Journal of Engineering and Sustainable Development
Vol. 30, No.02, March 2026
https://jeasd.uomustansiriyah.edu.iq/index.php/jeasd
ISSN 2520-0917
Research Article
https://doi.org/10.31272/jeasd.3084

Production of Heat-Insulating Concrete Hollow Block

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Article Info

Received	**11/10/2024**
Revised	**07/01/2026**
Accepted	**18/01/2026**

Abstract

Hollow concrete blocks are primarily used in residential buildings, factories, and multi-storied construction. The main goal is to produce a new insulation block from lightweight concrete by mixing light expanded clay aggregate (LECA) at a specified weight percentage with gravel. A trial-and-error method was used to determine the mixture ratio (cement: sand: lightweight aggregate) of (1:1.75:3.25) by weight, with a water-to-cement ratio of 0.48. Cubic, cylinder, and block samples were prepared with various volume proportions of LECA by natural coarse aggregate in percentages of (0, 50, and 75) %. Mechanical and physical properties, such as compressive and tensile strengths, density, and thermal conductivity, were investigated at ages 7, 14, and 28 days. The test results show that incorporating LECA reduces the density and compressive and tensile strengths, and enhances the blocks' insulating characteristics. Additionally, the thermal conductivity of the prepared specimens decreased by approximately 57% in blocks containing 75% LECA. The results are promising and indicate that the present insulation block can be used in composite slabs.

Keywords: Insulation hollow block, Light expanded clay aggregate, Lightweight aggregate concrete, Thermal conductivity

1. Introduction

Hollow concrete blocks are defined as large rectangular bricks that have a void greater than 25% of the total area. Concrete hollow blocks are produced by pouring concrete, i.e., Portland cement, sand, and small-size gravel, with sufficient water content to produce a dry-mixed mixture. It reduced cement content in masonry work and construction costs. Hollow concrete blocks are known for their low weight, which reduces the structure's dead load. Hollow block has many advantages, such as low energy consumption in production, a broad range of raw materials, avoidance of fired bricks and destruction, lower pollution, and the use of manufacturing waste, among others. In this article, procedures to enhance the thermal insulation performance of concrete hollow blocks are studied. [1]

Since the concrete block has lower thermal resistance than ceramic blocks, as mentioned in ABNT NBR 15220-3 [2], the concrete block thermal conductivity is (1.75 W/m^2.k), while equal to (0.90 - 1.05 W/m^2.k) for the ceramic block. Therefore, the use of concrete blocks in construction significantly affected employers' thermal comfort indoors.

Concrete blocks have poor thermal resistance. But their thermal performance improves by making these hollows.

Harmon S. Palmer designed the first hollow concrete block in the United States in 1890 and continued experimental research for an additional 10 years, obtaining a patent for the design in 1900. The block size was (20.3 x 25.4 x 76.2) cm³. The blocks were so heavy, and they were cast by hand [3]. A block has one or more large holes or cavities, and the solid material between (50 – 75) percent of the total volume of the block. A hollow block has two faces: the outer and the interior. When solar rays strike the hollow block's outer face, the heat-transfer environment differs due to the void within the block, which provides thermal insulation [4].

The compressive strength of masonry depends on several factors, including block size, mix proportions, materials, and the replacement of fine or coarse aggregate with waste materials. (20x20x40) A cm-sized block produced with a 1:2:0.5 proportion showed good compressive strength. A block with the same dimensions, but with the aggregate replaced with vermiculite, reduced the compressive strength by approximately half. On the other hand, using waste materials helps protect the environment from pollution [5].

Caruana et al. [6] used perlite as an insulating material to produce hollow concrete blocks and compared them with traditional hollow concrete blocks in terms of thermal insulation and compressive strength. Two methodologies have been adopted to determine the thermal performance (U-value) of the blocks: the heat-flow meter method and the infrared method. Researchers developed an innovative hollow block with a U-value 10% lower than that of traditional hollow blocks, without reducing the minimum specific compressive strength.

Chaure et al. [7] examine the effects of compaction methods on the performance of hollow concrete blocks. Blocks manufactured with fine granite particles as an additive achieve optimal packing and enhance cement particle dispersion, resulting in a good edge finish and surface. The results clearly indicate that proper compaction techniques improve performance and increase the compressive strength of hollow concrete blocks. Blocks prepared using uniform hand compaction exhibit greater compressive strength than those compacted with machine vibration. A 25% replacement of fine aggregates with granite fines yields optimal results; however, the strength of concrete blocks decreases with increasing granite-fine content.

Khan [8] studied the insulating properties and the possibility of increasing strength by using different cavity shapes (rectangular and circular) and by partially replacing cement with fly ash. Results showed that cavities with a circular shape exhibited better thermal insulation than rectangular cavities, whereas compressive strength was lower than that of the solid block. Additionally, incorporating fly ash into the concrete mix increased compressive strength and thermal insulation. Moreover, replacing cement with fly ash produces an environmentally friendly hollow concrete block.

