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Thermal and Structural Performances of Screen Grid Insulated Concrete Forms (SGICFs) Using Experimental Testing

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Thermal and Structural Performances of Screen Grid Insulated Concrete Forms (SGICFs) Using Experimental Testing

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Abstract: The demand for sustainable building materials and systems with the emphasis on energy efficiency is on the rise. Insulating Concrete Forms (ICFs) are an example of such structural systems. Screen Grid Insulated Concrete Forms (SGICFs) are an innovative system that combines structural strength and thermal performance. ICF walls are commonly used in Western countries to provide high-level insulation and internal weather control. Accordingly, the current research conducts a comparative thermal analysis for a market-supplied ICF wall, a SGICF proposed design, and three typical brick walls used regionally in the Middle East. The heat transfer through the five walls is simulated by COMSOL Multiphysics and validated experimentally by utilizing a guarded hot box facility under the regulations of the ASTM C1363 standard. The market-supplied ICF walls showed better thermal insulation properties than the proposed SGICF walls, because of their higher thermal mass of concrete than in the SGICF walls. However, both walls had a remarkably higher insulation performance than the other three typical brick walls available in the market. The results reveal that the market-supplied ICF walls are overdesigned for use in the Middle East region, and SGICFs, with their comparative thermal transmittance, are a very good competitor in the Middle East market.

Keywords: ICF; expanded polystyrene panels; COMSOL Multiphysics; guarded hot box; numerical simulation; heat transfer; building envelope; brick walls; thermal mass; specific heat

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1. Introduction

The topic of thermal performance evaluation and building envelopes is one of great interest in the field of construction and building research. One excellent type of energy-efficient wall is the Insulating Concrete Form (ICF) wall. ICF walls come in the form of hollow blocks or panels stacked on top of each other like Legos, forming a wall. The construction crew then fixes steel rebar in those hollow cores and fills them with concrete. Accordingly, the wall created has two layers of Expanded Polystyrene (EPS) with steel reinforcement and concrete in between [1]. ICF systems have two main characteristics: the shape of the EPS and the form of the concrete after pouring. EPS comes in either the form of blocks, planks, or panels, where the block type is the most used type [2]. As for the concrete, it takes the shape of the cavities inside the EPS forms. The result is either a uniformly solid concrete wall, a waffle grid wall, or a screen grid wall [1]. Figure 1 shows the three shapes of concrete after being poured. The first shape forms the flat ICF wall system, which is characterized by two exterior layers of EPS with uniform concrete thickness in between and embedded steel reinforcement. The second is the waffle grid ICF wall system, in which the interior concrete layer looks like a waffle, with both vertical as well as horizontal concrete members closely spaced, and a much less thick concrete web in between. Finally, there is the screen grid ICF wall system, which also has vertical and horizontal concrete members closely spaced, but without a web in between. The concrete in the screen grid ICF system looks like a thick concrete wire mesh [3].

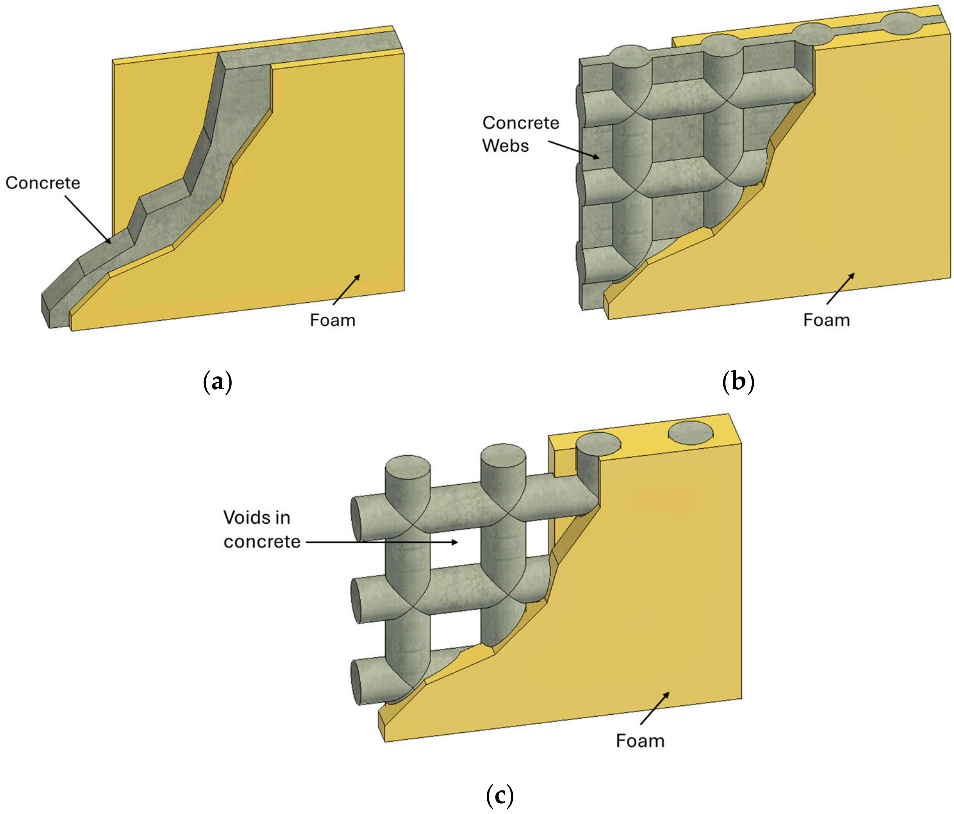


Figure 1. ICF wall types: (**a**) Flat ICF; (**b**) Waffle grid ICF; (**c**) Screen grid ICF.

The concept of incorporating EPS in ICF wall systems offers numerous advantages. Firstly, the EPS layer provides excellent thermal insulation properties, retaining heat inside during cold weather and keeping it cooler during hot weather, which is beneficial in desert-like conditions. Moreover, the presence of foam results in a lower concrete-to-foam ratio, reducing overall material costs. It also eliminates the need for traditional formwork such as wood or metal forms, thereby conserving natural resources. Additionally, ICF wall systems do not require curing, reducing water requirements and enhancing ease of construction while promoting environmental friendliness. These factors collectively contribute to meeting a crucial need in construction: sustainability [4]. From the definition above and as shown in Figure 1, it appears that SGICFs have a higher volume of EPS and lower volume of concrete when compared to the other types of ICF systems (namely flat and waffle grid), as they consist of intersecting beams and columns enveloped in EPS foam material. For this reason, manufacturers like Apex and Faswall assert that SGICFs can achieve concrete savings of up to 30% compared to other types of ICFs and consequently better thermal insulation [5].

The Screen Grid ICF wall is a relatively new, unexplored construction method, in contrast to more widely used construction systems. The implementation of Screen Grid ICF walls may have different consequences across different regions, and acknowledgement of their seismic performance has not yet reached a widespread understanding. For this reason, there may be a gap in the data on their seismic performance and behavior under loading conditions.

Several investigations have generally examined the structural behavior of SGICF walls. The studies listed below encompass much of the significant research on the SGICF system, highlighting the necessity for additional studies, particularly to determine seismic design parameters [6]. Kay and Dusicka, at Portland State University's Infrastructure Testing & Research Laboratory in Portland, Oregon, investigated SGICF walls. The walls were exposed to in-plane static cyclic loading, resulting in failures characterized by diagonal shear cracking through the vertical cores along a single horizontal plane [7]. Another study performed by the National Association of Home Builders (NAHB) Research Center, Inc., for the U.S. Department of Housing and Urban Development intended to determine an equivalent continuous wall thickness to relate to the SGICF system [8].

