (3.3).

Figure 3.3: sensor preparation

- **Test Rig Assembly:** Each brick is inserted into its designated cavity in the cork enclosure, positioned a second set of temperature sensor probes on the inner surface of the block, and finally, the gaps between specimens and cork block are sealed with silicone sealant. And the assembly is positioned outdoors, exposing the outer surface to ambient conditions. As shown in figure (3.4)

Figure 3.4: Final test rig assembly.

3.3 The inclusion of waste materials

Following the thermal performance evaluation of concrete bricks with various cavity geometries (rectangular, triangular, circular and square), there will be further enhancement of the thermal performance of the winning-shape cavity through the incorporation of waste materials within the cavity.

3.4 Measurement devices and tools

This section describes the measurement devices and tools employed to evaluate the thermal performance of concrete brick specimens with various air gap geometries. All specimens were manufactured with a consistent mixture ratio of cement:sand:gravel = 1:2:2, targeting a compressive strength of 20 MPa. The measurement setup was designed to capture the thermal behavior of specimens under controlled environmental conditions.

3.4.1 **Thermal measurement devices**

Digital thermometer

Four high-precision digital thermometers, were deployed for each brick specimen to monitor temperature gradients across the brick. The thermometer has a temperature range of (-50 to 110 °C) with accuracy of (±1 °C) as shown in Figure (3.2).

Figure 3.5 Digital thermometer

Digital anemometer

A portable digital anemometer, as shown in figure (3.3) was used to measure ambient air velocity near the specimen surfaces with a measuring range of air velocity of (0-45m/s ±3%) enabling more accurate thermal modeling and performance assessment.

Figure 3.6 Digital anemometer

Solar power meter

A solar power meter was utilized 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 energy incident on the test specimens. Figure (3.4) shows a picture of the device.

Figure 3.7 Solar power meter

Thermal camera

As shown in figure (3.5), a high-resolution thermal imaging camera was employed to capture comprehensive surface temperature distributions across the specimens.

Figure 3.8 Thermal camera

3.4.2 **Mechanical measurement devices**

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 behavior across brick designs.

The test was carried out using a digital compression testing machine, as shown in Figure (3.6). 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.

Figure 3.9 Compression machine

Table 3.1: Characteristics of the used measurement devices

Measurement device	No. of units	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	Visualize the temperature distribution on the outer surface of bricks	
Compression machine	1	Compressive strength identification	

3.5 Evaluation of bricks' thermal performance

To evaluate the thermal performance of concrete bricks with air gaps, temperature measurements were taken from both the interior and exterior surfaces. From these measurements, key indicators were calculated to show how effectively the bricks reduce and delay heat transfer — an important factor in determining their suitability for energy-efficient buildings.

3.5.1 **Temperature Parameters**

Average interior surface temperature (Ti): The temperature measured on the inner surface of the brick, representing the heat transmitted into the building interior.

Average Exterior Surface Temperature (To): The mean temperature recorded on the exterior surface of the brick exposed to solar radiation.

3.5.2 **Maximum temperature reduction (MTR)**

Maximum Temperature Reduction (MTR) refers to the highest observed difference in temperature between the exterior and interior surfaces of a concrete block. It indicates the block's ability to reduce heat transfer, with higher MTR values reflecting better thermal insulation performance. It is calculated using the following equation:

$$MTR = T_{o,max} - T_{i,max}$$

3.5.3 **Decrement factor (DF)**

DF represents the reduction in the brick's peak temperature, based on the interior and exterior surface temperatures (Ti and To). It is calculated using the following Equation:

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

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.

3.5.4 **Temperature gradient**

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

$$TG = \frac{T_{i,max} - T_{i,min}}{L}$$

3.5.5 **Time delay (TD)**

Time delay is the delay between the highest temperature on the outside of a concrete block and when that peak reaches the inside. A longer time lag means better heat resistance and improved indoor comfort.

Chapter 4: Results and Discussion

This chapter presents the experimental results obtained during experimentations. The discussion of all results is also presented in light with the thermodynamic and heat transfer approaches.

4.1 Study location

The experiments were conducted under hot climate conditions in Al Amarah city (Latitude: 31.84° and Longitude: 47.14°), Iraq, for four consecutive days of May 2025. This location is characterized by hot summer with long sunshine hours. Figure () shows a thermal photo of the location during experimental days.

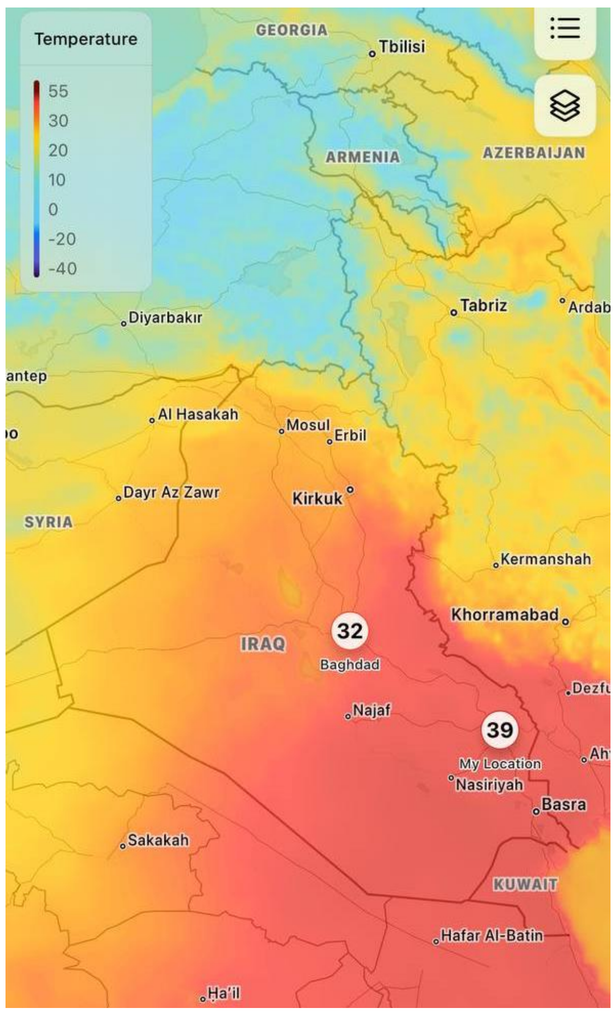

Figure 4.1: Thermal photo of the study location.