Lu et al. [9] used a nonlinear FE model to analyze slender unreinforced masonry hollow blocks under eccentric vertical loads, focusing on the cavity depth of the blocks. Using a damage model led to an acceptable estimation of the failure mechanisms of hollow masonry. Legemann et al. [10] presented the evolution of inserting corn stalks into the spaces of concrete masonry blocks to reduce weight and improve thermal insulation. Researchers found that concrete block cavities filled with corn stalks have positive effects on catch temperatures.

Fogiatto [11] aims to obtain thermal transmittance values for various hole configurations of concrete masonry units. They concluded that larger holes yield higher transmittance and that the influence of rays can affect heat transfer from side to side within the concrete hollow block.

Ye and Zhou [12] calculated the coefficient of thermal insulation of small concrete hollow blocks by numerical and theoretical methods. The effect of hole type was that rectangular holes exhibited better insulating performance than elliptical, circular, parallelogram, and triangular holes. In addition, reducing the hollow rate can improve thermal insulation performance. The results provide a valuable reference for assessing block producers.

Light Expanded Clay Aggregates (LECA) are artificial lightweight aggregates that have a wide range of applications. The utilization of expanded clay aggregates (ECA) in concrete increases thermal and sound insulation, fire resistance, and workability. On the contrary, its incorporation reduces density, strength, elastic modulus, and resistance to freeze-thaw action of concrete [13].

An insulating block could be used as an alternative to the standard hollow concrete block. It offers significant thermal insulation performance as an insulated core with good load-bearing capacity, while maintaining a slimmer profile, thereby saving valuable space in the building. The most common insulators (Cork), which are taken naturally from the cork tree, or can be made industrially from petroleum products, which is called Expanded Polystyrene (EPS), are used as acoustic and thermal insulators [14].

Yew et al. [15] studied the effect of replacing coarse aggregates with ECA on the properties of concrete. The percentages of replacement were (50 – 90) %. The researchers concluded that the density of concrete decreased with increasing replacement percentage. While workability, compressive, tensile, and flexural strengths decrease with increasing LECA content, a 70% replacement of coarse aggregates with expanded clay aggregates yields the highest values.

Rao et al [16] experimented with the strength of lightweight concrete produced by substituting (ECA) for coarse aggregate and fly ash for cement. The lightweight concrete produced with 25% to 35% replacement of aggregates was lighter and had the same strength as traditional concrete. Moreover, the addition of fly ash and ECA increased workability, as their spherical, fine particles improved workability.

Ayati et al [17] reviewed the properties of clay from which the lightweight aggregates were made. The porous structure of clay affects the strength, density, and water absorption of concrete. Using high temperatures during LECA production created continuous holes, thereby increasing aggregate porosity. Slow cooling of LECA during production also improved its crushing strength.

Kumar and Prakash [18] investigate the feasibility of using LECA to replace coarse aggregate in producing structural lightweight concrete of M20 grade. Results showed that LECA can replace the normal coarse aggregate to decrease the weight by 60%, but the strength decreases. Replacing 20% of cement with slag (GGBS) and 40% of LECA resulted in compressive strength values that were almost comparable to those of normal aggregate concrete. Moreover, there was a noteworthy cost reduction.

Lightweight concrete blocks made with Leca granules are an important component of the construction industry today due to their ease of transportation and installation. Leca concrete building units offer flexibility in design and achieve tangible savings by reducing dead loads, increasing the distance between piles, improving fire resistance, as well as reducing the size of the structural section, better response to earthquake resistance, and then increasing the safety factor due to better behavior of the structural system [19]. LECA is made from the treated clay in a rotary kiln at a high temperature, and organic compounds are present as a result of burning. Due to combustion, balls formed and spread from the structure, but each granule's external surface liquefied and then solidified. The product is clay balls with high anti-fracture strength and low porosity. Moreover, it is environmentally friendly [20], [21].

There are various uses of Leca as a coarse aggregate in producing lightweight concrete blocks. This type of block is used in retaining partitions, foundations, and other construction uses. LECA is an inorganic material. Blocks made with LECA provide protection against both dry and wet rot and against worm infestations or destruction [22]. Rashad [23] reviewed the LECA properties used as coarse and fine aggregates in concrete. Despite the higher water absorption of LECA, concrete workability increased with increasing content of pre-wetted LECA. Moreover, LECA decreases segregation, creep, shrinkage, and density. Additionally, as the ECA content increased, the concrete strength decreased. The aim of this work is to develop a building material with greater heat-transfer resistance than traditional construction materials. In particular, hollow concrete blocks are widely used in the construction sector in Iraq.

2. Material

2.1. Cement

Iraqi Standard No. 5-2019 [24] was used to test the physical and chemical properties, as shown in Tables 1 and 2. The results showed that the cement used conforms to Iraqi Specification No. 5-2019.