A study conducted by the Building and Housing Research Center (BHRC) examined full-scale SGICF walls. The walls were subjected to in-plane cyclic loading to determine the impact of voids on SGICF wall performance. The results of the test highlighted the behavior of the structural system in the plastic phase, which showed the system's energy absorption capabilities; those capabilities are crucial for applications in regions with high seismic hazard levels [9].

In more recent research, a numerical study was conducted to determine the ductility and response modification factor of SGICF wall systems. The results were then compared to those from experimental specimens. This study presented the ductility and response modification factor of the SGICF wall system based on its ductility [6].

In 2019, a study declared that the ICF system is now widely accepted in developed countries and has been incorporated into many building codes due to its advantages, such as light weight and energy efficiency. The study provided an extensive analysis of the structural behavior of conventional bearing walls, including bricks, blocks, and concrete, compared to ICF walls. The main objective of the study was to compare the effect of using foam in ICF walls to traditional bearing wall systems. The experimental results demonstrated that ICF is a superior alternative to traditional bearing walls. The study also concluded that using ICF in buildings, as opposed to traditional building materials, creates an optimal system that enhances building comfort and economic efficiency [10].

In 2021, Lopez et al. acknowledged that SGICF walls are becoming increasingly popular in the construction of low- and mid-rise buildings because of their distinctive constructability and insulation properties. Accordingly, the study aimed at validating the safety of this novel construction system in the face of seismic loads through experimental testing to gain further insights regarding the walls' non-linear behavior. The study showed that SGICF walls could achieve significant inelastic deformations and maintain a stable response, like conventional reinforced concrete (RC) walls of comparable geometric properties. Additionally, it has been confirmed that flexural resistance models used for solid cross-section RC members are applicable to ICF walls, considering section discontinuities [11].

As structural, construction, and building codes evolve and incorporate new materials and structural technologies, it becomes critical to conduct extensive research to ensure that SGICF walls comply with current seismic design requirements. Analyzing the dynamic response of these structures under seismic loading calls for sophisticated modeling and testing methods. For this reason, many researchers have attempted to explore the seismic response of SGICF walls under seismic conditions through laboratory testing and computer-aided numerical analysis as mentioned above, and have reached significantly useful conclusions. Accordingly, it is anticipated that SGICF walls are a sound structural system.

On the other hand, the thermal performance of ICF walls has been extensively investigated. Comparisons have been made between ICFs and other wall types. The advantages of thermal mass have been thoroughly examined, particularly at the Oak Ridge National Laboratory [12–14]. A report was drafted in 1999 for the United States' Department of Housing and Urban Development Office of Policy Development and Research. The report conducted an analysis of energy efficiency and thermal comfort, along with computer simulations of energy usage, for three adjacent residences. These homes, each with a floor area of 102 m^2, featured different construction methods: an ICF block system, an ICF plank system, and a conventional lumber wall (constructed using 2×4 wall stud framing, covered with Oriented Strand Boards (OSBs), and insulated with fiberglass batts placed in the wall cavities.). All properties had identical street locations, orientations, window areas, roof designs, footprints, ducting, and air handling systems. The findings revealed no notable distinction in air leakage test outcomes among the three residences. However, the two homes constructed with ICF systems exhibited approximately 20% greater energy efficiency compared to the wood-framed dwelling. This variance primarily stems from the superior R-values of ICF walls and the presence of insulation covering the slab [3].

Likewise, in 2001, a field investigation was conducted on two neighboring houses in Knoxville, Tennessee, USA. While nearly identical in structure, the houses differed only in their exterior wall construction, with one featuring ICF walls and the other conventional wood-framed walls. Results indicated that the ICF-equipped house consumed less energy than its counterpart with conventional walls, at a 7.5% reduction. This study highlights the main benefit of thermal mass in regulating indoor environments during large variations in outdoor temperatures [15].

In addition, a study utilized numerical simulations with DOE-2.1E software to examine the influence of different climates in six cities across the United States (Phoenix, Minneapolis, Dallas, Boulder, Knoxville, and Miami) on the energy usage of both ICF and conventional wood-framed dwellings. The results regarding cooling, heating, and total electricity usage demonstrated the benefits of thermal mass for both cooling and heating purposes. Specifically, the ICF residences exhibited annual energy savings ranging from 5.5% to 8.5% in comparison to conventional wood-framed houses [16,17].

In 2006, a collaborative project between the Canada Mortgage and Housing Corporation (CMHC), Enermodal Engineering Limited, and the Ready Mixed Concrete Association of Ontario (RMCAO) took place. They examined a seven-story ICF multi-residential building's performance in Waterloo, Canada. Temperature readings were taken at eight locations within the wall assembly from 1 December 2005 to 26 February 2006. The data analysis revealed that the concrete had a negligible impact on the steady-state R-value. Nevertheless, it revealed the thermal energy retention effects during temporary circumstances. Data analysis indicates assistance of concrete in reducing heat loss to the outside in cold-weather periods [18].

Recent research has focused more on utilizing simulation techniques to understand and quantify the thermal mass effect of concrete in ICF wall systems. Notable work in this area was conducted in 2010 and 2011. The research utilized COMSOL Multiphysics software version 3.5a to confirm a 3D thermal model against on-site measurements of the thermal behavior of an ICF wall in Canadian climate conditions. The main objective of this study was to evaluate the heat transfer properties of two medium-sized ICF walls [19,20].

Ultimately, ICF walls are one of the competitive energy-efficient walls that can be used. However, all the studies made up to this point have been on the very cold climates, like US and Canadian climates. No reliable data are available for moderate and hot climates like the Middle East climate.

Hence, in our study, a comparative study is applied between three differently designed ICF walls and three different brick walls that can be assumed to be the "typical" walls used in the Middle East for buildings and construction. This point of research can be conducted experimentally through various devices, and the mostly used are hot boxes or numerical simulations and analysis. Several simulation tools are available, both open source and commercial. Amongst these, COMSOL Multiphysics® [21] is the most famous and increasingly popular one.

The presented work investigated the thermal performance of six walls: three typical brick walls that are mostly used in the Middle East, and three ICF walls. Three different designs of ICF walls were studied, one with flat EPS structure, denoted as Wall (W_1); the other two cases are screen grid EPS insulated walls, denoted as Wall (W_2) and Wall (W_3), as shown in Figure 2. On the other hand, Figure 3 illustrates the three brick walls with plaster layers and different insulating layers that were also investigated experimentally and modelled numerically.