The solar radiation and wind speed variation are presented in Figures (4.2) and (4.3). As could be noticed, the solar radiation was highest for the west orientation surface, reaching 1045 W/m² in the afternoon. The south-facing surface reached its peak of 875 W/m² around midday, and the east-facing surface peaked at 669 W/m² in the late morning, at time around 10:30. Besides, the wind speed was varied between approximately 0 m/s and 2.7 m/s (east, south and west).

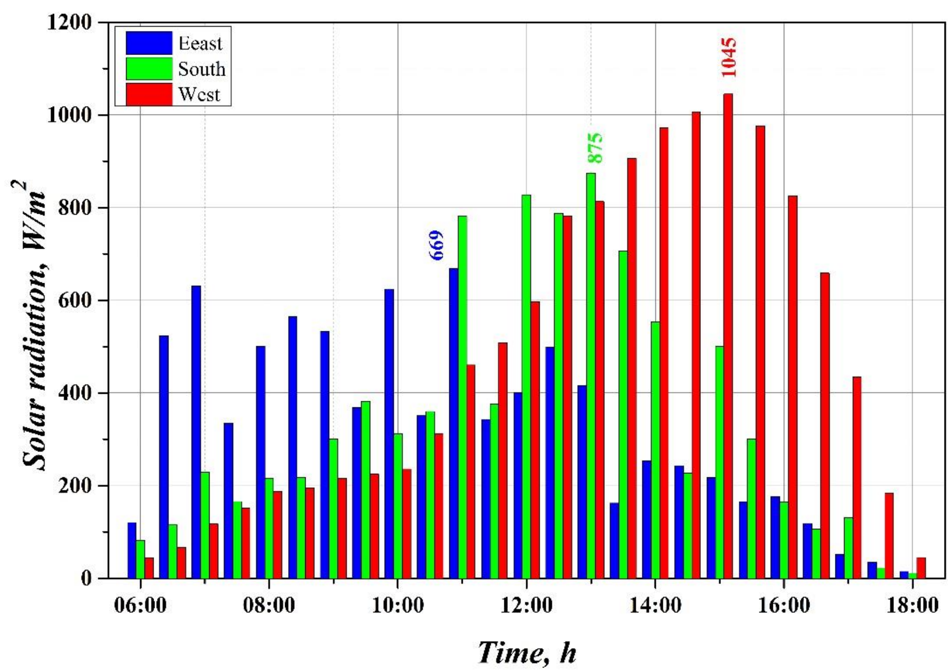

Figure 4.2: Solar radiation during experiments

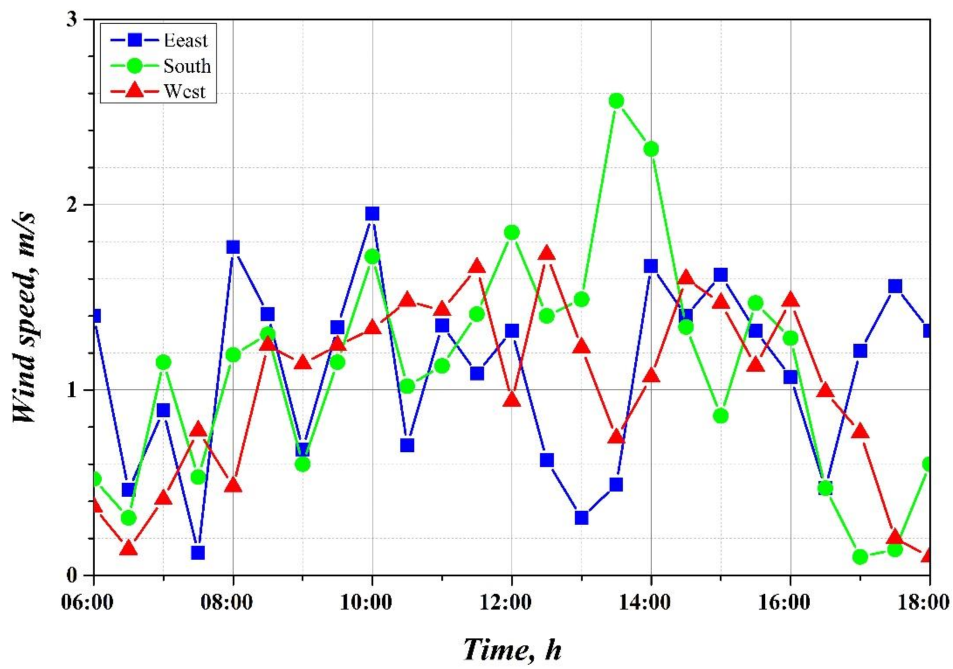

Figure 4.3: Wind speed variation during experiments

4.2 Surface temperature of bricks

Figures (4.4) to (4.10) show the surface temperature variation of tested bricks compared with the ambient temperature, in which Figures (4.4) to (4.6) present the outer surface temperatures, while Figures (4.7) to (4.9) are for the inner surface temperatures.

