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Using Clay-Straw-Cement Bricks to Improve Indoor Thermal Comfort and Energy Efficiency for Cooling in Dry, Hot Climates

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Abstract

This study investigates the potential of eco-friendly bricks to enhance thermal comfort and reduce cooling energy consumption in residential buildings located in hot and dry climates. These bricks are produced by compressing a mixture of clay, straw, and 6% Portland cement by volume, offering a sustainable alternative to traditional construction materials. The research is conducted in two phases. The first phase includes experimental testing, which involves manufacturing the bricks, evaluating their thermal properties, and conducting field measurements using a 1 m × 1 m test room model constructed in Qurna City, Egypt. The second phase employs Design Builder simulation software to assess the performance of various wall cross-section configurations in residential buildings. The findings reveal that eco-friendly bricks significantly reduce cooling energy demand by 34% compared to traditional bricks and 35% compared to cement bricks. These results highlight their effectiveness in improving energy efficiency while promoting sustainable building practices. Adopting eco-friendly bricks can contribute to energy conservation, cost reduction, and environmental sustainability in hot arid regions.

Keywords: Eco-friendly brick; Thermal comfort; Energy efficiency; Hot and dry climates.

Introduction

Since 2012, Egypt has experienced a significant increase in power outages, which has posed challenges to energy reliability. During the 2012-2013 period, the gap between power generation and demand reached 8.6% [1]. In the summer of 2013, power outages averaged 1-2 hours daily. By the summer of 2014, this had escalated to 4-6 hours per day, with up to six outages lasting around 2 hours each [1, 2]. Recent years have seen continued energy shortfalls, with frequent outages reported in 2023 and 2024. In some regions, power outages now occur daily, lasting between 2 and 4 hours per incident. To manage this, the government has implemented scheduled power outage plans during peak periods. The ongoing high annual growth rate in energy demand, combined with rising per capita energy consumption, suggests that energy production capacity will need to expand rapidly to meet future needs. Studies predict a power supply shortfall of 30 to 50 million tons per year between 2020 and 2050, representing 24-35% of demand [3, 4]. This underscores the critical need for reducing electricity consumption, particularly by minimizing reliance on mechanical cooling methods that are heavily dependent on fossil fuels. Reducing energy consumption can be achieved by significantly lowering the demand for air conditioning and achieving thermal comfort through passive strategies [5-8].

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The increasing population, rapid urbanization, and growing per capita electricity consumption in Egypt are exacerbating the energy crisis [9]. Architects and building designers must prioritize passive design strategies to minimize electrical energy use, ensure thermal comfort, and promote natural climate control within buildings [10].

Various methods can be used for buildings to reduce heat gain and increase heat loss to achieve thermal comfort within spaces (e.g., by installing insulation, shading windows, walls, and ceilings, using shading, natural ventilation, and insulation) [9, 11-18]. Summer thermal comfort is always a major concern in regions with hot and dry climates, such as Egypt [19]. It was calculated that in hot climatic zones, 70% to 80% of the total energy consumption is used to operate mechanical cooling systems (air conditioning) [20, 21]. In dry, hot areas, one of the most important inexpensive passive solutions for processing, reducing heat gain, and improving thermal comfort in indoor spaces is the material used to construct walls [22-24]. It is usually more cost-effective on both the building and urban level to use materials with good thermal properties for the wall during the initial design and construction process of the building, and this can save a significant amount of energy consumed in cooling [25, 26]. Although the potential benefits of walls on their energy-saving effect on interior spaces in hot and dry climates have received considerable attention in the hot and dry region, lots of research has been done on the subject, especially in the region of Upper Egypt, where the weather is dry and hot [27-30]. The primary goal is to enhance the materials used to build the wall by investigating several options and possibilities. On the other hand, this research studies a variety of wall layout options as ways to reduce heat gain.

To effectively address the challenges of heat gain in hot and dry climates, it is essential to explore the materials used for wall construction and innovative design strategies. Various studies have highlighted the significant impact that wall configurations can have on indoor thermal comfort and energy efficiency [31]. By examining a range of wall layouts and their thermal performance, we can identify optimal solutions that complement the benefits of specific building materials. This comprehensive approach enables us to better understand how different combinations of materials and designs contribute to reducing energy consumption and enhancing comfort in residential spaces. Sghiouri et al. [25] evaluated the impact of straw-clay building materials on energy demand and thermal comfort, finding that, during the hottest summer days, these structures lowered indoor temperatures by 5°C compared to conventional concrete buildings in Morocco. Additionally, these materials reduced total energy consumption by 65% and decreased hours of thermal discomfort by 25% when compared to concrete block buildings [32].

Al-Yasiri et al. [33] focused on the building envelope’s role in energy consumption and thermal comfort, with particular attention to the impact of the phase change materials system. They save a significant amount of energy needed for cooling compared with traditional building materials. Ashish et al. [34] discussed the global energy consumption for heating and cooling, which represents about half of total energy use, to maintain indoor thermal comfort. The study stressed the importance of construction materials in delaying heat transfer, utilizing reflective surfaces, and insulating building apertures to reduce thermal loads. Another study explores the effect of incorporating roofing materials with insulating substances and clay-straw mixtures. They observed an 8% reduction in cooling load in buildings with clay walls [23]. The literature reviewed underscores the critical role of both construction materials and innovative wall designs in enhancing thermal comfort and energy efficiency in hot and dry climates. It is evident that traditional materials like clay, along with modern alternatives such as geopolymer bricks, offer substantial benefits in reducing indoor temperatures and energy consumption. The consistent findings across various studies highlight the potential for significant energy savings and improved living conditions through thoughtful material selection and design strategies. This collective evidence suggests a promising avenue for future research and application, advocating for a shift towards more sustainable building practices that prioritize thermal performance and environmental impact.

One of the previous studies investigated using cement to improve low-plasticity clay soil by treating samples with 2%, 4%, and 6% cement and curing them for up to 90 days. Laboratory tests were performed, including unconfined compression, indirect tensile, gas permeability, and microstructural analysis. The results showed that cement addition improved the compressive and tensile strength of the soil, with further improvements over time. pH and electrical conductivity were key indicators of strength enhancement. Microstructural tests revealed that cement filled voids between soil grains, enhancing soil structure. Additionally, changes in the soil structure influenced gas permeability and soil-water retention, with pore size distribution and permeability being more sensitive to curing times at lower cement contents [35].This essay discusses unfired clay bricks for sustainable and ecological applications. Lower Oxford Clay was stabilized for the construction of unfired clay bricks using ground granulated blast furnace slag, an industrial by-product activated by lime or Portland cement. Energy efficiency has been demonstrated by the unfired clay material, which offers a strong and cost-effective substitute for firing clay building components. In addition to comparing burnt and unfired clay methods, this study is among the first to evaluate unfired clay bricks in comparison to bricks used in conventional buildings by combining energy consumption and CO_2 emissions [36]. Clay soil can be made more effective by adding 8% of its weight to cement to stabilize the mixture. To meet the requirements of the Egyptian Code for constructing stabilized blocks. Experimental results indicate that using building blocks constructed from stabilized soil with 8% cement helps to obtain thermal comfort ranging from 5% to 25% while using less energy [37].