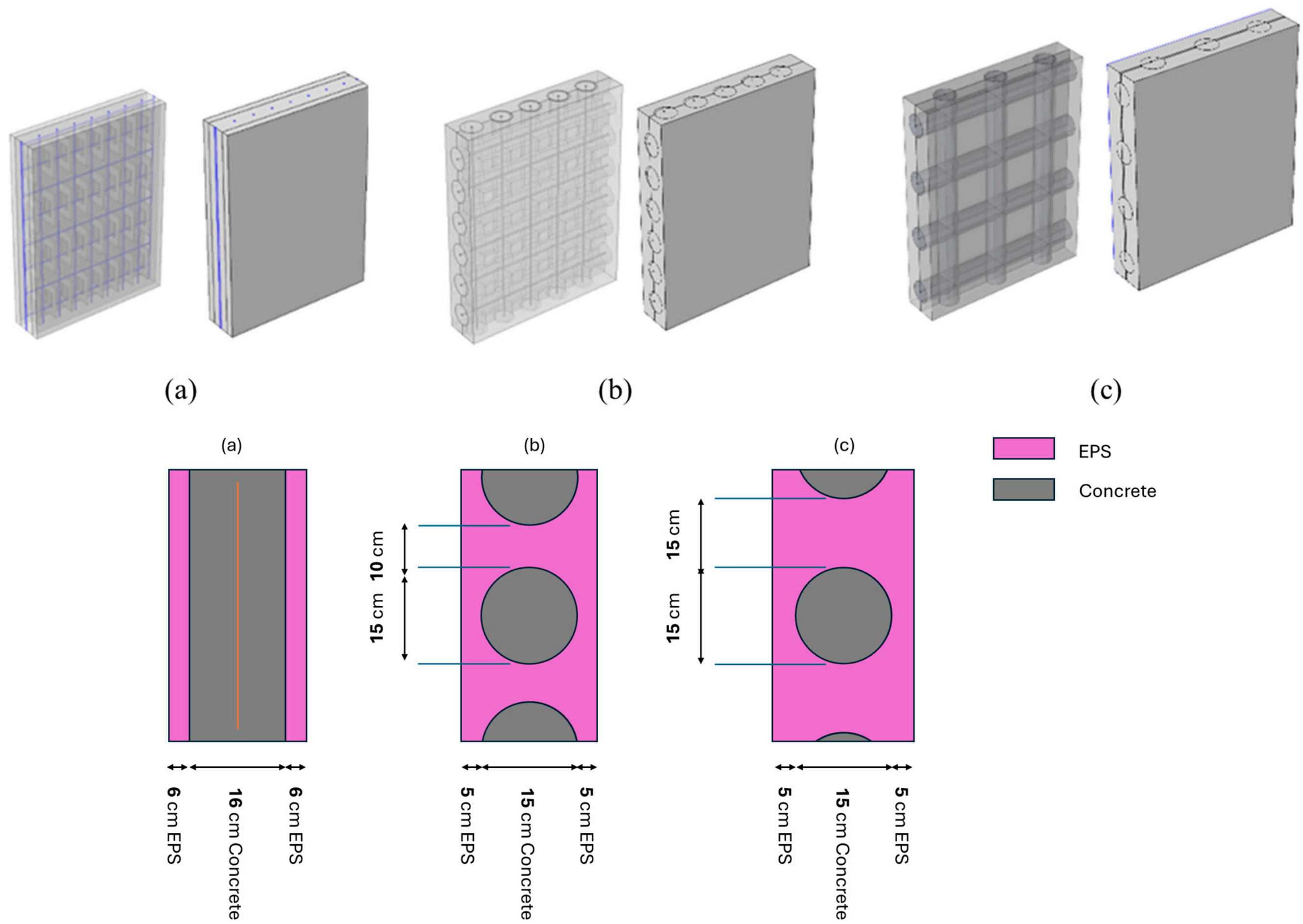


Figure 2. Illustrations of different designs of ICF wall systems: (**a**) Wall W_1; (**b**) Wall W_2; (**c**) Wall W_3.

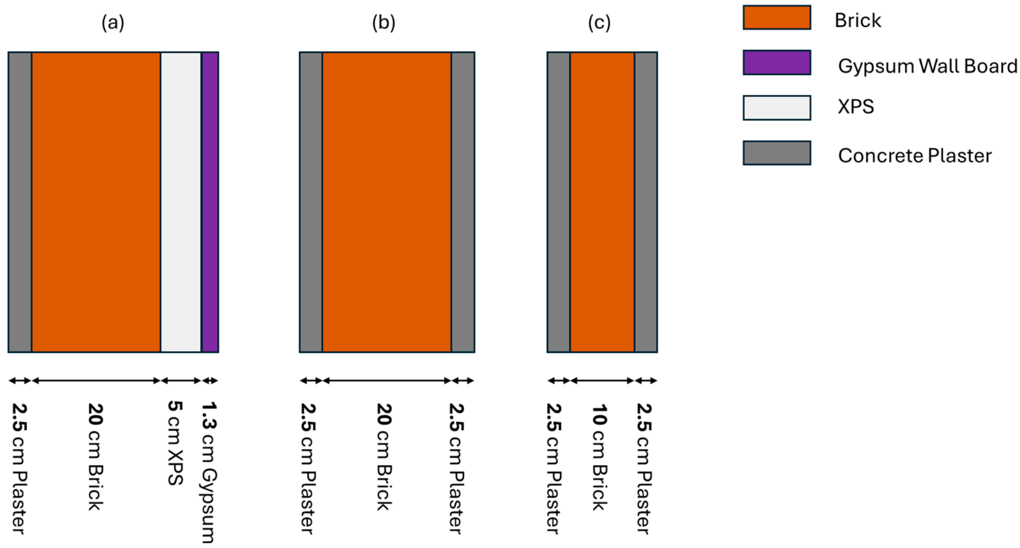


Figure 3. Illustrations of typical residential construction wall systems utilized in Egypt and the Middle East: (**a**) Wall T_1, (**b**) Wall T_2, (**c**) Wall T_3.

ICF wall systems have gained popularity recently due to several reasons. The construction of ICF structures offers numerous advantages over traditional methods, including cost efficiency, ease of construction, thermal insulation, heatproofing, soundproofing, faster construction times, lower maintenance, and resistance to insects, wind, and natural disasters. In the United States, approximately 3% of homes are built using ICF systems. ICF is considered a sustainable and eco-friendly alternative to conventional carbon-emitting cement-based construction methods, primarily due to the performance of EPS (Expanded Polystyrene). Since 2013, ICF has significantly benefited the construction sector in India and has been widely accepted in the US, Germany, Japan, Canada, and Mexico. Additionally, the construction cost of ICF structures is generally 5% to 10% lower than that of traditional methods. However, increased awareness is necessary for the broader adoption of ICF practices to meet current infrastructure industry requirements. Therefore, based on the numerous advantages offered by ICF systems and the need for further familiarity with the system, this research has been designed to gain more understanding of the system's properties [22].

The main purpose of the experimental and numerical work of this research was to test the validity and benefit of the ICF wall systems from a thermal perspective compared to the typical brick wall systems utilized in the Middle East. The literature mentioned previously has shown numerous studies that imply that ICF wall systems are structurally sound. In the current work, a comparative study is performed to explore the thermal insulation capabilities of the ICF walls compared to the brick walls.