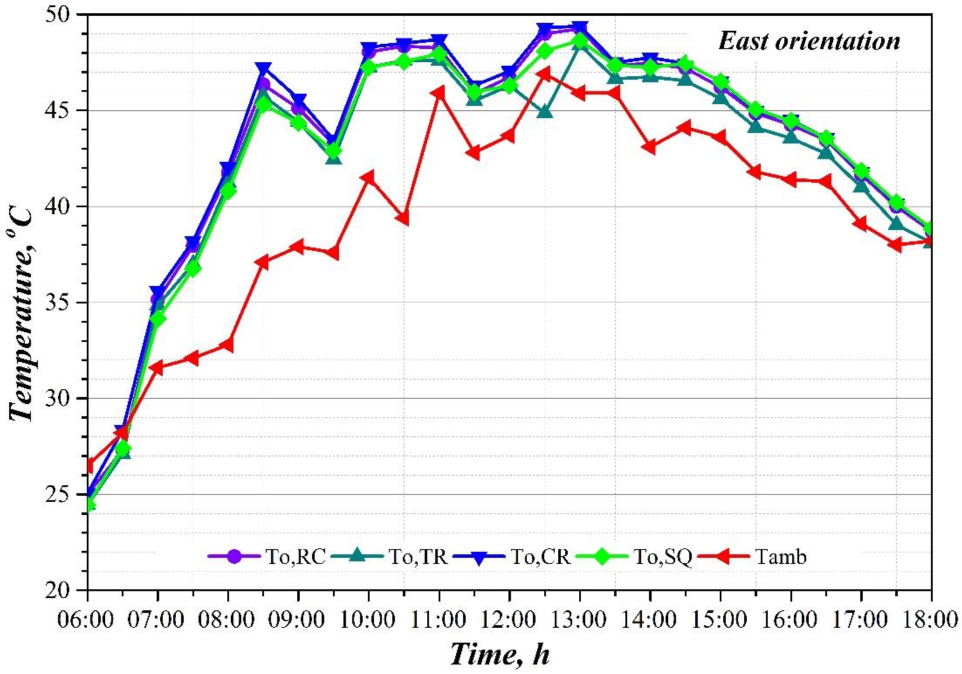

Figure 4.4: Outer surface temperature variation of bricks in the east orientation.

In this figure, the outer surface temperatures for the east orientation increases from approximately 25°C at 06:00 to a peak of around 49.5°C near 13:00, before gradually decreasing. The circular and rectangular cavity shapes generally exhibited marginally higher temperatures throughout the day, especially around the peak.

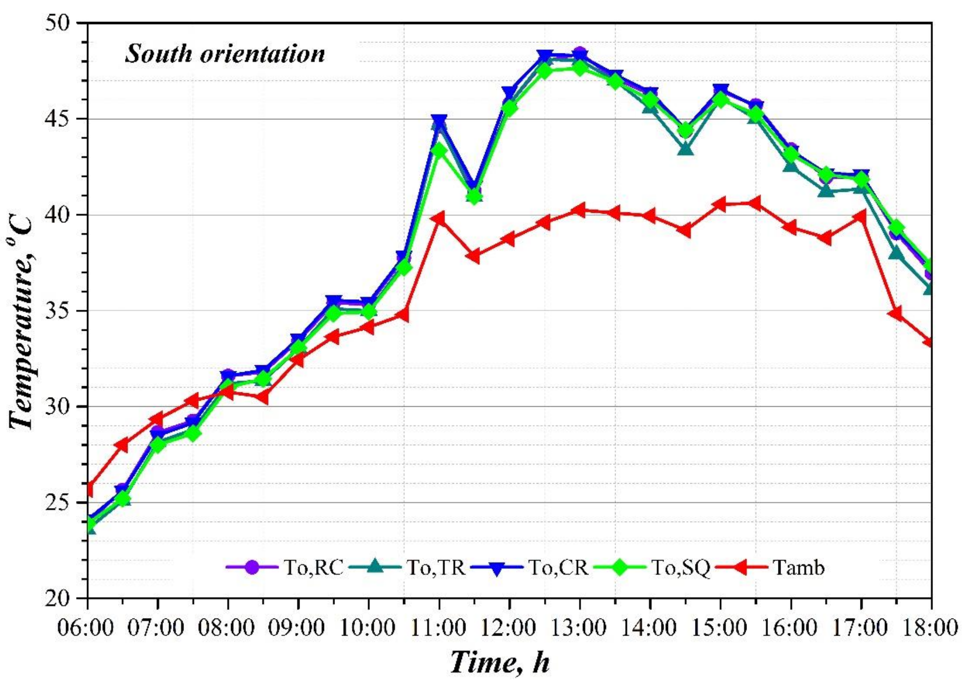

Figure 4.5: Outer surface temperature variation of bricks in the south orientation.

This figure shows the outer surface temperatures for the south orientation, which show similar pattern to the east orientation; increasing from approximately 24°C at 06:00 to a peak of around 49°C near 13:00, before gradually decreasing. The circular and rectangular cavity shapes generally exhibited marginally higher temperatures, particularly around the peak period.

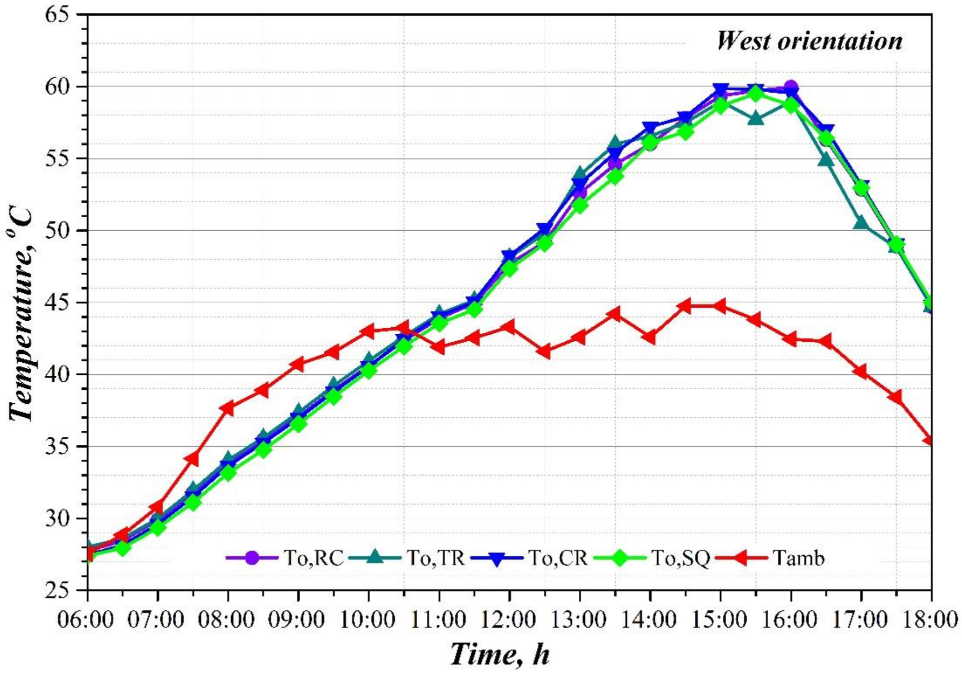

Figure 4.6: Outer surface temperature variation of bricks in the west orientation.

