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Effect of Thermal Bridges on Thermal Conductivity of Lightweight Block Units

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ABSTRACT

The objective of this study is to develop lightweight hollow concrete blocks for use as partition walls instead of load-bearing walls. These blocks aim to improve thermal insulation by reducing heat transfer through cavities of varying dimensions and shapes, thereby minimizing thermal bridges and enhancing thermal resistance. Six foam ratios (1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 L/m³) and seven cement-to-sand ratios (1:1.5 to 1:2.5) were tested. Experimental tests included compressive strength, wet and dry density, water absorption, and thermal conductivity on blocks with different cavity shapes (B0–B6). To evaluate thermal behavior, the blocks were also exposed to heat at 300°C. Wall thicknesses of 30, 35, and 40 mm were examined. Overlapping openings were designed to extend the heat transfer path, improving insulation. The use of foam enhanced thermal performance, reducing energy consumption and supporting sustainability through efficient heat insulation.

1. Introduction

When it comes to reducing electricity use and its effects on buildings, insulation from heat is a crucial subject. It is among the most crucial subjects that need to be covered in this study, particularly in Arab nations like Iraq, which experience hot, dry summers and cold, rainy winters. In the summer, the temperature outside can reach over 45 degrees Celsius, with relative humidity of at least 60%. Nowadays, the majority of buildings in industrialized nations have outside walls composed of either solid or hollow concrete blocks [1]. The low heat resistance of these walls is one of its defining characteristics. In the summer, the temperature inside these buildings without air conditioning is quite high.

Therefore, in order to run air conditioners, electrical energy must be consumed. In a year, this circumstance may last for more than five months. Designing structures with good thermal insulation is preferable [2]. Its goal is to lower environmental pollutants and cooling costs. Commercial complexes and government offices are the only buildings that employ insulating materials. The heat conductivity for concrete is known to be significantly higher than that of air. It is possible to decrease the concrete mass's heat conductivity by adding holes or air spaces. The amount of insulation rises with the size of air gaps.

2. Problem Statement

The effect of thermal bridging on walls can be significantly reduced by introducing as many air gaps or holes as possible into the block or wall unit, which significantly improves the thermal resistance of masonry walls. six types of concrete wall units have been produced: The thickness of the Cover is 30, 35, or 40 mm. The basic idea behind using cavities within the blocks is to create a heat flow path through the wall. As a result, the thermal conductivity values of the models must be calculated and compared.

3. Research objectives

The study focused on developing lightweight concrete blocks with different hole configurations to enhance thermal performance. This approach aligns with the findings of Yousefi et al. (2020), who demonstrated that incorporating lightweight materials with low thermal conductivity—such as recycled expanded glass aggregate—into cement-based composites can significantly improve thermal insulation while maintaining adequate mechanical strength. Similarly, the current study aims to offer a cost-effective solution by utilizing lightweight base materials and optimized cavity designs to reduce thermal conductivity and improve the overall energy efficiency of building components. [3].

Lightweight materials can be used as raw materials, sourced from natural resources, or derived as industrial by-products. Despite their favorable properties—such as reduced weight and excellent thermal insulation—lightweight concretes (LWC) typically exhibit lower mechanical strength, limiting their application to non-load-bearing walls. Many of these lightweight materials originate from waste streams and are often discarded without beneficial reuse. The development of LWC blocks using such waste or by-product materials as lightweight aggregates presents a sustainable approach with dual advantages: it reduces construction costs and provides an environmentally responsible method for managing waste.

This approach is supported by the findings of Solikin et al. (2019), who investigated the use of high-content Styrofoam as a partial substitute for fine aggregate in self-compacting lightweight concrete bricks. Their study demonstrated that waste materials like Styrofoam can effectively contribute to the production of lightweight concrete with desirable insulation characteristics, reinforcing the concept of utilizing waste to create sustainable and thermally efficient construction materials [4].