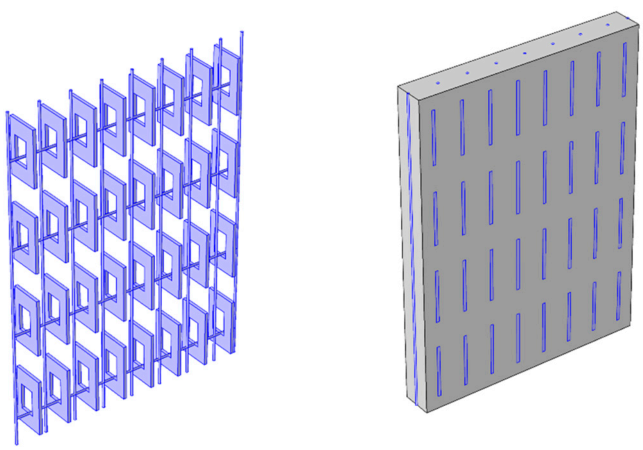
The results of this study are believed to give insights about the thermal capabilities of the proposed ICF wall systems compared to the typically employed brick wall systems. In the case where the results show better thermal insulation, the system could be recommended for use in the hot climates of the Middle East, and the system's various advantages can be utilized.

2. Specimen Preparation and Test Methods

2.1. Specimen Preparation

2.1.1. ICF Walls

As mentioned previously, in the current work, the thermal performance of three different ICF walls was assessed experimentally by using a guarded hot box facility and numerically via COMSOL Multiphysics®. Wall (W_1) consists of two enclosed panels of expanded polystyrene separated by injection-molded polypropylene crossties, as illustrated in Figures 4 and 5. As for Wall (W_2) and Wall (W_3), they consist of two thick EPS panels designed as shown in Figures 6 and 7, where the wall in this design is of a higher percentage of EPS than concrete. Concrete is enclosed between the two EPS panels and reinforced by steel bars. Wall (W_2) consists of 5 × 6 concrete grid cores while Wall (W_3) consists of 3 × 4 concrete grid cores. Figure 8 shows Wall (W_2) in real life with and without the EPS cover. Tables 1 and 2 show the wall dimensions and the properties of each specimen's component materials.



(a) (b)

Figure 4. Constituents of Wall (W_1): (**a**) Injected molded polypropylene crossties and steel bars; (**b**) Poured concrete and reinforced by the steel bars.

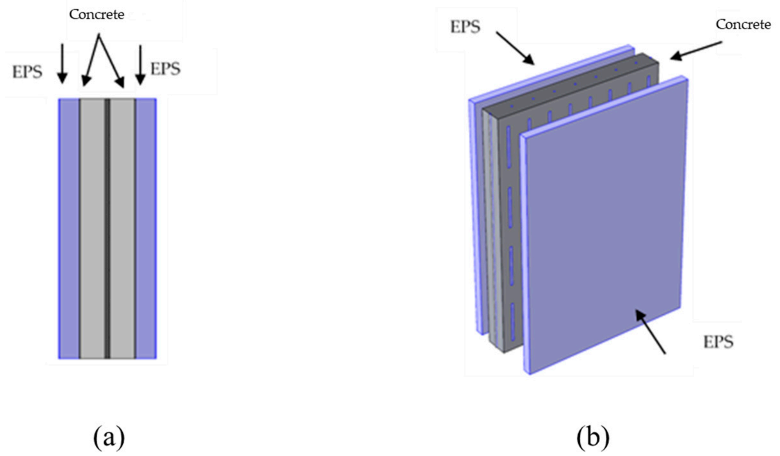


Figure 5. (**a**) Side view cross section of Wall W_1; (**b**) Whole assembly constituents of Wall W_1.

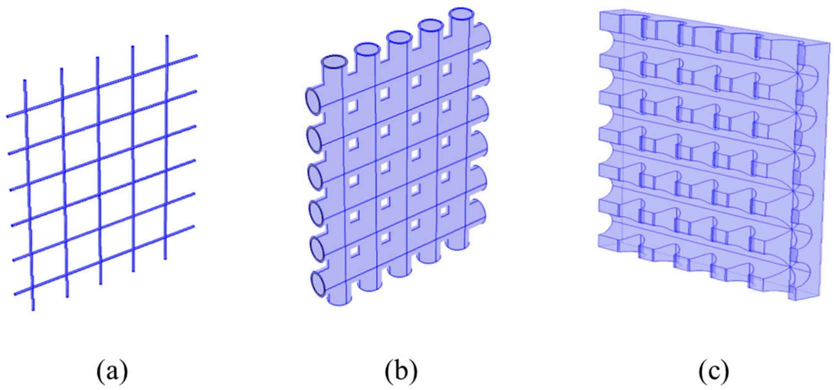


Figure 6. Constituents of Wall W_2: (**a**) Steel bars; (**b**) Concrete grid; (**c**) EPS sheet.

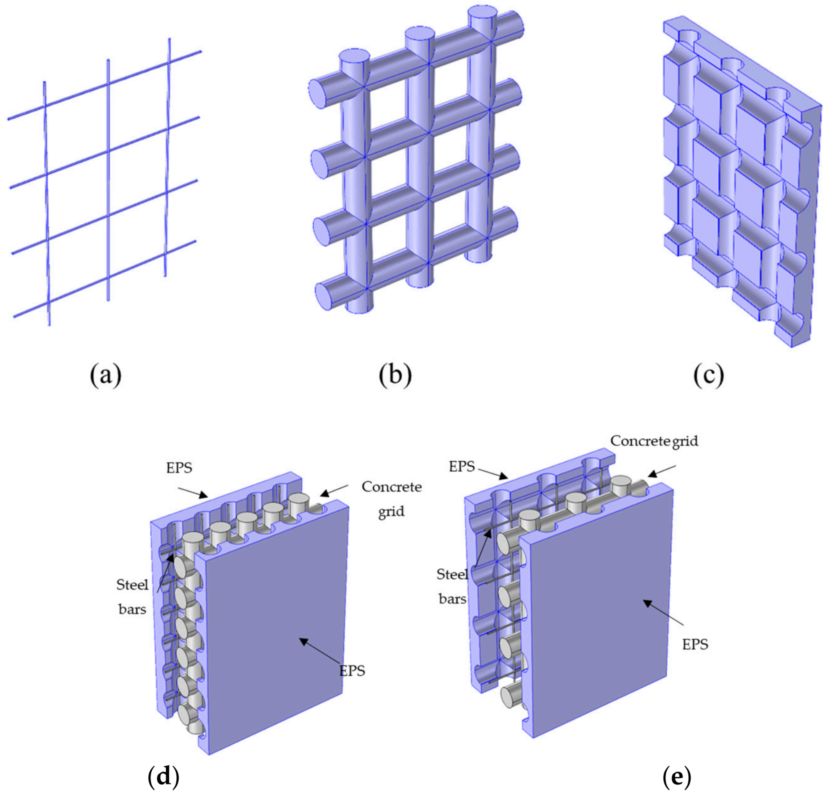


Figure 7. Constituents of Wall W_3: (**a**) Steel bars; (**b**) Smaller concrete grid; (**c**) EPS sheet; (**d**) Whole assembly constituent of Wall W_2; (**e**) Whole assembly constituent of Wall W_3.

(**a**) (**b**)

Figure 8. Constituents of Wall W_2: (**a**) With EPS cover; (**b**) Without EPS cover.

Table 1. Dimensions of ICF walls.

Dimension Parameters	Wall (W_1)	Wall (W_2)	Wall (W_3)
Thickness of the EPS layer (m)	0.06	0.05	0.05
Height of the wall (m)	1.62	1.49	1.49
Width of the wall (m)	1.2	1.24	1.24
Thickness of the concrete layer (m)	0.16	5 × 6 SGICF	3 × 4 SGICF

Table 2. Material properties of ICF walls.