In this figure, the outer surface temperatures for the west orientation increase from approximately 27.5°C at 06:00 to a peak of around 60°C near 16:00. The circular, rectangular, and square cavity shapes generally reached the highest temperatures around the peak, with the triangular shape being very slightly lower during this peak period.

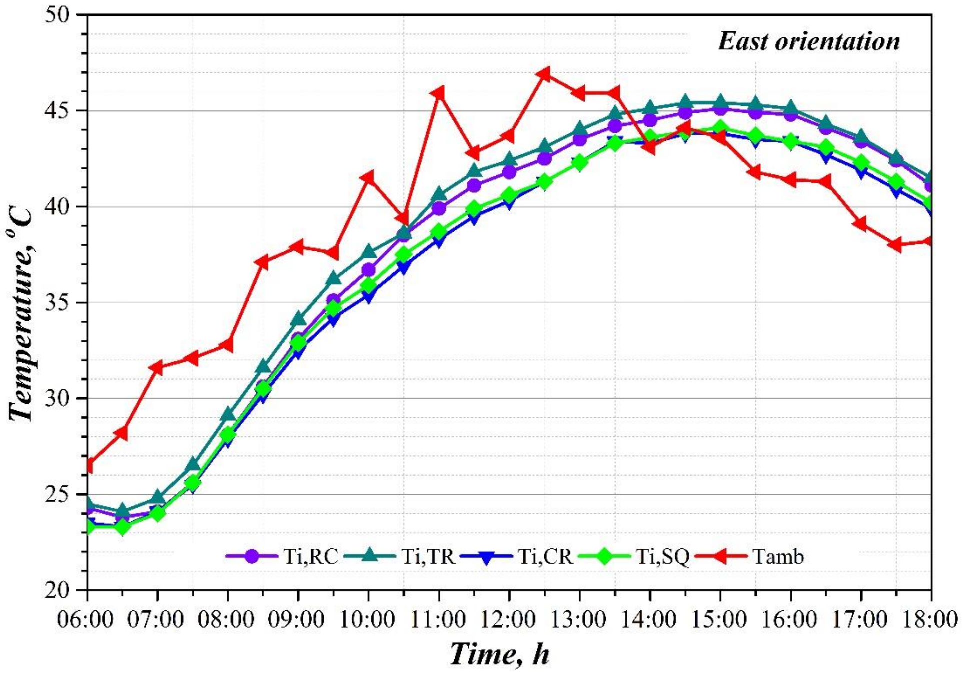

Figure 4.7: Inner surface temperature variation of bricks in the east orientation.

For the east orientation, the inner surface temperatures rose from approximately 23-24°C at 06:00 to a maximum of around 45-46°C between 15:00 and 16:00. The circular cavity shape consistently maintained a cooler inner surface alongside the square cavity shape compared to the rectangular and triangular cavities, particularly during the hours of peak temperature.

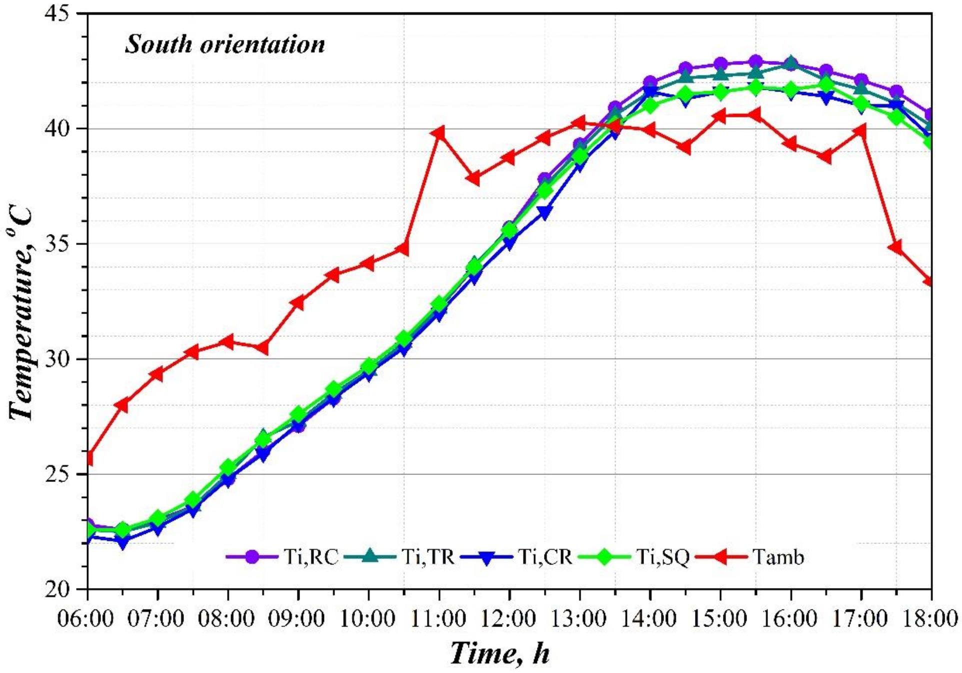

Figure 4.8: Inner surface temperature variation of bricks in the south orientation.

The inner surface temperatures for the south-facing bricks show an increase from around 22-23°C in the early morning (06:00) to a peak of approximately 42-43°C in the late afternoon (around 15:00-16:00). During the period of highest temperatures, the bricks with circular and square cavities demonstrated better thermal performance by maintaining slightly lower inner surface.