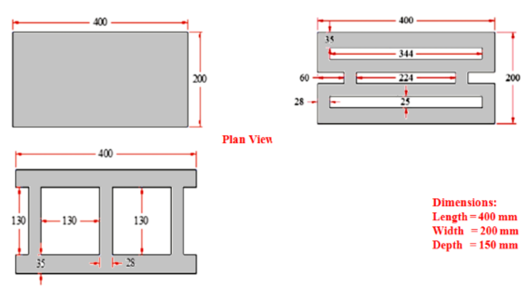

Fig. 1. Formation, size and dimensions of concrete blocks

4. Literature Review

There has been some LWFC study. Everyone agrees that LWFC offers benefits, such as outstanding fireproofing, thermal insulation, and sound insulation—lightweight, free-flowing, and resistant. LWFC may fill holes with no the need for vibrations because of her freedom of flow.

As a result, LWFC mixes have recently received approval for use in a variety of projects including wall constructions and void filling. Significant quantities of money, time, and effort are required. The outcome is kept as an intuitive one. LWFC exists for this reason. It is frequently seen as an affordable substitute for conventional concrete mixture.

There are some previous studies where the researcher did Mydin measured the thermal conductivity at foamed concrete with different densities of 650, 700, 800, 900, 1000, 1100, & 1200 kg /m3 using the Hot-Guarded Plate technique. elements that affect thermal conductivity. The results show that foamed concrete with a reduced density conducts heat less effectively [5]. The density for foamed concrete is determined by porosity, a lower density for spumed concrete indicates a higher porosity. Because of its molecular structure, air is less conductive than liquids and solids, which causes a drastic shift in the porosity for foam concrete. Heat conductivity thus undergoes a substantial modification [6].

Zhao et al. investigated the compressive strength and thermal insulation capabilities of foamed concrete made using granulated slag extracted from blast furnace slag. A 1300 kg /m^3 mass density foamed mortar was created. The ideal water-to-cement ratio of 0.56 was chosen. Two mix sample were made: one with cement with foam mortar (CFM) and the other with slag with foam mortar (SFM), in which slag was used to partially replace half of the cement weight. According to the experimental results, the foamed concrete's performance in terms of both its compressive strength and thermal conductivity might be improved by substituting 50% slag for cement [7].

According to Jalal et al., foam concrete's ideal strength makes it a viable alternative construction material for industrialized building systems. For a combination with a low density, the foam concrete There is hardly much strength. The increase in cavities created by foaming throughout the sample lowers the density of the concrete, which lowers the compressive strength. High levels of insulation from heat, freeze-thaw resistance. This is and fire protection are offered by foam concrete [8].

In a prior study, Mohammad Faisal Khalil and Eethar Thanon Dawood the Effects of Using Eco-friendly Materials for the Production of High Strength Mortar scientists assessed the impact of partially replacing ordinary Portland cement (OPC) with ecologically friendly mineral additives. These which included calcined clay (CC) silica fume (SF), & limestone (L), in the manufacturing of high-strength mortar (HSM), By preserving natural resources and lowering carbon dioxide emissions, the use of these materials helps to lessen the environmental effect of cement manufacture. Using super plasticizer (SP) type G various mixtures were created by increasing the binder's ratio and reducing the water-to-binder ration (w/b) in order to reach the necessary strength. The blended cement's strength and mechanical behavior were assessed, and the findings of tests on fluidity, strength, and mechanical behavior were used to establish the ideal combination. The findings demonstrated that the ideal mixture for the optimal mechanical characteristics in order to manage the mix's strength, Mix F32 is a combination of 8% SF, 4% L, and 13% CC with an approximate 35% increase. According to the study's findings, using CC, SF, and L in part instead of OPC can enhance the mechanical, durability, and service life of contemporary concrete/mortar mixes. Future research on design of concrete mixes can build on the findings of this study [9].