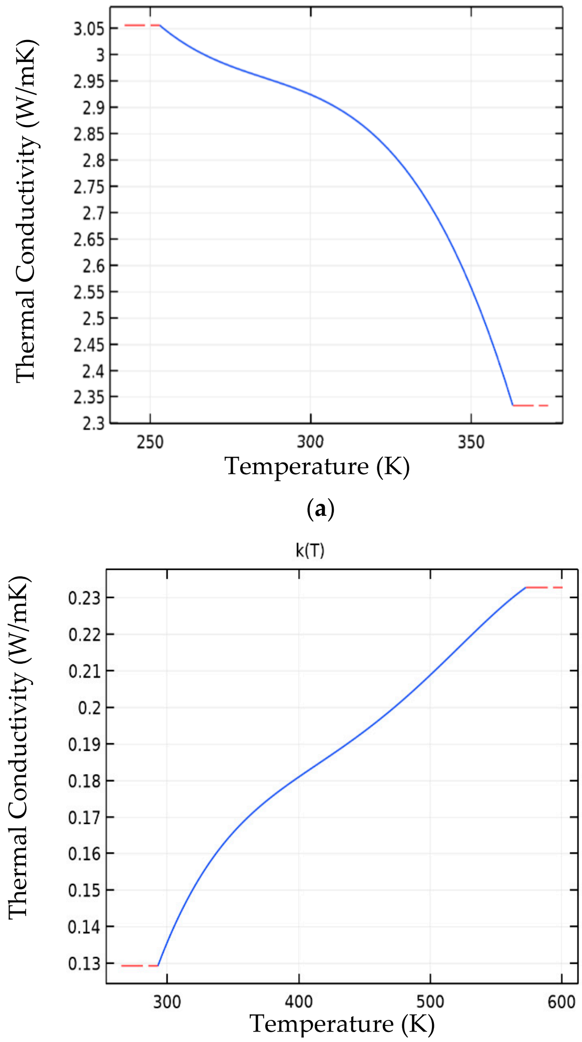
Material Type	EPS	Concrete	Polypropylene	Steel
Density (kg/m^3)	24.02	2400	900	7850
Thermal conductivity (W/mK)	0.03	Figure 9a [1]	Figure 9b [2]	44.5
Heat capacity (J/kg.K)	1300	880	Figure 10 [3]	475

[1] Value of thermal conductivity of concrete is conducted from COMSOL as a function of temperature and illustrated in Figure 9a. [2] Value of thermal conductivity of polypropylene is conducted from COMSOL as a function of temperature and illustrated in Figure 9b. [3] Value of heat capacity at constant pressure of polypropylene is conducted from COMSOL as a function of temperature and illustrated in Figure 10.

2.1.2. Typical Brick Walls

Bricks are widely utilized in construction, notably as exterior envelope materials, offering both structural support and aesthetic appeal. Manufacturing methods vary, incorporating diverse mixes and additives to bolster strength and achieve desired visual effects like color and texture. Across architectural styles, it is common to use bricks decoratively in exterior walls [23].

Numerous studies have examined the properties and patterns of traditional bricks. Among recent research, a study in 2014 emphasized the significance of material thermal flux in assessing the in situ thermal transmittance of materials for determining actual wall performance [24]. In 2017, another study investigated the thermal properties of brick masonry through a comparative analysis and in situ experimentation on contemporary industrial bricks used in Italy, contrasting them with historic brick masonry. The study introduced various measurement techniques to analyze the thermo-physical behavior of traditional masonry, drawing on conventional methods such as geometrical surveying, VI (visual inspection), IRT (infrared thermography), and hot-disk techniques [25].



(**a**) (**b**)

Figure 9. Thermal conductivity versus temperature (K): (**a**) Concrete; (**b**) Polypropylene.

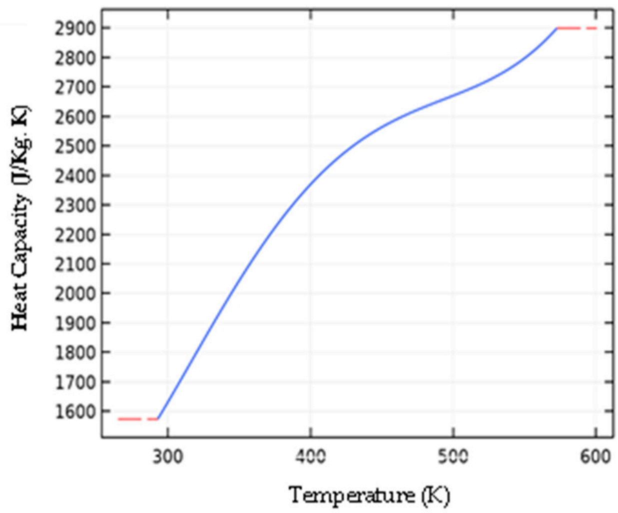


Figure 10. Heat capacity of polypropylene at constant pressure as a function of temperature (K).

In this study, the thermal performance of three brick walls featuring different thicknesses of brick and insulating layers was explored, as depicted in Figure 3. The investigation involved testing three wall systems with dimensions of 149 cm × 124 cm and varying thicknesses as follows:

1. Wall T_1: 2.5 cm Plaster layer + 20 cm Brick layer + 5 cm Extruded polystyrene insulation layer + 1.3 Plaster Gypsum Wall Board (GWB) and Paint layer.
2. Wall T_2: 2.5 cm Plaster layer + 20 cm Brick layer + 2.5 cm Plaster layer.
3. Wall T_3: 2.5 cm Plaster layer + 10 cm Brick layer + 2.5 cm Plaster layer.

The investigated brick walls represent the most typical brick walls that are used in the market, where "Wall T_2" is the most common wall that is constructed in Egypt. "Wall T_3", with the smallest thickness, is less used in Egypt, but it has its own users and still considered in the market. Wall T_1 is the fanciest wall among the three walls, and it was built and proposed to compare its performance with that of the other two market-based walls.

As mentioned before, the scope of this work is to investigate the thermal performance of six walls in terms of calculating the U-values. The U-values of five walls were investigated experimentally by using guarded hot box test facility and numerically by using the "Heat transfer module" in COMSOL Multiphysics software. Only the U-value of "Wall W_3" was calculated numerically by COMSOL after ensuring that the experimental and numerical results of the other five walls were nearly equivalent to each other.

2.2. Test Methods

2.2.1. Simulation Model

The recent literature extensively employs COMSOL for diverse building-related issues [26–30]. The accuracy of numerical results can be confirmed by comparing them with different control systems such as thermo-flow meters, guarded hot boxes, and thermographic methods. COMSOL is a versatile software that can solve finite element problems, perform analysis, and simulate multi-physics scenarios. It supports traditional user interfaces based on physics and can handle systems of linked partial differential equations (PDEs) [23]. Heat flow and temperatures were analyzed, with models constructed using COMSOL Multiphysics®.

The simulation model focused on three core heat equations as follows.

Heat equation of state:

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P u.\nabla T = \nabla.q + Q \tag{1}$$

Fourier's law of heat conduction:

$$q = -kA\Delta T \tag{2}$$

Newton's law of cooling controlling the hot and cold sides of the specimen:

$$q = h(T_{ext} - T) \tag{3}$$

Adiabatic condition controlling through the wall's boundaries:

$$-n.q = 0 \tag{4}$$

where q is the density of heat flow rate or heat flux (W/m^2), ρ is the density $\left(\text{kg/m}^3\right)$, C_P is the specific heat at constant pressure (J/kg K), k is the thermal conductivity [W/(m K)], and T is temperature [K].