The primary objective of this study is to explore the potential for energy savings in buildings and assess the economic feasibility of using EFB made from clay containing 6% straw and cement. This approach aims to minimize the energy demand for cooling in residential buildings in Luxor, Egypt. To achieve thermal comfort within these spaces, the study evaluates various wall options regarding materials and thickness. Initially, a comprehensive literature review was conducted to provide a basis for comparison and evaluation. The selected wall options were then applied to typical residential buildings in Luxor. Although the Egyptian energy code highlights the use of environmentally friendly materials as an effective way to reduce costs and achieve desired energy performance, Egyptian architectural regulations do not mandate their use. This study is motivated by the need to explore wall materials that can reduce the energy required for cooling, particularly during the summer, and thereby lower overall energy consumption. The research will calculate the initial costs of various cross-sections for EFB (EFB), traditional bricks (TB), and cement bricks (CB), as well as the energy savings for each type. This analysis will help determine the time required to recoup the initial investment, thereby providing a comprehensive evaluation of both energy and economic benefits.

Study area

This study focuses on regions with hot and arid climates, such as Egypt, where energy use has increased by 6-7% [34]. The research site is located in the Luxor governorate, specifically in the city of Qurna. Qurna is situated in the South Upper Egypt region, approximately 670 km south of Cairo, 220 km north of Aswan, and 280 km southwest of Hurghada. The coordinates for Luxor are approximately 25.7°N latitude and 32.6°E longitude. In Luxor, the annual average high temperature during the summer ranges from 25°C to 40°C, while the annual average low temperature varies from 15°C to 25°C. Summer temperatures can reach as high as 47°C [20]. The highest average relative humidity occurs in January at 55%, while May has the lowest average relative humidity at 29%. Wind speeds in Luxor average 8 m/s. Annually, the average daily solar radiation peaks in August and is at its lowest in January. The location of the study area is depicted in Figure 1. While Figure 2 displays the summer and winter temperatures of the Luxor governorate, with highs of 42 °C. and lows of 8.5 °C throughout the summer and winter, respectively.

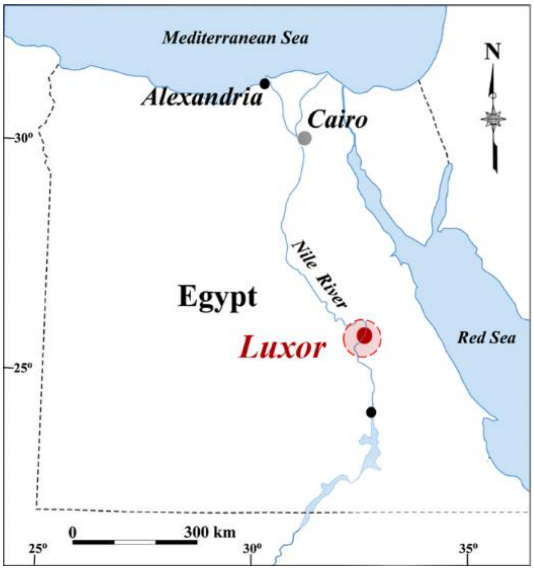


Figure 1. Location of study area; the red circle presents the location of Luxor governorate in Egypt [13]

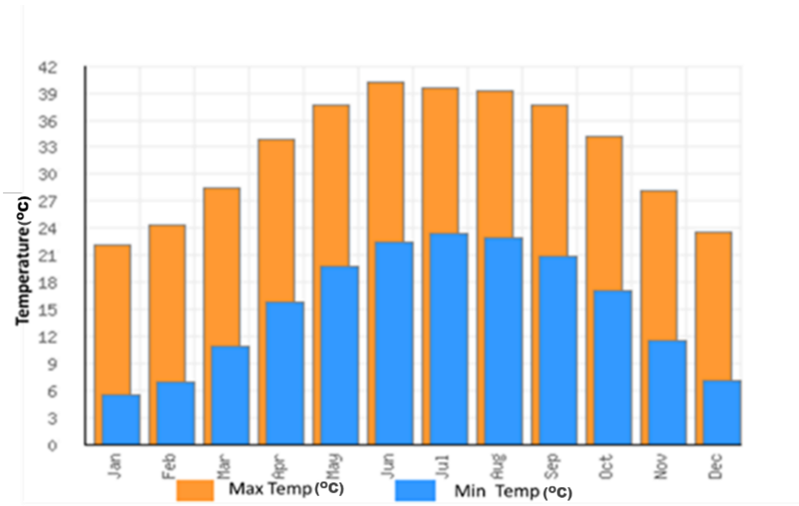


Figure 2. The maximum and minimum monthly air temperatures of Luxor [38].

Materials and Methods

This study examines the impact of using a proposed eco-friendly brick (EFB) in external walls on the energy demand for cooling in hot arid regions. It relies on existing literature to explore the relationship between building materials, environmental impact, and energy consumption. The aim is to demonstrate how eco-friendly building materials can mitigate negative thermal effects, protect the environment, and reduce energy consumption. The research highlights the significance of selecting appropriate building materials for external walls to optimize energy efficiency.

The analysis was conducted in two primary stages. The first stage involved producing brick samples, determining their physical characteristics, measuring their thermal properties, and validating the results. The second stage assessed the effect of these EFB when used in various proposed alternatives for exterior walls, focusing on their influence on the energy consumption of the proposed structure. Additionally, the study evaluated the feasibility of using the proposed EFB in Egypt. Figure 3 illustrates the methods employed in the study, which resulted in six alternatives for exterior walls using EFB and measured their impact on energy consumption.