The researchers also Ahmed Radhi Taha and Dr. Alyaa Abbas Al-Attar and Hasan Mohammed Ahmed by studying The impact of various limitations on the compressive strength for geopolymer concrete made of fly ash mixes optimized by the Taguchi technique using the Minitab program is shown in this research. Finding the ideal ratios that might result in the highest compressive strength for geopolymer concrete is the main objective. The impact of the addition for Alkali-Activator for the ratio of binder (AA/B), the concentration of NaOH (M), the effects of Na_2SiO_3 for NaOH ratio (SS/SH), and the influence of binder contents (B) were evaluated for a total of twenty geopolymer concrete combinations with five mixtures of regular concrete.

This study employed a range of molarities, including 8, 10, 12, 14, & 16. In order to create geopolymer concrete, flay ash is utilized as a waste material in the following ratios: 15, 17.5, 20, 22.5%, and 25%. It is replaced with 90% regular Portland cement. Additionally, sodium hydroxide and sodium silicate are used in ratios of 1, 1.5, 2, 2.5, & 3. Sodium silicate, hydroxide of sodium, and water were combined in the following ratios to create the alkali activator: 0.3, 0.35, 0.4, 0.45, & 0.5. In place of regular coarse aggregate with diameters of 19 mm, fine aggregate, one kind of local crushed coarse aggregates was utilized. Compressive strength is a mechanical characteristic that has been explored. According to the results, the geopolymer concrete demonstrates When the alkali-activator for binder ratio was 0.45, the NaOH concentration was 16, the alkali-activator / binder ratio was 1, and the binder content was 25%, the maximum compressive strength was achieved. Additionally, the results indicated that as curing age increases, compressive strength increases. The microstructure of geopolymer concrete was assessed using scanning electron microscopy [10]

The researchers also Eethar Thanon Dawood and Alyaa Abbas Alattar and Waleed Abdulrazzak Abbas and Yahya Ziad Mohammad, conducted a study The behavior is concrete with foaming reinforced with one or both carbon and polypropylene fibers under high temperatures is illustrated in this work. To strengthen the foamed concrete mix, different volumetric percentages of carbon fiber (0.5, 1, and 1.5%) were utilized. Additionally, 1%CF + 0.5% PPF with 0.5%CF + 1% PPF hybrid fibers were made using carbon fibers (CF) with polypropylene fibers (PPF). Finally, the foamed concrete mix was reinforced with mono polypropylene fibers at a 1.5% PPF content.

The compression strength, splitting tensile and flexural strength, and flexural toughness tests were performed on these various mixtures. In addition, the samples were heated to several temperatures—200, 250, 300, 350, and 400 °C—to complete the heating process. The findings showed that when the temperature rose, lightweight foamed concrete's (LWFC) compressive & flexural tensile strengths dropped. However, after the temperature reached 400 °C, the strongest effects of these strengths were apparent. Because polypropylene fiber has a low melting point, LWFC mixes reinforce with it are more susceptible to high temperatures as LWFC mixes reinforce with carbon fiber **[11]**.

Table 1. Typical properties of LWFC [12]

Dry Density (kg/m^3)	Compressive Strength (MPa)	Thermal Conductivity (W/mK)	Modulus of Elasticity (GPa)	Drying Shrinkage (%)
400	0.5--1.0	0.1	0.8---1.0	0.3--0.35
600	1.0--1.5	0.11	1.0---1.5	0.22--0.25
800	1.5--2.0	0.17--0.23	2.0--2.05	0.20--0.22
1000	2.5--3.0	0.23---0.3	2.0---3.0	0.18--0.15
1200	4.5--5.5	0.38--0.42	3.5---4.0	0.11--0.09
1400	6.0--8.0	0.5--0.55	5.0--0.6	0.09--0.07
1600	7.5--10	0.62--0.66	10---12	0.07--0.06

Table 2. Density Classification Requirements (C129 – 17) [13]

Density Classification	Density Classification Oven-Dry Density of Concrete, lb/ft^3 (kg/m^3) Average of 3 Units
Lightweight	Less than (1680)
Medium Weight	than (1680 to 2000)
Normal Weigh	(2000) or more

5. Materials

In reference to the materials employed in this study, their functioning mechanism was understood and their qualities were examined and analyzed. The following lists the characteristics for the materials used to make foamed concrete:

5.1 OPC, or ordinary Portland cement

is the type of cement use all cement properties are in accordance with Iraqi Requirements No. 5/1984, which were adopted for this research [14].