Simulation parameters: The simulations were conducted under forced air convection conditions, with the hot side's air speed set at 0.1 m/s and the cold side's at 1.9 m/s. The COMSOL model operated based on the aforementioned heat equations to analyze heat flow and temperatures within the SGICF and typical walls.

Material properties: The simulations used typical values of material properties as per Tables 2 and 3.

Table 3. Material properties of three typical brick walls.

Material Type	Brick	Concrete Plaster	Extruded-Polystyrene Board	Gypsum Wall Board
Density (kg/m^3)	2000	2300	34	574
Thermal conductivity (W/mK)	0.5	1.8	0.041	0.27
Heat capacity at constant pressure (J/kg.K)	900	880	1450	1100

The simulation steps were set up as follows:

1. Defining the dimensions and location of all layers in the modeled wall elements;
2. Defining the physical properties (specific heat capacity, thermal conductivity, density) of all layers in the model elements;
3. Defining the initial and boundary conditions;
4. Recording the U values and thermal masses for all wall types.

2.2.2. Experimental Setup

In the current study, the guarded hot box was used as an experimental setup facility to calculate the U-values of the specimens experimentally. The guarded hot box system consists of three chambers: cold (outdoor, fixed position), hot (indoor, mobile), and a tempering ring (encircling the test specimen). The outdoor chamber and tempering ring remain stationary, while the hot chamber is mounted on casters and rails for mobility.

The guarded hot box can be either designed and constructed [31–33] or purchased from reputable manufacturers. The guarded hot box employed in the current experiment was manufactured by Angelantoni Test Technologies [34].

The test facility consists of:

- Chamber structure;
- Air treatment unit;
- Cooling plant;
- Control system;
- Pre-tempering chamber;
- Special wall;
- Metering box;
- Measurement system.

The study of the thermal performance evaluation and building envelopes by guarded hot boxes has been done extensively before. The calculations and validations of the results are regulated and illustrated in detail by mainly two standards: ASTM C1356-11 standard [35] and ISO 8990 standard [36]. These standards give detailed steps for calibration of the guarded hot box and methods of calculating the U-value of the tested sample.

Guarded hot boxes are primarily utilized to assess the decreases in heating and cooling loads that can be ascribed to the implementation of attic radiation barriers, as well as to determine the environmental factors that impact this reduction [35]. In addition to that, due to the wide range of temperatures they can simulate, they are used to examine the performance of different types of wall and fenestration thicknesses and materials in tropical areas and summer conditions, and this can facilitate the process of verifying the thermal performance of both ordinary and intricate fenestration systems, which is essential for constructing energy-efficient buildings in tropical regions [37]. Moreover, guarded hot boxes were also used to detect the presence of workmanship defects in walls, especially insulated ones, and the consequences of reducing heat transfer through the damaged envelope [30]. The variety of topics that guarded hot boxes can be used to study and analyze makes them a powerful tool to be used for addressing these topics. However, as mentioned before, guarded hot boxes are either self-designed and constructed or bought from a manufacturer. In the case of manufacturing the guarded hot box, cautions should be taken because inaccuracy in design will cause deceiving results. It is much better to work with a manufactured guarded hotbox, but, on the other hand, the costs of the experiment will increase significantly when compared to using a self-designed guarded hot box. Due to these challenges, biasing towards using simulation tools is increasing, as it is less costly and more accurate than using experimental devices.

The test setup depicted in Figure 11 and comprises three chambers: cold (OD) and hot (ID), representing the outside and inside building environments, respectively; and a tempering ring surrounding the test specimen.