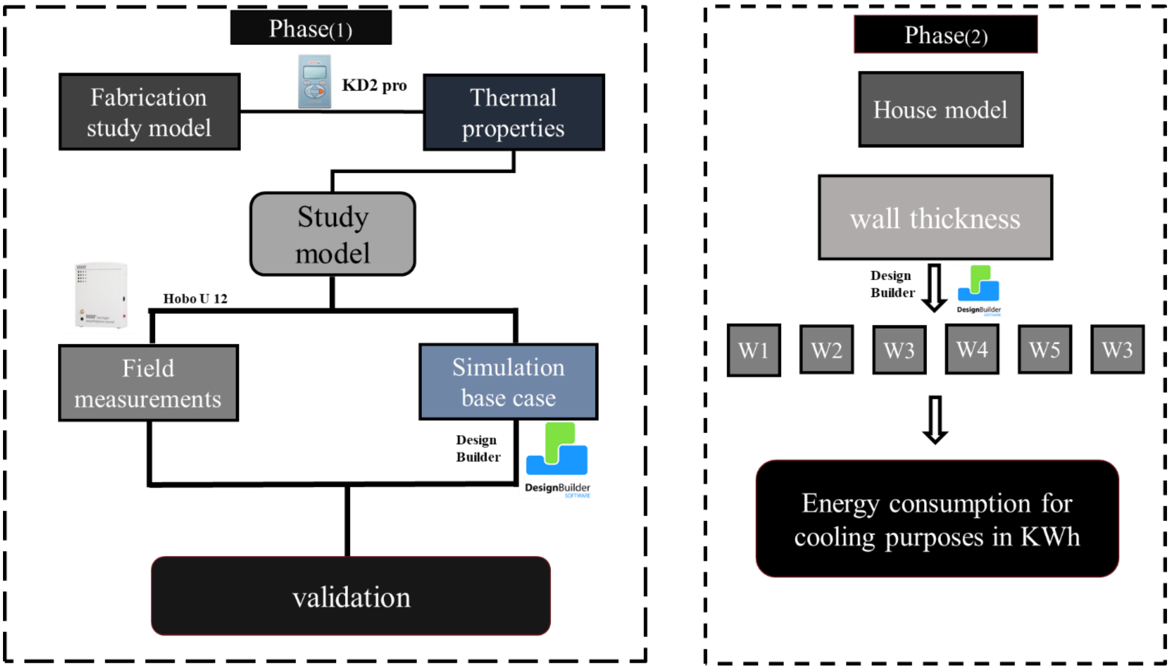


Figure 3. The study framework.

Characteristics of EFB

This research aims to make EFB by incorporating a controlled amount of cement into the soil, with the premise that this addition will not significantly impact the brick's thermal properties while preserving its essential physical characteristics. The primary objective is to enhance the physical properties without increasing thermal conductivity, thus ensuring the bricks contribute to energy efficiency in buildings. Clay served as the primary component in the brick formulation utilized in this study. The mineralogical composition of the clay was analyzed using X-ray diffraction (XRD), which identified kaolinite as the dominant mineral phase. Additionally, X-ray fluorescence (XRF) analysis was conducted to determine the clay's chemical composition. The analysis revealed that the clay primarily consists of 48.93 wt.% SiO_2, 32.90 wt.% Al_2O_3, and 1.19 wt.% Fe_2O_3, along with trace amounts of CaO (0.50 wt.%), TiO_2 (5.92 wt.%), and other oxides. The loss on ignition (LOI) was measured at 9.2 wt.%, reflecting the volatile components present in the clay. The average particle size of the clay was determined to be 0.27 mm, highlighting its fine-grained nature and suitability for the intended application. These results confirm the clay's composition is ideal for producing eco-friendly bricks with improved thermal and structural performance [29]. Laboratory tests will assess the thermal and physical properties of the cement-stabilized bricks to confirm their alignment with EFB and energy efficiency standards in construction. EFBs, made from locally sourced materials, reduce environmental impact and natural resource reliance. Their low thermal conductivity (0.3-0.7 W/m·K) [39] enhances energy efficiency, lowering utility costs. These bricks can be repurposed or recycled at the end of their life cycle, promoting sustainability and reducing landfill waste. When a brick has these features, it is considered eco-friendly and makes a feasible alternative to traditional building materials in construction [40] [41].In this study, the objective is to produce a brick that aligns with the industry's push towards energy-efficient and sustainable building materials, bridging the gap between conventional materials and environmentally responsible alternatives. To strengthen the eco-friendly claims of the proposed brick, future work should incorporate a detailed Life Cycle Assessment (LCA). This evaluation should encompass the environmental impacts associated with raw material extraction, transportation, manufacturing, and end-of-life disposal. While this study focuses primarily on thermal and energy performance, conducting an LCA would provide a more comprehensive understanding of the environmental benefits and trade-offs of the proposed bricks.

Fabrication process for the proposed EFB

The use of compressed clay brick pistons has significantly revolutionized the building process. Introducing innovative technologies in clay brick fabrication can enhance their physical and mechanical properties. In this study, bricks were produced using a mixture of clay, straw, and 6% cement by volume of the clay mixture (Figure 4). The raw materials clay, straw, and cement were thoroughly combined with water to form a homogenous mixture. This mixture was then poured into molds measuring 250 mm by 120 mm by 60 mm and mechanically pressed using a mechanical press to ensure proper compaction and shape. Finally, the pressed bricks were left to cure naturally in sunlight, as depicted in Figure 5. This process aims to improve the bricks' durability and thermal performance, making them suitable for sustainable building practices.

(a) (b) (c)

Figure 4. The raw materials that used in the fabrication of the EFB; (a) Clay, (b) Portland cement, and (c) straw

(a) (b) (c)

Figure 5. The steps of the fabrication process; (a) mixing, (b) forming and drying, (c) final product.

Proposed study variables

Two models were modeled and simulated. The first model is a small test room with dimensions of 1x1x1. It has been built using the fabricated EFB. The exterior walls were built with a brick thickness of 12 cm. For the roof, wooden beams were utilized, and the same EFB material was used to cover them. To facilitate air circulation and prevent heat buildup inside the model, two ventilation holes with a diameter of 10 cm each were created. These holes allowed air to enter and exit the investigated room model. To assess the impact of these exterior walls on the interior thermal conditions, the test room was positioned such that all its faces were exposed to direct sunlight, with none in the shade. The form of the constructed test room is presented in Figure 6.

Figure 6. Study room model.

The second model is a common residential building that has been constructed in Qurna city. The building in consideration has two stories and a rectangular shape. Each floor is 3 m high. One flat, identical to the ones on the floors above and below, is located on each floor. The overall floor area of a unit is 150 m². Bedrooms are the most heavily influenced rooms in a flat; therefore, that's where the experiment will take place. One wall of the room is lined with windows facing south. The bedroom has a total floor space of 20 m² and a window space of 1.20 m². According to the Egyptian Ministry of Housing, Utilities, and Urban Development's geographic information system (GIS) database, the Qurna City of modern traditional buildings in Luxor is made of cement brick (CB) for walls and a reinforced concrete flat roof. The horizontal plan of the residential building under study and the 3d model are shown in Figure 7. Generally, the first model has been constructed, modeled, and simulated to validate the model as well as investigate the impact of the EFB experimentally. Whilst the second building model is a residential building located in Qurna City. It was modeled and simulated to carry out a comparison between the eco-friendly brick (EFB), traditional brick (TB), and cement brick (CB) considering different brick thickness and wall cross-section.