5.2 Fine Aggregate

The sieve examination of fine aggregate, which had an acceptable maximum measurement of 4.75 mm that was reasonably priced in the local market, was done for this investigation. Table 3 lists a sieve analysis of sands in accordance with ASTM C330/C330M-14. [15], The fine aggregate had an absorption of 2.7% and a specific gravity of 2.63

Table 3. The Sieve Analysis of fine aggregate ASTM C136

Sieve size(mm)	Passing%	ASTM C330[15].
9.5	100	100
4.75	92	85-100
2.36	73	-
1.18	61	40-80
300	17	10-35
150	14	5-25

5.3 Mixing Water

During the experiments and specimen curing, all of the mixes were made using the standard (tap) water that was accessible in the Concrete Laboratory

5.4 Foam Agent

Cemairin F300, an insulating foam material made by DCP, was utilized. The substance was diluted by combining water with varying amounts of foam in accordance with ASTM C 796-97 [16] requirements. The material was then subjected to resistance, density, absorption, and insulating tests, and the best one was chosen, as seen in the Fig. 2.

Fig. 2. Weight and mix foam

Table 4. physical properties of foam [16]

Type of foam agent	Compound foam agent
Foaming ratio Wet densities (kg/m design dry grades(kg/m^3) >55	
Foaming densities (kg/m^3)	40-60
Ph. value	7.04
Foaming bleeding rate	<20%
Increasing rate of wet density determined by defoaming test	<10%

6. Methodology

6.1 Lightweight Foam Concrete

In this study, unlike previous works, the focus is on developing concrete blocks with various cavity shapes and configurations, incorporating different foam dosages to enhance thermal insulation—an essential aspect of the current research. To formulate a lightweight foamed concrete mixture, a series of experimental trials were conducted by casting and testing samples after accurately determining the weights of sand and cement used in the mixes. The optimal mix was selected based on achieving the lowest possible density while maintaining adequate compressive strength and ensuring good workability and cohesion.

Seven different cement-to-sand ratios were tested (1:1.5, 1:1.6, 1:1.7, 1:1.9, 1:2.1, 1:2.3, and 1:2.5). Among these, the 1:2.5 ratio—with a cement content of 532 kg/m^3—was identified as the most suitable mix. To produce the foamed concrete, various dosages of foam agent were introduced into the selected mix to evaluate their effect on the physical and thermal properties of the resulting blocks.

Six foam concrete mixes (FC1–FC6) were prepared with varying foam agent dosages of 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 L/m^3. These dosages were incorporated into the concrete mixtures, which were subsequently cast, cured, and tested to evaluate their compressive strength, wet density, and water absorption, with the aim of identifying the optimal foam content. After several minutes of mixing in a mechanical mixer, the foamed concrete was poured into cast iron molds measuring 100 × 100 × 100 mm. Prior to casting, a thin layer of mineral oil was applied to the inner surfaces of the molds to facilitate demolding. The concrete was placed in layers, and each layer was compacted using a vibrating rod for no more than 10 seconds to ensure uniform consolidation.

The specimens were left in laboratory conditions for approximately 24 hours before being demolded. In accordance with ASTM C192 [17], the demolded samples were then submerged in a water curing tank maintained at a temperature of $23 \pm 1°C$ until the testing date. Based on the results of the tests conducted on the different mixtures, the optimum balance between density and compressive strength was determined. The resulting concrete was deemed suitable for use in non-load-bearing partition walls only, due to its limited structural capacity.

6.2 Foam Concrete Block

The FC3 mix, containing 2.0 L/m³ of foam, was selected for the production of six different types of foamed concrete blocks. It was observed that incorporating foam into conventional concrete leads to a reduction in compressive strength, proportional to the amount of foam added. Key properties such as age, porosity, dry density, and compressive strength of the foamed concrete were determined. Compressive strength is also affected by additional factors, including the water-to-cement ratio, curing method, type of filler, as well as the shape and size distribution of air voids.