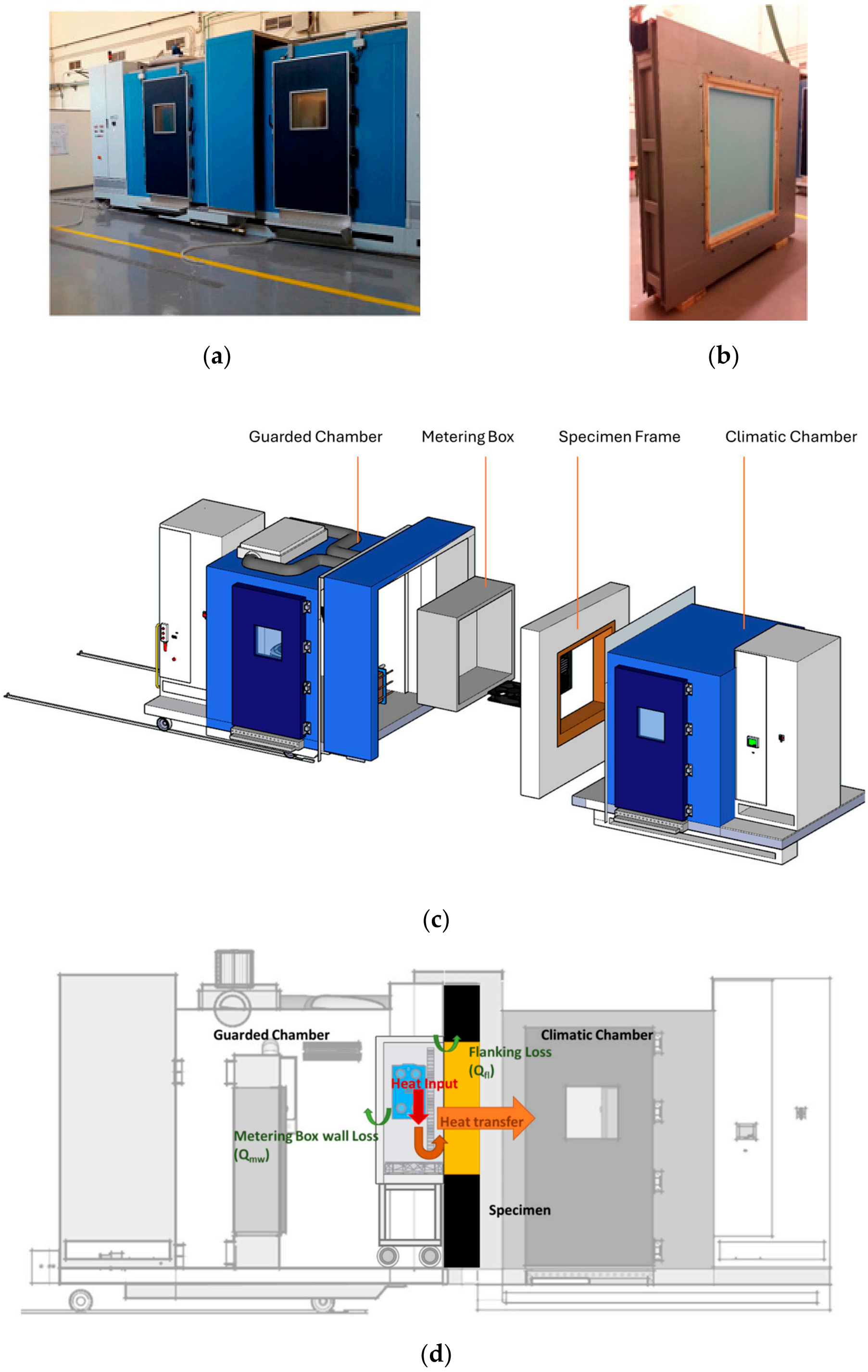


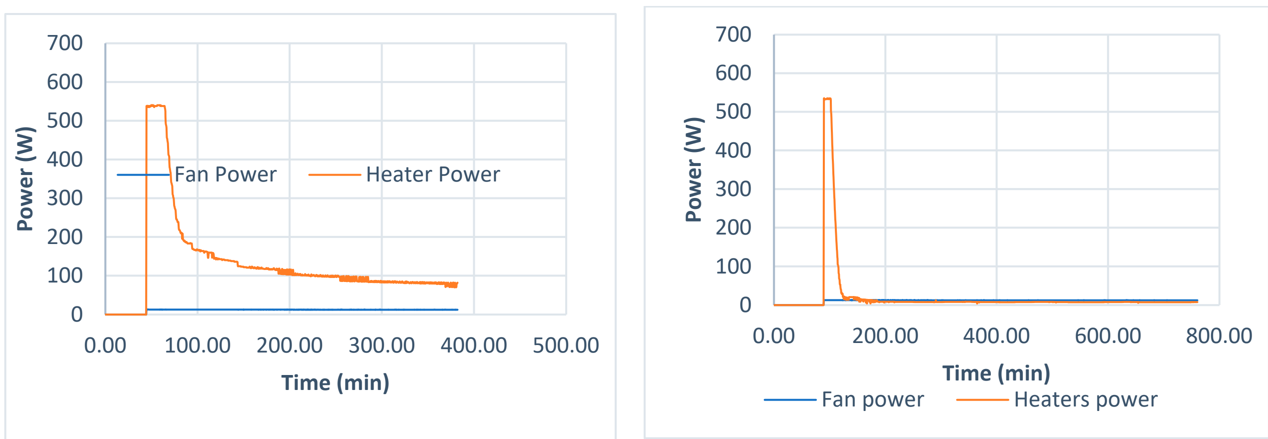
Figure 11. Test apparatus and specimen: (**a**) Test rig; (**b**) Testing frame; (**c**) Exploded 3D model of the test apparatus and components; (**d**) Schematic diagram of the heat transfer in the hotbox apparatus.

The outside chamber and tempering ring are stationary, while the other chamber is movable and equipped with casters and rails for transportation. The equipment is adjusted to meet the specifications given in ASTM C1363-11 [35]. The requirements of the specimen matched the standards, and the specimen was set in the tempering ring, which was located between the two chambers. For laboratory testing, a wall frame was constructed for various wall samples, as illustrated in Figure 11b. The two chambers employed an indirect thermoregulation system with a rate of 0.2.

3. Results

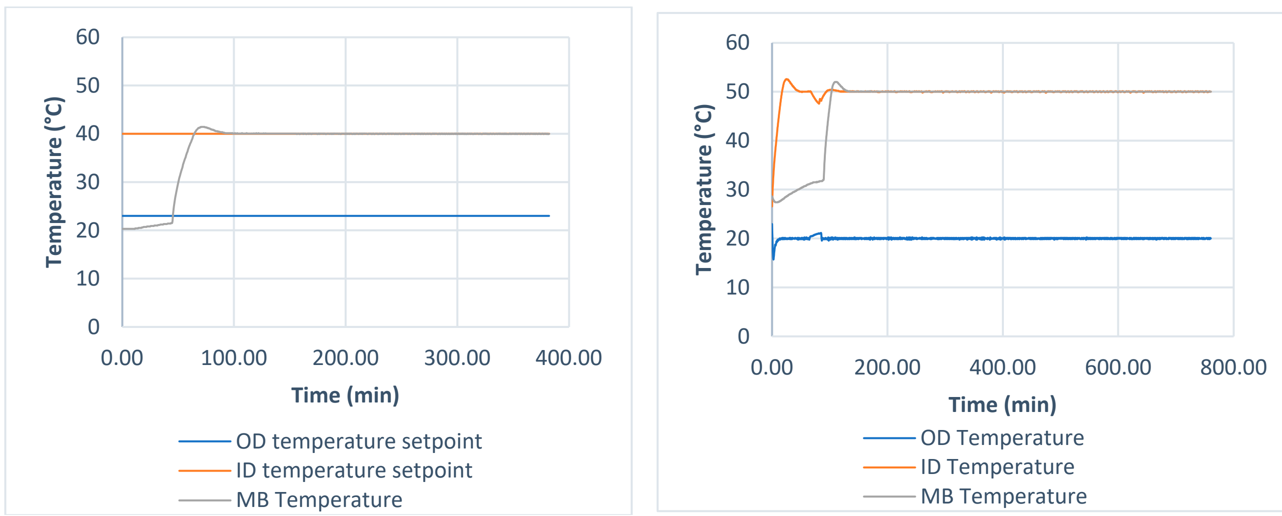
3.1. Experimental Results

Experimental tests were performed on walls T_3 and W_1. Walls T_3 and W_1 were exposed to temperature differences of 17 °C and 30 °C, respectively. Figure 12 illustrates the variations of heater and fan powers for both tests, and the changes in temperatures of the cold and hot sides of the guarded hot box are illustrated in Figure 13.



(**a**) (**b**)

Figure 12. Variations of heater and fan power with time during Test 1: (**a**) Wall T_3; (**b**) Wall W_1.

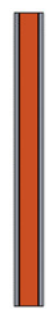
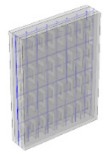


(**a**) (**b**)

Figure 13. Variations of ID, OD, and MB (Mean Box) temperatures with time during Test 1: (**a**) Wall T_3; (**b**) Wall W_1.

As illustrated in Table 4, the two walls have different areas and thicknesses due to constructions limits and specifications, and thus, the U-values of both walls under these variable conditions were not comparable. The valid comparison between the insulation abilities of all walls will be illustrated in Section 3.2, while in this section, only the experimental U-value results of both walls will be previewed. Afterwards, the latter results will be compared to the numerical results to validate their accuracy and eventually will be used to compare the U-values of all walls.

Table 4. The experimental and numerical U-values of the experimentally tested walls T_3 and W_1.

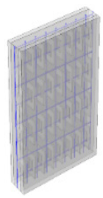
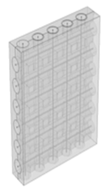
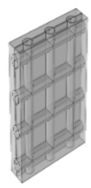
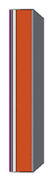
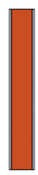
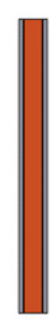
Property	Wall T_3	Wall W_1
		
Experimental U-value	2.652	0.304
Numerical U-value	3.216 (+21.25%)	0.254 (−16.4%)
Thickness (cm)	15	28
Area (cm^2)	1.8476	1.944

As shown in Table 4, the experimental U-value of wall T_3 is 2.652, while the numerical value calculated by COMSOL is 3.216. For wall W_1, the experimental U-value is 0.304, while the numerical one is 0.254. The percent errors of the numerical U-values of walls T_3 and W_1 compared to the experimental results were −16.4% and +21.25%. We account these remarkable percent errors to the differences between the "Density", "Heat capacity" and "Thermal conductivity" of the materials used for constructing the wall samples and the values used in COMSOL software. This was due to the absence of accurate specifications and catalogs of the wall building materials. Therefore, the material specifications of the COMSOL's library as illustrated in Tables 2 and 3 and Figures 9 and 10 are the ones used in the numerical model.