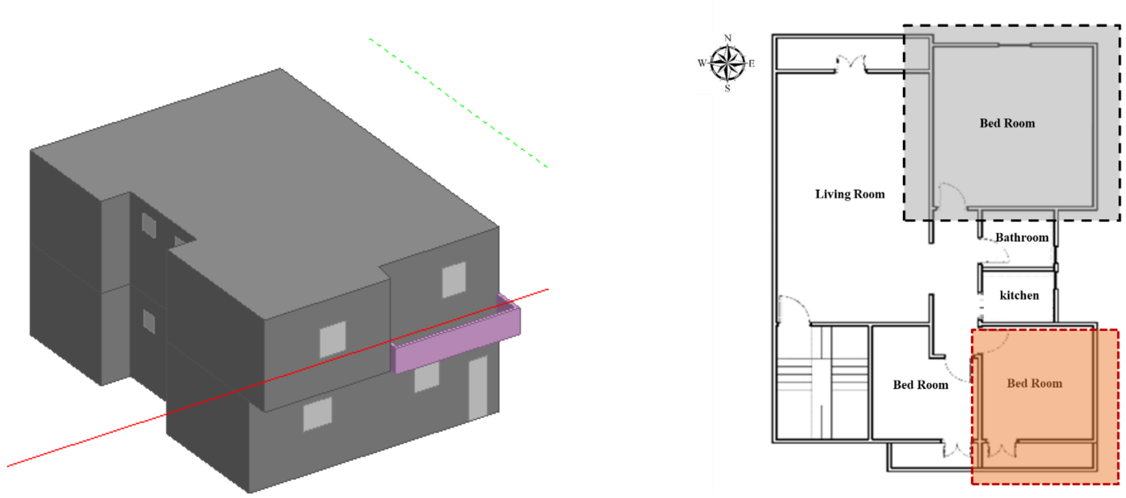


Figure 7. The typical floor for the investigated building in Qurna city.

Field Measurements

The study employed a methodology based on verification and field measurements to gain a comprehensive understanding of the performance of compressed bricks made from environmentally friendly materials. To achieve this, a device called Hobo 12 Pro (Figure 8) was used to measure and evaluate the internal temperatures of the test room that has been constructed in the city of Qurna. Temperature readings were taken at the top of every hour for a continuous period of 15 days. Simultaneously, external temperature measurements were obtained from the Bureau of Meteorology at Luxor International Airport, also recorded hourly over the same 15-day period. August was chosen for this study as it is the hottest month in Luxor, providing a rigorous test of the thermal performance of the EFB. The comparison of internal and external temperature data aimed to assess the effectiveness of the bricks in mitigating heat transfer and maintaining thermal comfort within the test room.

Figure 8. The measurements device (Hobo U 12).

The field measurements of the study model involved comparing the internal temperatures recorded by the Hobo 12 device inside the test room with the external temperatures reported by the meteorological office at Luxor International Airport. This comparison aimed to demonstrate the effectiveness of the EFB bricks in reducing heat gain, thereby lowering energy consumption for cooling. Figure 9 illustrates a significant difference between the internal and external temperatures, showcasing the enhanced thermal performance of the bricks used in the study model. The data revealed a notable temperature variation between 12 p.m. and 4 p.m., which aligns with peak power usage times. During this period, the temperature inside the room constructed with EFBs was consistently 4 to 7 degrees Celsius lower than the external temperature. This temperature discrepancy underscores the efficacy of EFB in maintaining cooler indoor environments, thereby reducing the need for mechanical cooling and contributing to energy savings.

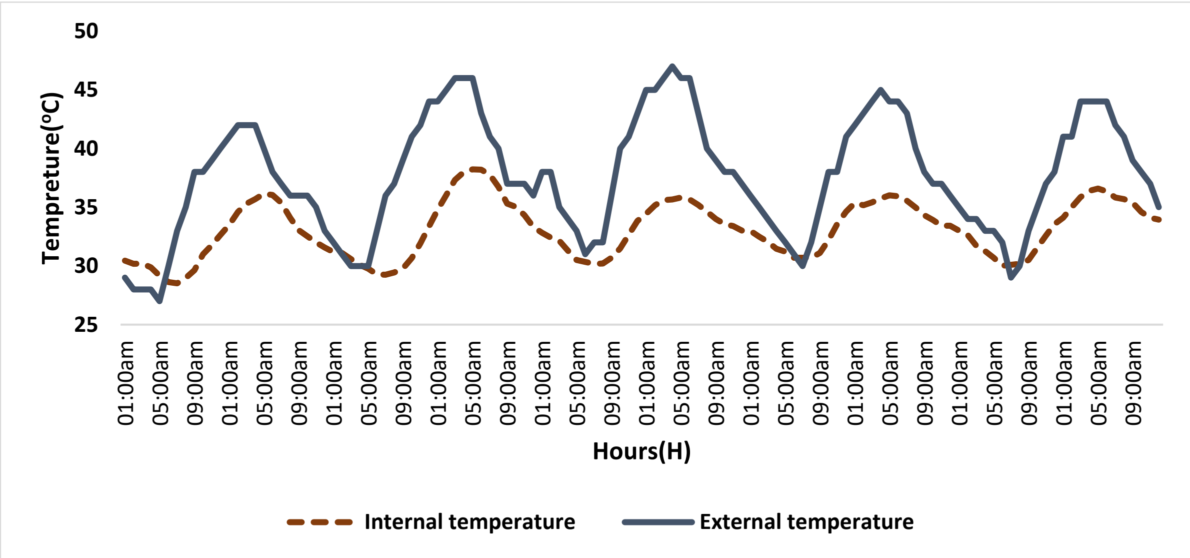


Figure 9. Study model internal-external temperature difference

Physical, Mechanical, and Thermal properties of the fabricated Eco-friendly brick

Experiments were conducted to determine the physical and mechanical properties of the fabricated EFB before assessing their thermal properties. The bricks were tested for vertical pressure, showing values of 1.6 N/mm² and 4.37 N/mm² after 3 and 90 days of dry storage, respectively, and 1.05 N/mm² and 3.83 N/mm² after 90 days of water immersion. The thermal conductivity of building materials significantly influences the cooling load in interior spaces, as heat transfer can occur from inside to outside or vice versa. To measure the thermal conductivity, the study utilized the KD2 Pro device from the Housing and Building National Research Center (HBRC) in Egypt, as shown in Figure 10. The density and specific heat values of the eco-friendly brick samples were also obtained with the assistance of HBRC. The investigation adhered to the ASTM D-5334 standard specification, with test conditions set at a temperature of 24°C and a relative humidity of 55%. The thermal properties of the eco-friendly brick samples, along with those of other brick types such as traditional brick and cement brick, are detailed in Table 1. This table provides a comprehensive comparison of the thermal parameters of the various wall materials used in the study.

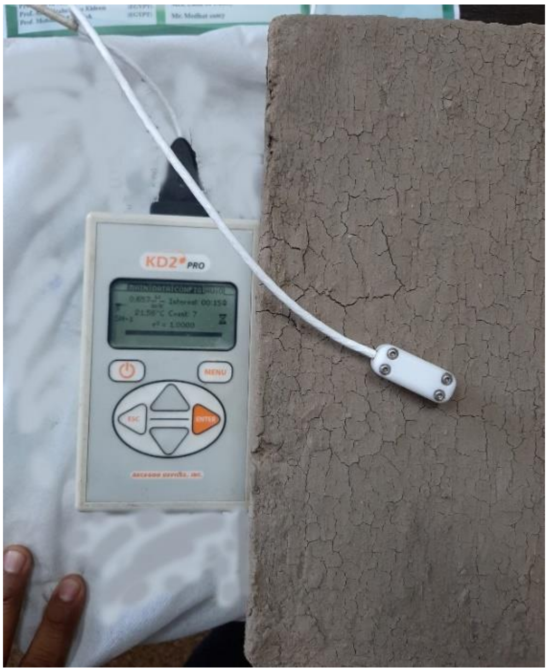


Figure 10. Extraction of thermal properties of the fabricated brick using KD2 pro device.