Once the optimal mix proportions were established through a series of trial mixes, primary concrete blocks with dimensions of 200 × 200 × 400 mm were cast using cement–sand mortar incorporating the selected foam dosage. Internal cavities were formed within the blocks to enhance thermal insulation. To ensure uniform filling and minimize air entrapment caused by the foaming action, the mixture was thoroughly compacted during casting. This helped eliminate air bubbles and ensured that all voids were properly filled. After casting, the blocks were subjected to water curing by immersion in laboratory tanks maintained at a constant temperature of 23 °C for a period of up to four weeks, in accordance with standard curing practices. Fig. 3 illustrates the sequential stages involved in preparing and casting the foamed concrete mixture.

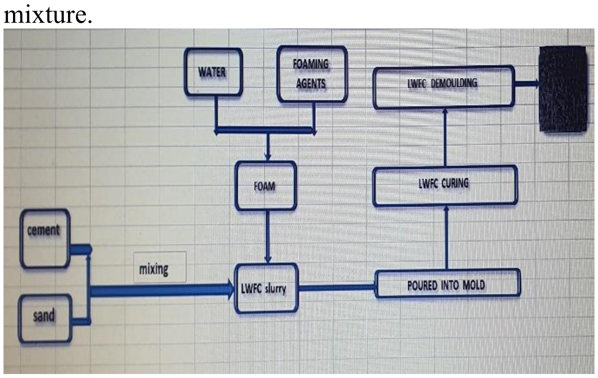

Fig. 3. Stages of preparing a lightweight concrete block model

Lightweight cellular concrete blocks, which are used to offer thermal insulation and are constructed as partitions inside structures rather than walls that bear loads, have a density ranging from 400 to 1800 kg/m^3[20]

Fig. 4. Details of the dimensions and shape of the cavities inside the concrete blocks

The density of foamed concrete is inversely related to its thermal resistance. The insulating performance of foamed cement was found to be comparable to that of conventional concrete. In one study, it was reported that introducing 23% air voids into concrete resulted in a 25% increase in thermal resistance, along with a reduction in dry density of approximately 100 kg/m³, which corresponded to a decrease in thermal conductivity by 0.04 W/(m·K) [18]. In the present study, thermal conductivity was measured in accordance with the ASTM C177 standard, as referenced by Medin [19].

7. Mechanical Properties of Concrete Blocks

In addition to the other variables that affect the calculation and information, such as the density, age, porosity in it water-to-cement ratio, a foam type, treatment, design, dimensions, type of gaps, and other factors, compression strength is a crucial component and has a significant impact on the lightweight concrete, also known as foamed concrete Through the work we noticed that the mixture of fine sand and evenly distributed pores had better compressive strength, and the compressive strength of the mixture of coarse sand with irregular pores was lower Fine sand is properly dispersed between air spaces to make foamed concrete Results were obtained regarding the conductivity of lightweight foamed concrete's mechanical and thermal qualities as well as the impact of the type of cavities that were employed inside the formwork six varieties of lightweight concrete(B0, B1, B2, B3, B4, B5 and B6). which has a density of 800–1200 kg/m^3, for non-load-bearing walls. According to IQS 1129 Specifications for Non-Load-Bearing Hollowed Building Unit and ASTM C-129 [21]. Standards, gaps of various sizes and dimensions are created during casting.

8. Direct Thermal Conductivity Method

Concrete blocks were fabricated and cured prior to conducting thermal conductivity tests. The evaluation process commenced approximately 14 days after curing. The experimental setup for measuring thermal conductivity consisted of a thermometer, a test specimen holder insulated with glass wool, and a heating element. The test procedure involved applying heat to one side of each concrete block specimen, with temperature readings recorded at different time intervals due to the variation in block configurations and the staged nature of the test. Measurements were taken at three key intervals: after 3 hours (initial reading), after 6 hours (intermediate reading), and after 12 hours (final reading). The 12-hour reading was found to be the most representative of real-world conditions, as it coincided with stabilized temperatures and moderate ambient conditions. During testing, the temperature gradient applied across the specimens ranged between 75°C and 300°C per hour.