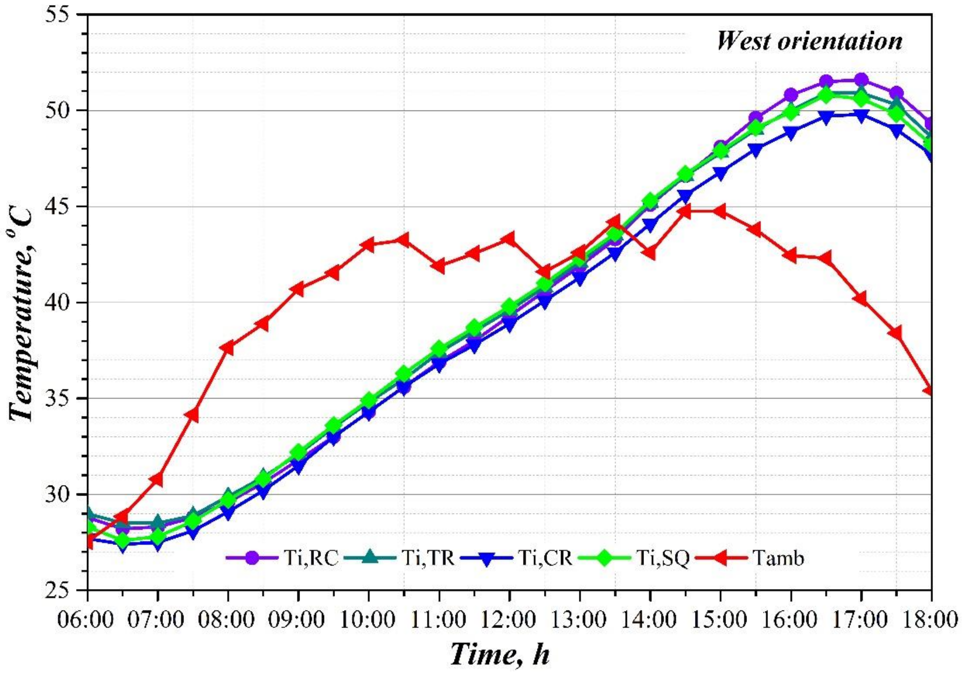

Figure 4.9: Inner surface temperature variation of bricks in the west orientation.

The inner surface temperatures (Ti) for the west-oriented bricks in figure (4.9) started at approximately 27-28°C at 06:00 and climbed to a maximum between 16:00 and 17:00. During this peak period, the circular cavity design clearly demonstrated superior thermal insulation, maintaining an inner surface temperature around 49.5-50°C. In contrast, the rectangular, triangular, and square cavities resulted in higher inner surface temperatures, reaching approximately 51-52°C, indicating that the circular cavity was more effective at mitigating heat gain on the inner surface for this orientation.

Thermal images of outer surface temperature are shown in Figure (4.10).

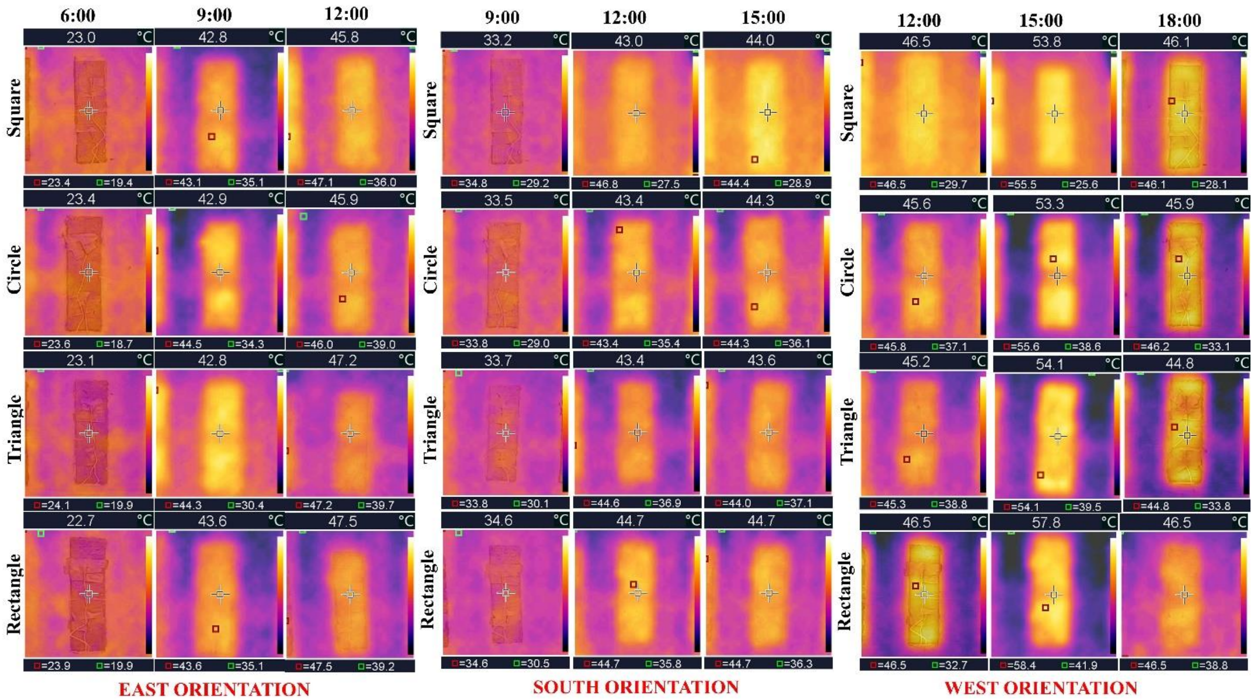

Figure 4.10: Thermal photos of outer surface temperatures.

4.3 Analysis of thermal effectiveness of bricks' cavities

The thermal behavior of bricks with different air gaps was evaluated in terms of the MTR, DF and TG. Figure (4.11) displays the MTR of bricks, across all three orientations, the circular cavity design consistently provided the highest MTR, achieving 5.1°C for East, 6.3°C for South, and a notable 10.1°C for the West orientation. This suggests the circular cavity is most effective at reducing the peak temperature transfer from the outer to the inner surface.