Table 1. The thermal characteristics of eco-friendly brick and the brick that are most frequently employed.

Brick	Density (kg/m^3)	Thermal Conductivity (W/m. k)	Specific heat capacity (j/kg)
Traditional brick	1950	1	829
Cement brick	1800	1.6	880
Eco-friendly brick	1485	0.657	800

Simulation process and model validation

A building model corresponding to the room was created on the simulation program (Design Builder) .The modelling software (Design Builder) was used to examine the impact of eco-friendly brick on interior air temperature. The Design Builder software was used to obtain the Luxor city weather data file, which reflects the present climate conditions. According to the US Department of Energy's website, the 2002 epw file (Energy Plus Weather) for the Luxor climate zone is included in the simulation software. These epw files are text-based CSV files providing hourly meteorological parameter data for the study region for a whole year. To simulate a realistic scenario, the in-situ weather data files have replaced the software's current weather data files for Luxor's 2018 weather, as determined by an airport meteorological station. Since it was not possible to directly change the EPW file containing weather data, it was converted to a CSV file to receive meteorological data retrieved from the weather station. The weather station's input data includes dry-bulb temperature, relative humidity, solar radiation, wind direction, and wind speed. The element software was used to determine direct radiation and dew point, whereas the auxiliary tool (element software) was employed to calculate direct radiation and dew point. The modified CSV was exported to a new EPW, which served as the data input for Design Builder.

The Design Builder Program was utilized to simulate the thermal performance of the test room (case study). These simulation results were then compared with the field measurements obtained using the Hobo U12 device. The validation of the simulation findings was conducted following

ASHRAE Guideline 14-2002, ensuring the accuracy and reliability of the results. By modeling the current scenario, it was determined that the average discrepancy between the energy simulation results, and the field measurements was only 1.78%, as illustrated in Figure 11. This minimal difference highlights the high degree of accuracy and similar performance between the simulated data and the actual measured data. The close alignment of these results underscores the effectiveness of the Design Builder Program in accurately predicting the thermal behavior of the eco-friendly brick construction, thereby validating the simulation model's reliability for future studies.

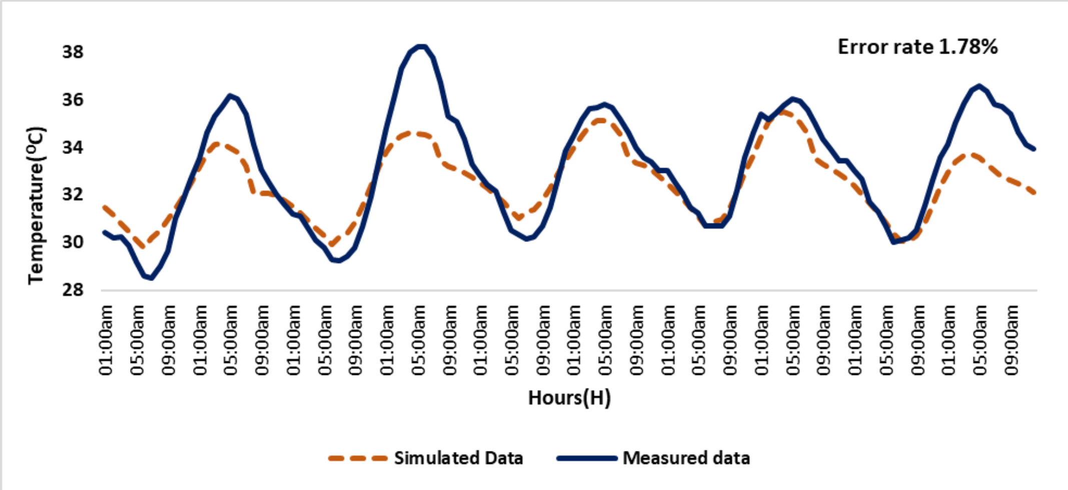


Figure 11. The validation of the study model.

Proposed wall options

Several external walls with different materials and brick thicknesses (120-250-380 mm) were investigated to determine their effectiveness in terms of heat transfer and energy efficiency in buildings (Figure 12). Six different eco-friendly brick construction options were proposed for this investigation. The primary objective was to explore various modifications to EFB to identify the most energy-efficient methods for reducing heat transfer through walls and minimizing cooling hours during the summer.

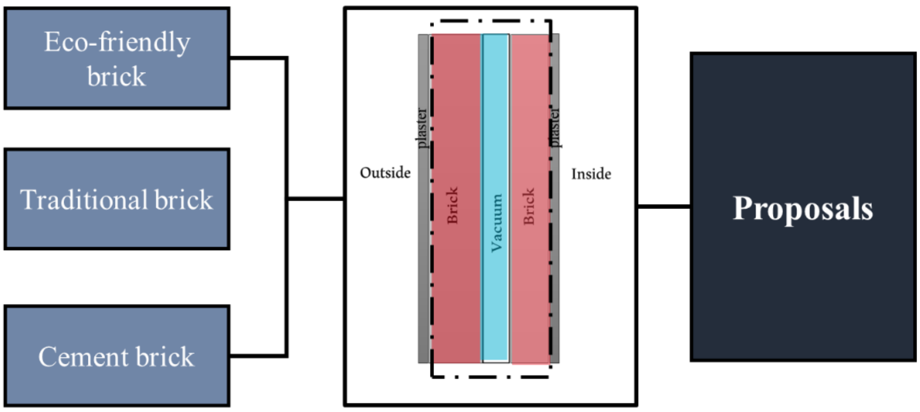


Figure 12. Configuration of the external wall

Figure 13 presents a comparison of six different wall options, labeled W1, W2, W3, W4, W5, and W6, based on their composition and thermal properties. Each wall option is described by its layers, thickness, and U-value, which measures thermal conductivity.