According to Calisher and Rethwisch 2007 [22] and Halliday, Walker and Resnick54-2010 [23], and to the Fourier rule, the rate of heat transference and heat resistivity at every hour can be determined by applying the formulas K according to the following:

$$K = (Q \times d) / (A \times t \times \Delta T) \quad (1)$$

$$Q = m \times c \times \Delta T \quad (2)$$

Fig. 5. Direct thermal conductivity method
(a)Convection oven
(b)Thermometer

Table 5. Concrete Blocks Compressive Strength

Blocks	Dry Density Kg/m^3	Absorption %	Compressive Strength. Mpa 14 day
B0	1670	18.56	4.50
B1	972	6.98	2.03
B2	1012	11.90	1.74
B3	1305	3.90	1.44
B4	1050	9.70	2.31
B5	1198	5.78	1.96
B6	942	8.40	1.21

At 14 days of age, concrete blocks made with liquid foam showed varying compressive strengths depending on cavity geometry, foam content, and water-to-cement (w/c) ratio. The solid B0 model, with no cavities, achieved the highest strength (4.5 MPa), while hollow models (B1–B6) ranged from 1.21 to 2.31 MPa. According to ASTM C90 standards, mixes B1, B4, and B5 exceeded the 1.7 MPa minimum required for lightweight structural blocks. Mixes B3 and B6, though lower in strength, remained within acceptable limits (≥1.2 MPa) for non-structural thermal insulation use.

The B3 mix, despite a high density of 1305 kg/m³, showed relatively low strength (1.44 MPa) due to poor foam distribution and increased porosity. This highlights the weakening effect of excessive foam content. In contrast, B4, with circular cavities, achieved the highest hollow block strength (2.31 MPa at 1050 kg/m³), benefiting from efficient load distribution and reduced stress concentrations. Mix B1 also showed good strength (2.03 MPa) due to a low w/c ratio and better paste bonding.

These results align with previous research, confirming that porosity, foam ratio, and cavity shape significantly affect mechanical performance. Overall, mixes B1, B4, and B5 provide an effective balance of weight, insulation, and structural performance, while B6 is more suitable for interior or non-load-bearing applications.

Depending on the cavities design, density, and composition, temperature readings taken after 3, 6, and 12 hours of thermal exposure show a noticeable variation in thermal performance of blocks of concrete made with liquid foam. After 12 hours, the conduction temperature of model B0 was the highest and the absorption rate was the highest value because the model was solid and k is also high did not contain cavities filled with polystyrene compared to the other models, followed later by models B1 to B6 which contain cavities filled with polystyrene.

Table 6. Thermal Conductivity of Concrete Blocks

Block	Size of voids %	Temperature After 3 Hour	Temperature After 6 Hour	Temperature After 12 Hour	K-Value
B0	0.00	67.00	78.00	91.00	1.30
B 1	50%	30.60	35.80	34.10	0.80
B 2	46%	35.60	40.40	36.30	0.90
B 3	32%	33.00	36.50	38.50	1.07
B 4	28%	39.00	42.00	41.00	0.84
B 5	20%	42.40	45.00	43.00	0.92
B 6	60%	40.40	43.00	41.00	0.93

The variation in heat conductivity (K-value) of blocks of concrete with various internal geometries and void ratios is shown in Table 5. The findings show a direct correlation between each model's thermal performance, void size, and the quantity and thickness of thermally bridges. Direct passage for heat through a solid construction is demonstrated by Block B0, which has the maximum thermal conductivity value (1.30 W/m·K) and no internal cavities. Block B1, on the other hand, has the low K-value (0.80 W/m·K) due to its 50% voids and evenly distributed interior arrangement that is filled with insulation (polystyrene). The existence of gaps that break thermal bridges and impede heat transport is responsible for this considerable decrease.