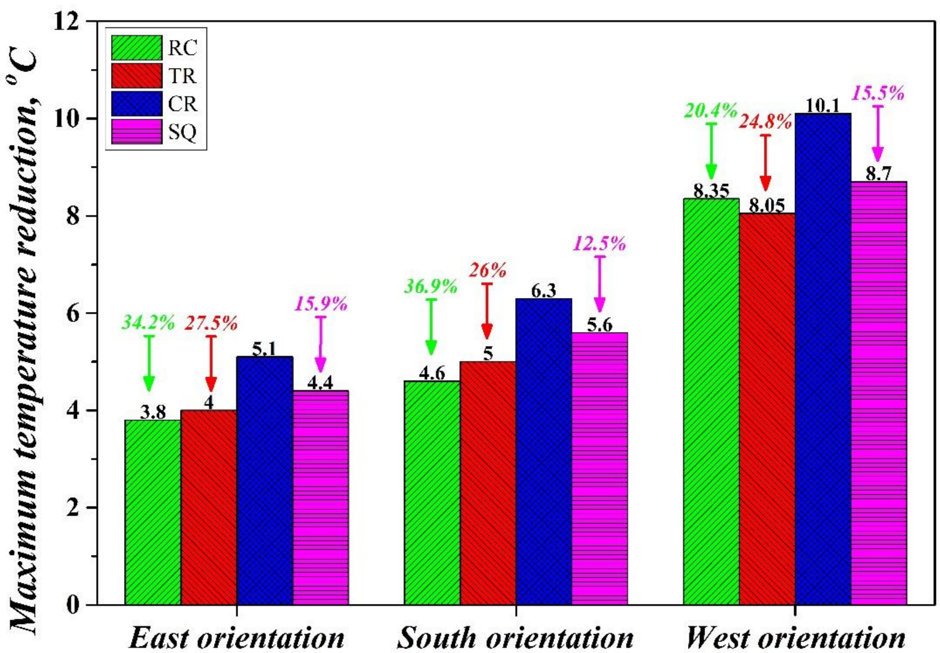

Figure 4.11: Maximum temperature reduction of tested bricks.

The DF, as previously stated, indicates the effectiveness of tested bricks to minimize the temperature fluctuations. Figure (4.12) indicates the DF of bricks. For all orientations, the circular cavity design consistently exhibited the lowest Decrement Factor. For the East orientation, circular had a DF of approximately 0.37, for South around 0.21, and for West about 0.14. This demonstrates that the circular cavity is superior in reducing the amplitude of temperature swings from the outside to the inside.

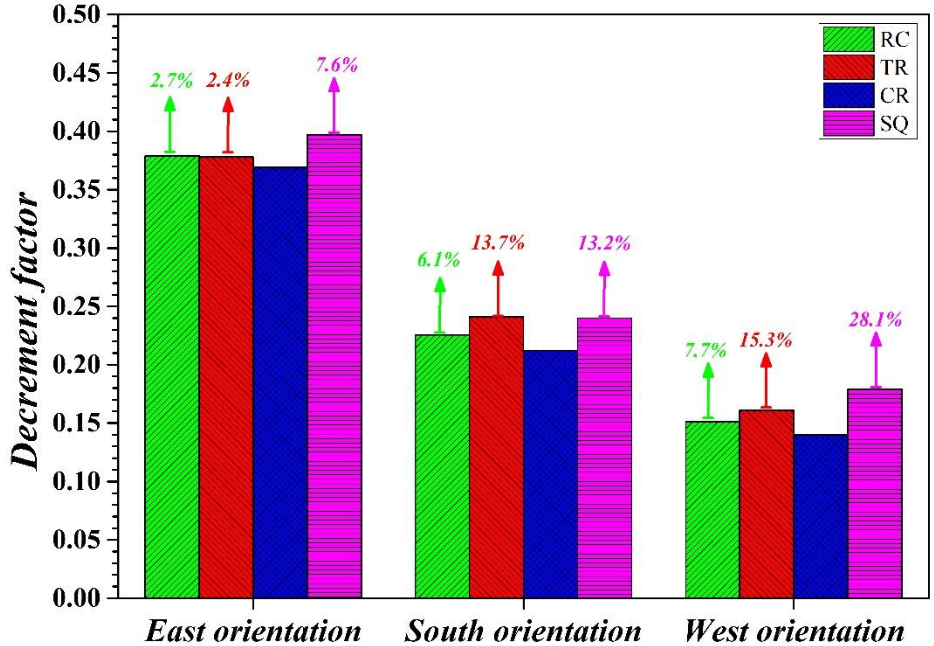

Figure 4.12: Decrement factor of bricks.

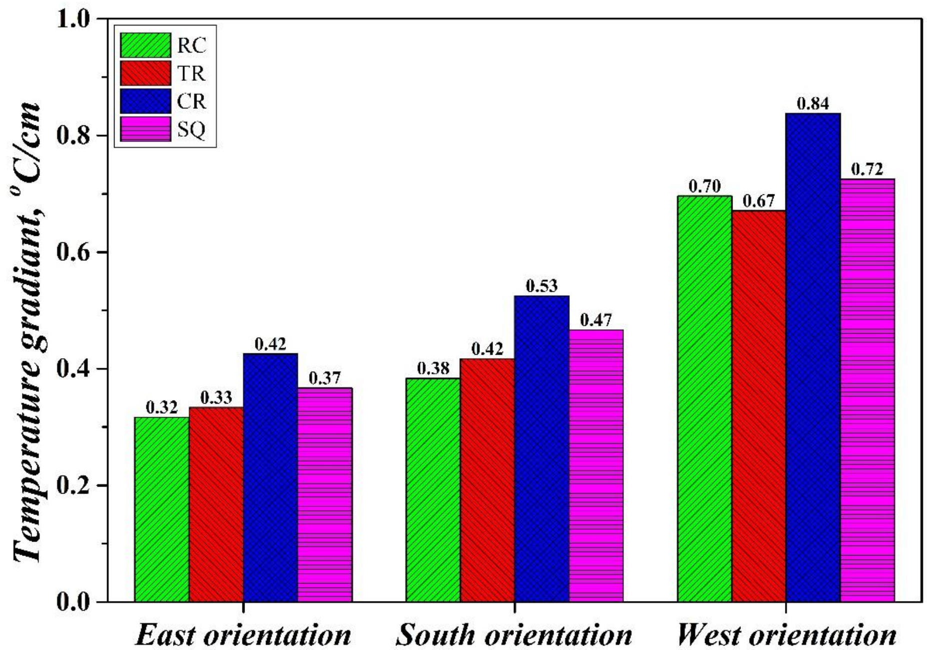

Figure 4.13: Temperature gradient of bricks.