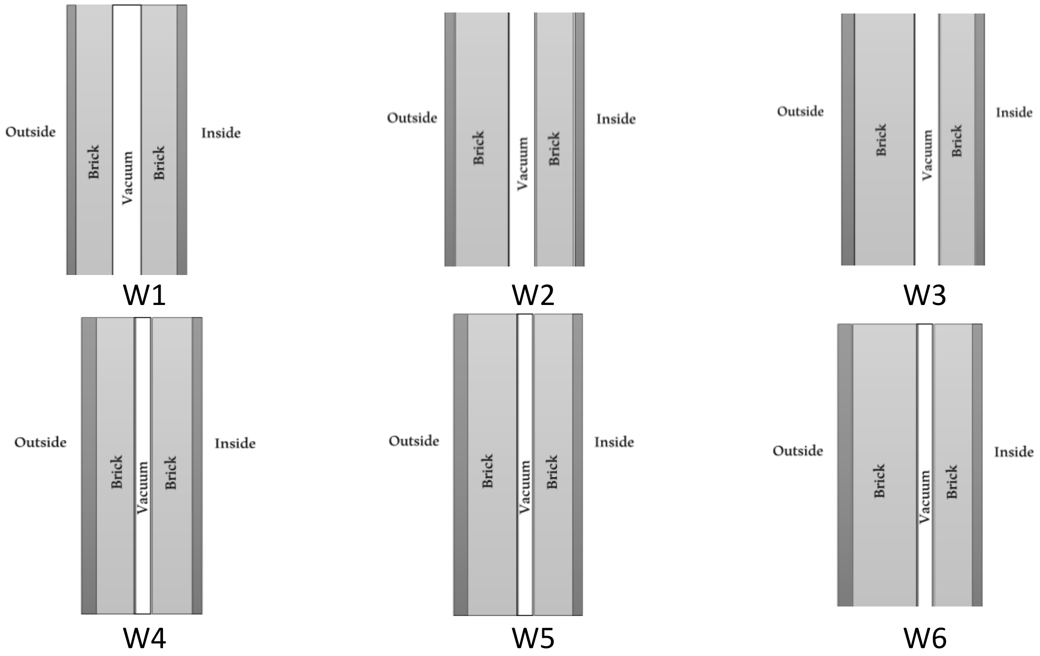


Figure 13. The wall sections properties.

For the case study, the six wall options were simulated and compared to a traditional wall, which served as the baseline for the summer season. The Design Builder simulation tool was employed to evaluate the thermal performance of different wall sections. The study aimed to determine the most effective brick thickness, type, and wall cross-section by examining various wall layers and the internal space variations between these layers. The results of these simulations, including the thermal properties and energy efficiency of each wall option, are detailed in Table 2. This comprehensive analysis provides insights into the most effective wall configurations for enhancing energy efficiency and thermal comfort in buildings.

Table 2. Description of walls thickness and U-value, which measures thermal conductivity.

Wall options	Thickness (m)	U-Value(w/m^2-k)
W1	20 mm plaster + 120 mm eco-friendly brick + 100 mm air cavity +120 mm eco-friendly brick +20 mm plaster	TB (0.627) CB (0.645) EFB (0.566)
W2	20 mm plaster + 250 mm eco-friendly brick + 100 mm air cavity +120 mm eco-friendly brick +20 mm plaster	TB (0.580) CB (0.613) EFB (0.509)
W3	20 mm plaster + 380 mm eco-friendly brick + 100 mm air cavity +120 mm eco-friendly brick +20 mm plaster	TB (0.539) CB (0.584) EFB (0.466)
W4	20 mm plaster + 120 mm eco-friendly brick + 50 mm air cavity +120 mm eco-friendly brick +20 mm plaster	TB (0.913) CB (0.952) EFB (0.790)
W5	20 mm plaster + 250 eco-friendly mm brick + 50 mm air cavity +120 mm eco-friendly brick +20 mm plaster	TB (0.816) CB (0.884) EFB (0.683)
W6	20 mm plaster + 380 mm eco-friendly brick + 50 mm air cavity +120 mm eco-friendly brick +20 mm plaster	TB (0.738) CB (0.825) EFB (0.602)

Simulation input for the residential building model

Simulation modeling was achieved using the simulation of the outer wall with the Design Builder software in its fourth version (V.4.0.0.105), The case consists of a common building in the village of Qurna in Luxor governorate. The construction plan was drawn using 2D AutoCAD and exported to the software for simulation testing. The simulation hypothesis of the study building is shown in Table 3. The occupants' activities have been assumed according to the Egyptian lifestyle [13, 24, 42]. The building in consideration has two stories and a rectangular shape, as shown in Figure 12. Each floor is 3m high. The efficiency of tested bricks in cutting down on HVAC energy consumption for homes was calculated using Design Builder (version 4.5.006). This was done by figuring out how much energy a single-family home in the Qurna Luxor governorate used (in kWh) and how much energy it saved (in kWh).

Table 3. Information on the study building's specifications for the simulation procedure.

Item	Specific
Type	Common residential building
Location	Luxor – Qurna City
Ground floor area (m^2)	130
Typical floor area (m^2)	150
Floor Hight (m)	3.10
Building orientation	North-South
Occupancy (persons per flat)	5
Window glazing	3mm single-glazed

Energy price catogries in Egypt

The annual energy consumption cost per flat, calculated in Egyptian Pounds (EGP), was determined based on the rates established by the Egyptian Ministry of Electricity and Renewable Energy for the residential sector (Table 4).

Table 4. Categories of energy price in Egypt.

Bracket	Category (kWh)	Price (EGP)
1st	0:50	0.68
2nd	51:100	0.78
3rd	101:200	0.95
4th	201:350	1.55
5th	351:650	1.95
6th	651:1000	2.10
7th	more than 1000	2.23

Result & Discussion

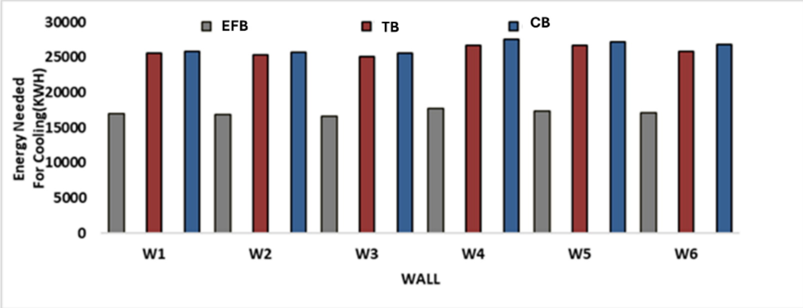
There were two major sections of findings. whereby the first section addresses cooling-related energy savings, and the second section contains the economic feasibility of each suggested wall option. Here, the study presents the simulation results that were obtained in terms of calculating the total energy needed to attain the optimal internal thermal conditions within the building, to determine the most energy-efficient brick type and their potential energy savings.

Influence of the proposed wall options on the energy demand for cooling

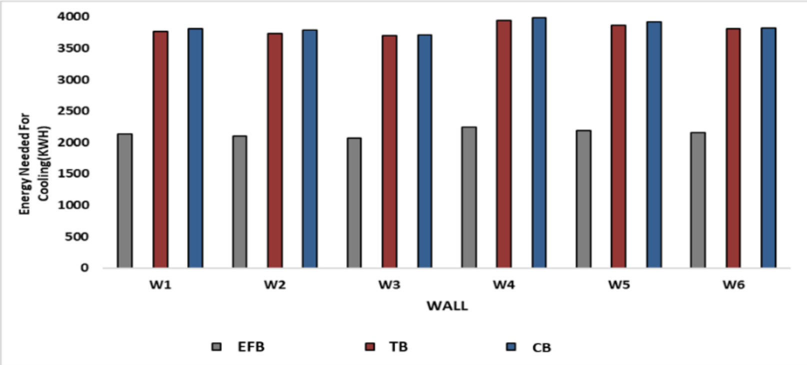
The thermal efficiency of eco-friendly brick samples was evaluated using the Design-Builder program to compare their thermal performance with traditional and CB. This was accomplished by measuring the inside temperatures and examining their impact on energy consumption caused by air conditioning. The results compare the yearly energy consumption of buildings made with TB and CB, compared to buildings made with EFB. The potential variants of TB, CB, and EFB are simulated here (W1-W2-W3-W4-W5-W6). The first layer has a brick thickness range of 120-250-380 mm; the second layer has an internal spacing of air cavities with a thickness of 50 and 100 mm. The third layer has a brick thickness of 120 mm.