In models B2 through B5, the K-value rises in proportion to the decrease in the void percentage, suggesting that thicker thermal bridges and smaller voids lead to increased thermal conductivity. Blocks B5 (20% voids) achieves a K-value of 0.92 W/m·K, whereas Blocks B2 (46% voids) is a K-value for 0.90 W/m·K. Interestingly, Block B4 achieves a reasonably low K-value (0.84 W/m·K) while having only 28% voids.

This suggests that void geometry and orientation, as well as decreased thermal bridge connection, are important factors. Unexpectedly, Block B6, which has the highest vacancy ratio (60%) has a K-value for 0.93 W/m·K. This can be explained by the possibility that structural reinforcements or inefficient void arrangement will result in an increase of thermal bridges, upon further investigation of the B6 model, which contains curved and irregular-shaped voids, the unexpected increase in thermal conductivity—despite the larger void volume—can be attributed to inefficient distribution of insulation material (polystyrene) and the geometry of the voids. The curved voids in B6 may have allowed for more direct heat transfer paths through the solid concrete portions, creating thermal bridges that bypass the insulation. Additionally, the complex shape likely caused gaps or incomplete contact between the insulation and the concrete surface, reducing the insulation's effectiveness. As a result, the intended interruption of heat flow was compromised, leading to higher thermal conductivity compared to other models with more regular void geometry. In conclusion, the data confirm that the distribution, shape, and configuration of voids, as well as thickness and continuity of thermal bridges, all affect ideal thermal performance in addition to the proportion of voids.

. The following is how the B1 model's insulation ratio was calculated:

$$\text{Insulation} = (1 - T\ \text{Surface} \ / T\ \text{Source}) \times 100 \quad (3)$$

$$(1 - 34.1 / 300) \times 100 = 88.63\%$$

When it comes to mechanical, thermal, and weight qualities, B1 is regarded as the best overall. It has best heating performance (insulation ratio = 88.6%), low density, and an acceptable strength at compression (2.03 MPa) [25].

The blocks compressive strength results fall within ASTM C90[24]. minimum permissible limits (≥ 2.0 MPa at non-load-bearing block). Additionally, absorption rates fall within the permissible ranges established by international standards, which are normally less than 12%. Comparing the thermal performance to traditional concrete, it is good [26].

9. Conclusion

This study aimed to investigate the mechanical and thermal behavior of concrete blocks enhanced with foam insulation, focusing on how foam content and internal cavity shapes affect performance. The results clearly demonstrate that incorporating foam at a content of 2.0 l/m³ leads to a significant reduction in density without compromising compressive strength, which remained within acceptable limits defined by ASTM C90 for non-load-bearing blocks (≥ 2.0 MPa). However, when the foam content exceeded 2.5 l/m³, the mechanical integrity of the blocks declined substantially, aligning with previous findings by Al-Jabri et al. (2012) and Jones & McCarthy (2005), who reported a sharp decrease in compressive strength as foam volume increased due to the excessive entrapped air reducing the solid matrix continuity.

In terms of geometry, the study revealed that hollow concrete blocks with open square or circular voids, particularly Model B1, achieved superior performance. The square-shaped cavities in B1 not only optimized weight and absorption but also improved insulation, especially when combined with 2.0 l/m³ foam and polystyrene inserts. Similar conclusions were drawn by Khan et al. (2016), who showed that void shape significantly influences both thermal and structural performance, with symmetrical voids (square/circular) distributing stresses and thermal resistance more evenly than irregular or solid configurations.

Regarding thermal performance, this study found that the surface temperature of Model B1 stabilized at 34.1°C after 12 to 24 hours of exposure to a 300°C heat source, indicating a thermal insulating rate of approximately 88.6%. While this is a notable improvement over traditional concrete blocks, which recorded higher surface temperatures and thermal conductivity, it is slightly less efficient than some results reported in the literature. For instance, Serrano et al. (2020) achieved insulating efficiencies above 90% in aerated concrete blocks with microcellular foam and Nano-additives. Nevertheless, the insulation rate achieved in this study remains competitive and practically significant, especially given that the blocks maintain structural compliance.