Consistently across all three orientations, the circular (CR) cavity design achieved the highest Temperature Gradient. For the East orientation, CR showed a TG of 0.42 °C/cm; for the South, it was 0.53 °C/cm; and for the West orientation, it reached 0.84 °C/cm. This indicates that the circular cavity configuration provides the most effective thermal barrier, leading to a steeper temperature drop across the brick's thickness.

4.4 Mechanical test

The mechanical test of 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. Figure (4.19) shows the maximum load of samples.

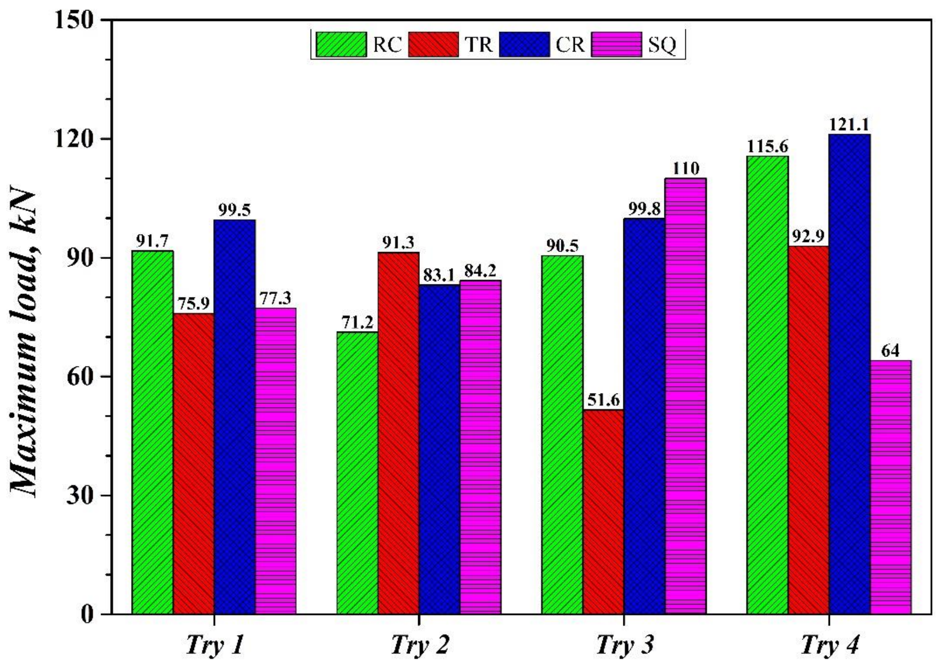

Figure 4.14: Maximum load of tested bricks.

The mechanical test data indicates that the circular air-gap brick exhibited the highest average compressive strength, achieving approximately 3.65 MPa. This performance was notably better than the other designs, as the circular cavity brick was stronger than the rectangular, triangular, and square shapes by approximately 9.28%, 29.43%, and 20.07%, respectively, according to the average compressive strengths and declination percentages presented in Table 4.1. The bar chart showing maximum load further supports that the circular design generally withstood higher loads across multiple test samples.

Table 4.1: Maximum compressive strength of test brick (in MPa).

Sample No.	RC	TR	CR	SQ
1	3.322464	2.75	3.605072	2.800725
2	2.57971	3.307971	3.01087	3.050725
3	3.278986	1.869565	3.615942	3.985507
4	4.188406	3.365942	4.387681	2.318841
Avg	3.342391	2.82337	3.654891	3.038949
Avg	3.34	2.82	3.65	3.04
Declination %	9.281437	29.43262		20.06579

Figure 4.15: The before and after results of the compressive strength test on bricks

Chapter 5: Recommendations for future research

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

1. Different concrete mixing ratios could be experimented to improve the mechanical strength of modified bricks. This could cope the decline mechanical properties of developed bricks due to high volume air-gaps.
2. Same air gaps with smaller volume could be tested in comparison with the big ones studied in this project. The thermal and mechanical tested should be considered in this regard.
3. Studying the economic and environmental benefits of utilizing waste materials are recommended for future studies. This could shed light on the sustainability gain of this inviro-economic application.
4. Plastic waste could be incorporated with the concrete bricks during molding phase to produced innovative bricks after a careful procedure including heating process. This technique could result in a lighter weight with interior air gaps to improve the thermal insulation. However, the mechanical strength of bricks could be influenced in the process.

Chapter 6: Conclusions

The main conclusions that could be derived from the current project are summarized as follows:

1. The circular air-gap shape has the best thermal performance compared with the rectangular, triangle and square shapes in all orientations.
2. The maximum temperature reduction for the circle air-shape reached a mark of 10.1 °C in the West orientation. Correspondingly, the temperature gradient for this air-gap also showed a maximum value of 0.84 °C/cm at the West orientation.
3. The circle air-gap brick also showed the best decrement factor, showing an advancement of 7.7%, 15.3%, and 28.1% over the rectangle, triangle and square shapes, respectively (values from West orientation).
4. Waste materials indicated superior thermal enhancement for the circle air-gap bricks over the air-gaped one
5. For the mechanical test, the circle air-shaped brick showed high compressive strength values for the 4-sample tests. On average, the compressive strength of the circle-gap brick was better than the rectangle, triangle and square shapes by 9.28%, 29.43% and 20.07%, respectively.

Publications:

The results of this work has been published at the Results in Engineering Journal, and can be accessed and downloaded freely from the link below:

https://www.sciencedirect.com/science/article/pii/S2590123025042586

References

[1] IEA (2023), Tracking Clean Energy Progress 2023, IEA, Paris https://www.iea.org/reports/tracking-clean-energy-progress-2023, License: CC BY 4.0

[2] Abbood, A. W., Al-Obaidi, K. M., Awang, H., & Rahman, A. M. A. (2015). Achieving energy efficiency through industrialized building system for residential buildings in Iraq. International Journal of Sustainable Built Environment, 4(1), 78-90.

[3] Homod, R. Z. (2014). Assessment regarding energy saving and decoupling for different AHU (air handling unit) and control strategies in the hot-humid climatic region of Iraq. Energy, 74, 762-774.

[4] Ibrahim, A. K., Dhahir, H. Y., Mohammed, A. S., Omar, H. A., & Sedo, A. H. (2023). The effectiveness of surrogate models in predicting the long-term behavior of varying compressive strength ranges of recycled concrete aggregate for a variety of shapes and sizes of specimens. Archives of Civil and Mechanical Engineering, 23(1), 61.