3.2. U-Value Calculations

The U-values for all specimens were calculated at the six typical environmental conditions matching the weather in Western and Middle East regions, as shown in Table 5.

Table 5. Thermal properties of all numerically tested walls.

Property	WallW_1	Wall W_2	Wall W_3	Wall T_1	Wall T_2	Wall T_3
						
Numerical U-value	0.254	0.358	0.280	0.556	1.957	3.216
K-value		0.093		0.170	0.489	
Thermal mass (10^3)(KJ/°K)	4.085	0.679	0. 491	0.871	0.850	0.519

It is worth mentioning that the results of wall (W_1) are close to the U-value of the same market product wall with an EPS thickness of 57 mm and a concrete thickness that varies from 146 mm to 248 mm where the market's product U-value is 0.28 [33].

Despite the SGICF system having a much higher volume of foam than the flat ICF wall, the insulation of the latter has proven to be better. This could be attributed to the low thermal mass of concrete in the SGICF wall. Thermal mass denotes the capacity of a building's mass to absorb and retain heat, thereby offering resistance to abrupt temperature changes. Furthermore, the continuous concrete layer in flat ICF walls provides a uniform and uninterrupted thermal mass that helps in maintaining steady indoor temperatures by absorbing and slowly releasing heat. This uniformity ensures that there are no weak spots where heat can easily penetrate. Conceptually akin to thermal capacitance or heat capacity, thermal mass reflects a structure's ability to accumulate and hold thermal energy. In this context, materials such as concrete function as conduits for thermal energy, with higher thermal mass resulting in a decreased rate of thermal energy conductivity.

$$Q = mC_P\Delta T \tag{5}$$

where Q is the thermal energy transferred, m is the mass of the body, C_P is the isobaric specific heat capacity, and ΔT is the change in temperature.

$$C_{th} = mC_P \tag{6}$$

where C_{th} is the thermal mass of the body. The following Figure 14 previews the relation change of the U-values with respect to different wall thermal masses.

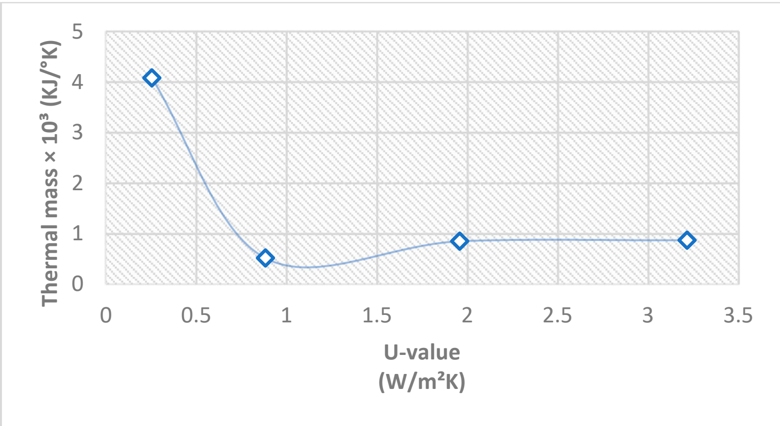


Figure 14. Change in the U-values with respect to different wall thermal masses.

4. Conclusions

The current research conducts a comparative study between typical brick walls, flat ICF, and SGICF walls from a thermal behavior point of view. Experimental testing was carried out with a guarded hot box, and a numerical model was built and analyzed with COMSOL Multiphysics. The analysis showed that the flat ICF wall system is a better thermal insulator than the SGICF wall system. This is due to the low thermal mass of concrete in the SGICF wall, which makes the SGICF a lower heat conductor than the flat ICF system. Moreover, the ICF walls in general were found to provide a comparative thermal performance to the typical walls used in Egypt and the Middle East.

However, the study faced several limitations that should be acknowledged. Due to funding constraints and the premature end of financial support during the COVID-19 period, the scope of the experimental work was restricted. Consequently, the number of comparative working conditions tested was limited, and the range of variables explored was narrower than initially planned. These constraints have been a significant factor in the observed differences between the experimental and numerical results, which can also be attributed to material imperfections and workmanship during the construction of the test specimens.

Despite these limitations, the findings from the current study provide a solid foundation for future research. It is essential to conduct further experimental studies with a broader range of variables to validate and extend the results presented in this work. Future research should include more extensive experimental setups and comparisons across different working conditions to enhance the robustness and applicability of the findings.

There are material property discrepancies. Significant discrepancies were observed between the experimental and numerical U-values. For wall T_3, the experimental U-value was 2.652, while the numerical value was 3.216, resulting in a percent error of −16.40%. For wall W_1, the experimental U-value was 0.304, while the numerical value was 0.254, with a percent error of +21.25%. These errors are attributed to differences in the density, heat capacity, and thermal conductivity of the materials used in the experiments versus those specified in the COMSOL library. To minimize such discrepancies in future research, it is crucial to obtain accurate material property data for all components used in both experimental investigations and numerical analyses. This can be achieved by conducting thorough material characterization tests and incorporating these precise values into the simulation models.

The literature showed that SGICF wall systems have a reliable structural performance. However, the market-supplied wall (flat ICF) gives better thermal performance than the SGICF walls. Still, the difference between the thermal performances of both walls is not considerable, and thus this work suggests SGICF as an alternative for the market-supplied wall, designed for its sound structural performance, numerous advantages such as reduced concrete volume and lighter weight, and its comparable thermal performance.

The significance of this research lies in its potential to influence both academic understanding and practical applications in the field of sustainable construction. Screen Grid Insulated Concrete Forms (SGICFs) represent an innovative approach that combines the structural strength of traditional concrete forms with enhanced thermal performance due to the integration of expanded polystyrene (EPS). This combination addresses two critical aspects of modern construction: energy efficiency and structural resilience.

- Energy efficiency. The study provides detailed insights into the thermal performance of SGICF walls compared to flat ICF walls and typical brick walls used in the Middle East. By demonstrating that SGICF walls offer comparable thermal insulation properties with a potentially lower thermal mass, this research highlights the viability of SGICF wall systems in hot climates where energy efficiency is paramount. This can lead to significant reductions in energy consumption for heating and cooling, contributing to sustainability goals and cost savings for building owners.
- Structural resilience. In addition to thermal performance, the study underscores the structural benefits of SGICF walls. The grid pattern of concrete in SGICF systems offers a robust framework that can enhance the durability and seismic performance of buildings. This is particularly relevant in regions prone to seismic activity, where the adoption of SGICFs is structurally sound.
- Economic and environmental impact. The use of SGICFs can reduce the overall material costs due to the lower volume of concrete required. Additionally, the environmental impact is minimized as the system reduces the need for traditional formwork and promotes the use of recyclable materials like EPS. This aligns with global trends towards greener construction practices and supports efforts to mitigate the environmental footprint of the construction industry.
- Practical applications. The findings from this research can inform best practices and guide the development of building codes and standards that incorporate SGICF technology. Practitioners in the construction industry, including architects, engineers, and builders, can leverage the insights from this study to design and construct more efficient and resilient buildings. Moreover, policymakers and regulators can use this evidence to support the adoption of innovative construction techniques that promote sustainability and resilience.

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