In order to determine the impact that bricks having different quantities of cement have on the cooling loads in residential construction, the simulation program Design-Builder was used. The findings of the simulation demonstrated how the composition of environmentally friendly bricks used for the outer wall of the building influenced the amount of electrical energy required for providing cooling. The findings illustrate that CB are the worst-case scenario in terms of the amount of energy that is required for cooling, and TB require less energy than CB. It also illustrates the convergence of the ratios of energy required for cooling between TB and CB. Furthermore, environmentally friendly bricks have demonstrated their capacity to significantly reduce the amount of energy that is required for cooling. When compared to other months of the year, July is the warmest month, and it is also the month that achieves the largest use of electrical energy due to cooling. During this time of the year, Luxor temperatures reach more than 45 ̊C. Figure 14(a) shows the results of the simulation of the energy consumed for cooling for the alternatives used over the entire year for the study model used and the percentage difference between them; Figure 14(b) shows the results of the simulation of the energy consumed for cooling for a room facing north within the study model used; and Figure 14(c) shows a room facing south within the study model used.

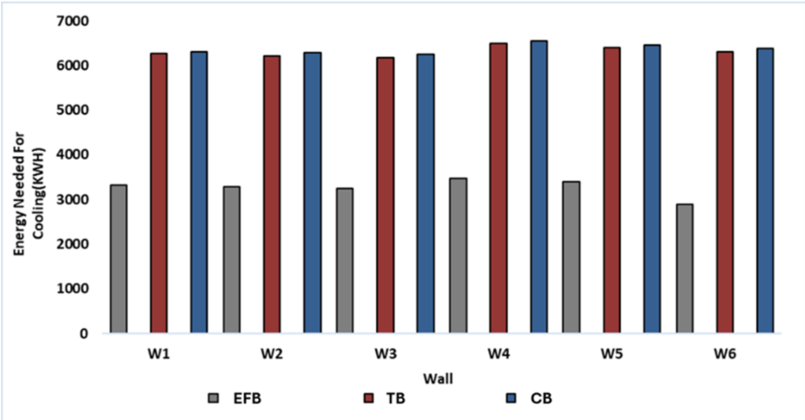
The results indicate that EFB exhibits the lowest energy consumption for cooling, with a requirement of 16,820 kWh. In contrast, the energy needed for cooling using TB increases to 25,342 kWh, while CB demonstrates the highest energy demand, reaching 25,736 kWh. These findings highlight that EFB outperform CB by approximately 35%. Among the alternatives assessed, the south-facing room shows the lowest energy requirement for cooling: EFB at 2,899 kWh, TB at 6,315 kWh, and CB at 6,380 kWh. In the case of W4, CB require the highest cooling energy at 6,545 kWh, followed closely by TB at 6,497 kWh. Using EFB results in a significantly reduced cooling requirement of 3,478 kWh, indicating a 47% improvement over CB. Furthermore, the north-facing room (W3) exhibits the lowest cooling demand for EFB at 2,071 kWh, compared to 3,704 kWh for TB and 3,711 kWh for CB. In W4, CB again record the highest energy requirement for cooling at 3,989 kWh, whereas TB require 3,947 kWh. The cooling requirement using EFB in this scenario is 2,248 kWh, demonstrating a 44% improvement over CB.



(a)



(b)



(c)

Figure 14. Simulation results in terms of the difference between EFB, TB, and CB in terms of the energy needed for cooling in different places. (a) whole building, (b) northern room, and (c) southern room

The simulation results indicated the total energy consumption for cooling over a year across various common construction types. A comparative analysis of TB and CB, which are widely used, against EFB was conducted across several alternatives (W1, W2, W3, W4, W5, W6). The findings demonstrate that EFB consume less energy than both cement and TB. The results suggest that CB exhibit the highest energy demand for cooling to maintain thermal comfort within a designated space. The implementation of EFB can lead to significant reductions in electrical energy consumption for cooling, with potential energy savings ranging from 5% to 36%. As illustrated in Figure 15, the highest savings percentage occurs in alternative W6, where EFB provide a 36% reduction compared to CB, while TB offer only a 3.5% reduction. Conversely, W1 shows the lowest savings percentage, with EFB achieving a 35% improvement and TB yielding only a 1% savings.

Statistical data indicate that substituting cement and TB with EFB in wall construction has the potential to decrease cooling energy usage by up to 35% to achieve thermal comfort.

Furthermore, this study investigates the maximum achievable thickness of various brick types, including traditional brick, cement brick, and eco-friendly brick. The research examines how different brick types perform in terms of thermal efficiency and structural integrity during construction. There was found to be a linear relationship between the wall thickness and the energy needed to cool this building, as depicted in Figure 16. Overall, the use of EFB results in lower energy consumption for cooling compared to traditional and CB used in wall construction.

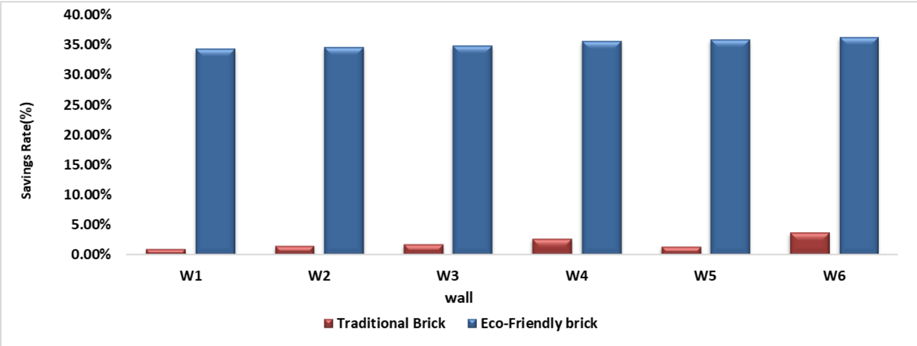


Figure 15. Energy saves by Eco-friendly brick and cement brick

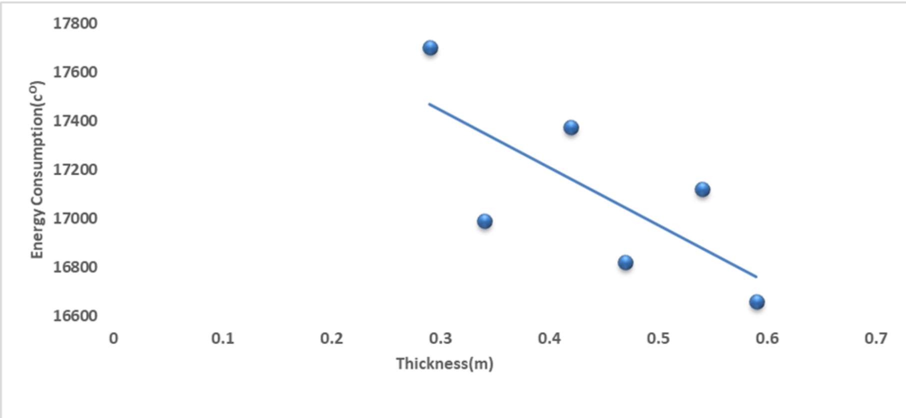


Figure 16. Relationship between the wall thickness and energy consumption in the investigated building.