In terms of thermal conductivity, the B1 model exhibited a K-value of 0.80 W/m·K, whereas prior studies on foamed concrete (FC) reported values as low as 0.34 W/m·K under optimal lab-controlled conditions and with highly porous structures (Awang & Mydin, 2014). However, many of those studies involved non-structural elements or used higher foam contents that sacrificed compressive strength. The current research strikes a balance by maintaining both acceptable mechanical performance and a significant 34.1% improvement in thermal insulation compared to standard concrete.

Economically, a life cycle cost comparison showed that foamed concrete incurs approximately 26% higher initial cost than Ordinary Portland Cement (OPC) concrete. This increase is attributed to its superior thermal insulation, lower water absorption, and adequate mechanical strength. production cost (82,000 IQD vs. 65,000 IQD per m² for traditional concrete), the long-term energy savings due to reduced heat transfer justify the investment, particularly in energy-efficient and environmentally sustainable construction projects. These findings support the argument presented by Kersley & Wainwright (2001), who emphasized the long-term cost-effectiveness of lightweight, thermally insulated concrete despite higher initial costs.

In summary, while the thermal insulation rate of 88.6% may be marginally lower than that of some advanced studies using aerated or Nano-enhanced materials, it remains highly effective given the realistic materials, cavity design, and conservative foam dosage. The compressive strength of 2.03 MPa is also well-aligned with similar research using low-density concrete with moderate foam content, ensuring the practical applicability of the results. The trade-off between structural reliability, insulation efficiency, and economic feasibility in this study represents a balanced and applicable solution for sustainable construction practices

10. Recommendations

While this study has successfully demonstrated the thermal and mechanical performance of lightweight insulated concrete blocks—particularly Model B1—there remain several key areas that warrant further investigation to enhance the applicability and innovation of such materials in sustainable construction.

First, it is recommended to select and optimize Model B1 as a standard prototype for non-load-bearing, thermally insulating concrete blocks in energy-efficient and green building applications. Future studies should evaluate its performance over extended periods in full-scale wall assemblies to determine real-world insulation effectiveness, durability, and behavior under fluctuating environmental conditions.

Second, there is a need to conduct time-dependent evaluations of insulation performance under various climatic scenarios. This includes accelerated aging tests, repeated heating–cooling cycles, and long-term exposure to humidity and UV radiation, which can help simulate different geographic and environmental settings. These assessments will provide a more robust understanding of material stability and long-term thermal resistance in practical applications.

Third, numerical modeling techniques such as Finite Element Modeling (FEM) should be employed to simulate and predict heat transfer behavior in blocks with novel cavity geometries—including hexagonal, pyramidal, or biomimetic shapes inspired by nature. This approach enables optimization of cavity configurations for enhanced insulation while maintaining structural integrity and minimizing material usage. Advanced simulations can reduce the need for extensive physical prototyping and guide experimental validation.

Fourth, it is essential to integrate environmental and acoustic considerations into future research. This includes testing the VOC (volatile organic compound) emissions of insulation materials—especially foams and polystyrene—and assessing their sound insulation properties. Such data will support the design of multi-functional blocks that not only limit heat transfer but also improve indoor acoustic comfort and meet indoor air quality standards, making them ideal for residential and educational buildings.

Additionally, investigating the compatibility of these blocks with renewable energy systems, such as solar-integrated walls or phase change materials (PCMs), could open up avenues for passive energy management. Incorporating recycled or bio-based materials as part of the concrete or insulation mix can also align the research with circular economy principles.

In conclusion, future research should adopt an interdisciplinary approach—combining materials science, thermal modeling, environmental engineering, and building physics—to develop high-performance, eco-friendly, and economically viable insulating block systems suitable for the evolving demands of modern construction.

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