[5] Prusty, J. K., & Pradhan, B. (2020). Multi-response optimization using Taguchi-Grey relational analysis for composition of fly ash-ground granulated blast furnace slag based geopolymer concrete. Construction and building materials, 241, 118049.

[6] Piro, N. S., Mohammed, A., Hamad, S. M., & Kurda, R. (2022). Electrical resistivity-Compressive strength predictions for normal strength concrete with waste steel slag as a coarse aggregate replacement using various analytical models. Construction and Building Materials, 327, 127008.

[7] Pavlík, Z., Jerman, M., Fořt, J. et al. Monitoring Thermal Performance of Hollow Bricks with Different Cavity Fillers in Difference Climate Conditions. Int J Thermophys 36, 557–568.

[8] Marwan, M. (2020). The effect of wall material on energy cost reduction in building. Case Studies in Thermal Engineering, 17, 100573.

[9] Savchenko, O. (2021). A review of energy saving and energy effective roofings. Zeszyty Naukowe Politechniki Częstochowskiej. Budownictwo, 219-224.

[10] Ying, X., & Li, W. (2020). Effect of floor shape optimization on energy consumption for u-shaped office buildings in the hot-summer and cold-winter area of China. Sustainability, 12(5), 2079.

[11] Ghamari, M., & Sundaram, S. (2024). Solar Window Innovations: Enhancing Building Performance through Advanced Technologies.

[12] Bagheri, S., Moradinasab, H., & Yeganeh, M. (2024). The effect of window proportions in low-rise residential buildings on annual energy consumption in humid temperate climate (case study: Rasht city in Iran). Frontiers in Energy Research, 12, 1463678.

[13] Ghisi, E., & Tinker, J. A. (2004, May). Window sizes required for the energy efficiency of a building against window sizes required for view. In Proceedings of the CIB World Building Congress, Toronto, Canada.

[14] Designing Buildings Wiki. (n.d.). Thermal conductivity. Designing Buildings. https://www.designingbuildings.co.uk/wiki/Thermal_conductivity

[15] Makrygiannis, I., & Karalis, K. (2023). Optimizing building thermal insulation: the impact of brick Geometry and thermal coefficient on energy efficiency and comfort. Ceramics, 6(3), 1449-1466.
[16] Ismaiel, M., Chen, Y., Cruz-Noguez, C., & Hagel, M. (2022). Thermal resistance of masonry walls: a literature review on influence factors, evaluation, and improvement. Journal of Building Physics, 45(4), 528-567.
[17] Radovanović, Ž., Grebović, R. S., Dimovska, S., Serdar, N., Vatin, N., & Murgul, V. (2015). The mechanical properties of masonry walls-Analysis of the test results. Procedia engineering, 117, 865-873.
[18] Mosalam, K., Glascoe, L., & Bernier, J. (2009). Mechanical properties of unreinforced brick masonry, section1 (No. LLNL-TR-417646). Lawrence Livermore National Lab.(LLNL), Livermore, CA (United States).
[19] Bustamante, W., Bobadilla, A., Navarrete, B., Vidal, S., & Saelzer, G. (2009). Thermal improvement of perforated ceramic bricks. Revista de la Construcción, 8(1), 24-35.
[20] Shibib, K. S., Qatta, H. I., & Hamza, M. S. (2013). Enhancement in thermal and mechanical properties of bricks. Thermal Science, 17(4), 1119-1123.
[21] Mahapatra, D., Madav, V., & Setty, A. B. T. P. (2024). Mechanical and dynamic thermal performance evaluation of rice husk blended cement plaster when used with different bricks. Journal of Building Engineering, 82, 108120.
[22] Kantasiri, T., Kasemsiri, P., Pongsa, U., Posi, P., & Chindaprasirt, P. (2024). Optimization of concrete containing waste crumb rubber mix design for thermal insulating applications using Taguchi method. Construction and Building Materials, 434, 136636.
[23] Abdellatief, M., Ahmed, Y. M., Taman, M., Elfadaly, E., Tang, Y., & Abadel, A. A. (2024). Physico-mechanical, thermal insulation properties, and microstructure of geopolymer foam concrete containing sawdust ash and egg shell. Journal of Building Engineering, 90, 109374.
[24] Ahmed, S., El Attar, M. E., Zouli, N., Abutaleb, A., Maafa, I. M., Ahmed, M. M., ... & Ragab, A. (2023). Improving the thermal performance and energy efficiency of buildings by incorporating biomass waste into clay bricks. Materials, 16(7), 2893.
[25] Canım, D. S., & Kalfa, S. M. (2023). Development of a new pumice block with phase change material as a building envelope component. Journal of Energy Storage, 61, 106706.
[26] Mukram, T. A., & Daniel, J. (2024). Performance evaluation of a novel cement brick filled with micro-PCM used as a thermal energy storage system in building walls. Journal of Energy Storage, 77, 109910.
[27] Zhang, Y., Sun, X., & Medina, M. A. (2024). Experimental assessment of concrete masonry units integrated with insulation and phase change material: A wall-pattern study. Energy, 289, 130038.
[28] Taj, S. A., Khalid, W., Nazir, H., Khan, A., Sajid, M., Waqas, A., ... & Zaki, S. A. (2024). Experimental investigation of eutectic PCM incorporated clay brick for thermal management of building envelope. Journal of Energy Storage, 84, 110838.

[29] Al-Tamimi, A. S., Al-Amoudi, O. S. B., Al-Osta, M. A., Ali, M. R., & Ahmad, A. (2020). Effect of insulation materials and cavity layout on heat transfer of concrete masonry hollow blocks. Construction and Building Materials, 254, 119300.
[30] Shah, S. N. R., & Khan, R. (2024). Optimising thermal conductivity of insulated concrete hollow blocks in hot climates: Experimental–numerical investigation. Asian Journal of Civil Engineering, 25(8), 5955-5973.
[31] Makrygiannis, I., & Karalis, K. (2023). Optimizing building thermal insulation: the impact of brick Geometry and thermal coefficient on energy efficiency and comfort. Ceramics, 6(3), 1449-1466.