The investigation concluded that the use of EFB is the most effective strategy for minimizing energy consumption. These findings are compitable with previous studies which achieved a significant energy savings using waste materials [28-30, 42]. In contrast, traditional building systems often overlook design principles and materials that are essential for effective energy savings. The simulation results comparing various brick types indicate that incorporating clay mixed with 6% cement by volume and straw to produce compacted brick units (EFB) can significantly reduce energy consumption required to achieve therma.

Cost Analysis

Currently, there is a global trend towards energy conservation due to the significant costs associated with energy consumption. Insulating ceilings has become a common practice, as it effectively reduces heat absorption. However, walls, which constitute a substantial portion of the external surface area, are often overlooked. This experiment aims to evaluate the feasibility of producing EFB by combining cement and clay, with the potential for significant cost reductions. According to the study's findings, EFB can reduce energy consumption by as much as 35-36%. This information served as the basis for our assessment of potential cost savings, helping to determine the viability of manufacturing EFB. Building owners in Egypt are continually seeking ways to lower operational costs. Nevertheless, there is a tendency to minimize the duration of air conditioner usage for cooling purposes. Moreover, strategies that rely on passive climate solutions are rarely selected, primarily due to the costs associated with their implementation. This research investigates the potential financial benefits of using EFB in low-income housing in Luxor, Egypt. While EFB have demonstrated effectiveness in reducing energy consumption, other factors, such as economic viability and the costs of new construction units, must also be considered to assist Egyptian decision-makers and architects. To conduct the cost analysis, a simple payback period (SPP) approach was utilized. This analysis considers the additional investment required for each of the various proposed actions, along with the equivalent annual savings in Egyptian pounds from reduced energy costs. The following formula can be applied to calculate the additional investment and the simple payback period:

$$\text{SPP} = \frac{\text{Additional Investment}}{\text{Annual energy savings}}$$

Table 5 summarizes the materials cost used to produce the units. The cost of these materials has been derived from the local market.

Table 5. The cost of the used materials (Local market, October 2024).

Materials	Quantity (m^3)	Cost (EGP)
clay	1	160
Cement	0.06	63

As the study focuses on the EFBs efficiency, the study compared different EFB wall options and the CB base wall. Table 6 provides a summary of the construction costs per meter square for different wall alternatives, including CBs and EFBs (EGP/m^2).

Table 6. The cost of the used units (Local market, October 2024).

Brick	Unit Cost (EGP/m^2)
Eco-friendly brick	66
Cement brick	198

The expected annual energy costs and SPP for all evaluated options were calculated, and the results demonstrated the effectiveness of all EFB wall options in achieving energy savings. The cost and payback analysis of six wall configurations (W1–W6) constructed using EFBs highlights the financial feasibility of adopting these sustainable materials. Initial wall costs range from 34,560 EGP (W1 and W4) to 60,160 EGP (W3 and W6), reflecting differences in material thickness. The additional investment required to transition from traditional construction methods to EFB varies between 2,560 EGP (W1 and W4) and 28,160 EGP (W3 and W6). Despite these variations, the annual energy savings achieved are significant, ranging from 28,984.77 EGP/year (W4) to 31,261.05 EGP/year (W3). These savings underscore the potential of EFB to reduce cooling energy demand substantially, offering a cost-effective solution for enhancing thermal performance in hot arid climates. The simple payback period (SPP) analysis reveals rapid returns on investment for all configurations, ranging from 0.08 years (W1) to 0.93 years (W6). Thinner and less complex walls, such as W1 and W4, demonstrate the shortest SPP, making them ideal for projects prioritizing quick cost recovery. Conversely, configurations with thicker walls, like W3 and W6, achieve higher annual savings but require slightly longer periods to recover the initial investment. The findings confirm that EFB walls not only improve energy efficiency but also provide substantial economic benefits, with payback periods of less than one year across all configurations. These results validate the use of EFB as a financially viable and sustainable alternative to traditional building materials. Table 7. Presents the SPP values for all EFB proposed wall options.

Table 7. Cost analysis of the proposed options.

	Wall cost (EGP)	Additional investment (EGP)	Energy cost (EGP/year)	Annual saving (EGP/year)	SPP (year)
W1	34560	2560	38462.59	30548.20	0.08
W2	47360	15360	38141.42	30869.37	0.50
W3	60160	28160	37749.74	31261.05	0.90
W4	34560	2560	40026.02	28984.77	0.09
W5	47360	15360	39319.68828	29691.10	0.52
W6	60160	28160	38682.22029	30328.57	0.93

Conclusion

The study investigated the incorporation of cement as a supplementary component in clay, constituting 6% of the total volume of the mixture, utilizing mechanical piston and natural drying methods. The findings indicate that the resulting bricks meet eco-friendly specifications and demonstrate significant energy savings, with a reduction of approximately 34–35% in cooling energy compared to traditional bricks and a 33% reduction relative to cement bricks. Additionally, the proposed eco-friendly bricks offer a cost-effective solution for construction projects, achieving a minimum simple payback period of not more than one year. Despite these promising results, the study has certain limitations. First, the environmental impact of the production process, including embodied energy and carbon emissions associated with the raw materials, was not comprehensively assessed. Second, the long-term durability and weathering performance of the eco-friendly bricks under varying climate conditions require further investigation. Lastly, the study primarily focused on thermal and economic performance in hot arid regions, leaving its applicability in other climate zones unexplored. To address these limitations, future research should consider conducting a detailed life cycle assessment (LCA) to quantify the environmental benefits and potential trade-offs of the proposed bricks. Additionally, experimental studies on the durability and mechanical performance of the bricks over time in diverse environmental conditions are necessary. Investigating the potential for scaling up production techniques and assessing the feasibility of using alternative waste materials as supplementary components would also expand the applicability of this approach. Based on the findings, the following recommendations are suggested:

- Integrate eco-friendly bricks into building codes and regulations.
- Establish partnerships between investment companies and local governments to foster the development of the eco-friendly brick industry in Egypt.
- Create decentralized research and application centers in various geographic regions to conduct material testing and identify suitable soil types for use in brick production.

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