Table 1. Physical properties for cement.

Properties	Content %	Iraqi Standard No.5-2019 limits [24]
Fineness (m^2/kg)	315	≥ 250
Initial Setting (min)	70	≥ 45 min
Final Setting (min)	305	≤ 600 min
Compressive strength (MPa)		
2 days	23.5	≥ 10
28 days	35.4	≥ 32.5

Table2. Chemical properties of cement.

Oxides	Content %	Iraqi Standard No.5-2019 limits [24]
CaO	62.5	
SiO_2	21.4	
Al_2O_3	4.5	
Fe_2O_3	3.8	
MgO	2.5	≤ 5
K_2O	0.7	
Na_2O	0.3	
SO_3	2.4	≤ 2.5
Loss on Ignition	1.2	≤ 4
Insoluble Residue	0.55	≤ 1.5

2.2. Fine aggregate

Natural sand with a maximum size of 4.75 mm was used. The results show that sand from zone 3 conforms to Iraqi Specification No. 45-1984 [25]. Grading of sand is shown in Table 3.

Table 3. Grading of sand.

Sieve Size (mm)	Passing %	Iraqi Standard No.45-1984 limits [25]
10	100	100
4.75	97	90-100
2.36	90	75-100
1.18	74	55-90
0.600	64	35-59
0.300	23	8-30
0.150	4.5	0-10

2.3. Coarse aggregate

Gravel is used in all work with a maximum size of 9.5 mm. Results show that gravel conforms to Iraqi Specification No. 45-1984 [25] with a specific gravity of 2.68 and a density of 1653 (kg/m^3). Grading of gravel is shown in Table 4.

Table 4. Grading and properties of gravel.

Sieve Size (mm)	Passing %	Iraqi Standard No.45-1984 limits [25]
14	100	100
10	92.6	85-100
5	19	0-25
2.36	0	0-5

2.4. Light expanded clay aggregate (LECA)

LECA was a private kind of aggregate produced by heating clay to a temperature of 1100-1200 °C in a rotary kiln to have a light-weight globular shape and a soft surface that contained several cavities. The chemical composition of LECA includes: Silica (SiO2), Alumina (Al2O3), Calcium Oxide (CaO), Magnesium Oxide (MgO), Iron Oxide (Fe2O3), and the PH (7-9), which typically refers to alkaline conditions. LECA properties are deeply affected by clay type, heating temperature, and the type of agent used to form pores [26]. The LECA has been used in all experimental work, with a maximum size of 10 mm. The grading and properties of LECA were performed and are shown in Tables 5 and 6.

Table 5. Grading of LECA.

Sieve Size (mm)	Passing %	ASTM C332-17 limits [27]
12.5	100	100
9.5	88.6	80-100
4.75	9.4	5-40
2.36	3.3	0-20
1.18	1.1	0-10

Table 6. Properties of LECA.

Physical Properties	Test Results
Max. size (mm)	10
Specific gravity	0.50
Dry density (kg/m^3)	402
Absorption (%)	18

3. Experimental Program

The production of concrete blocks comprises the following basic procedures: proportioning, mixing, casting, curing, and storage until testing. The experimental program involved developing three concrete mix designs with varying percentages of lightweight expanded clay. The trial-and-error method has been used to determine the appropriate mixing ratio. (1: 1.75: 3.25) for cement: sand: gravel, respectively, by weight, and a water/ cement ratio equal to 0.48. The experimental program was summarized in Fig. 1.

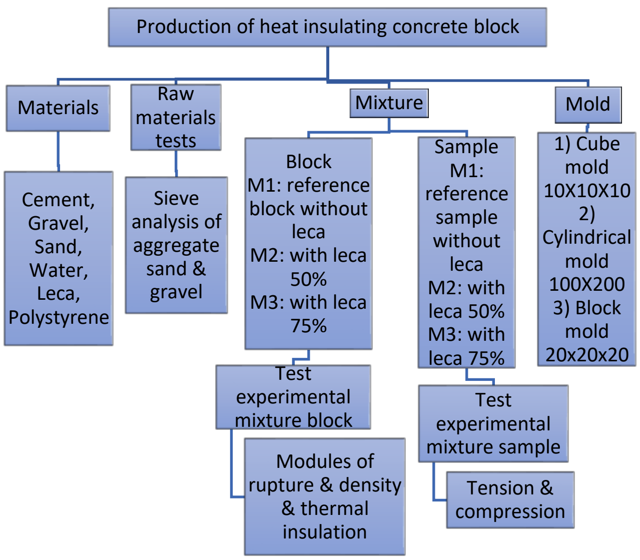

Figure 1. Flow chart for experimental work.

Fig. 2 shows the molds and specimens (cubes, cylinders, and blocks) prepared by replacing LECA with natural coarse aggregate at 0, 50, and 75% by weight. In addition to tests on the raw material, the mechanical and physical properties of concrete specimens and blocks, such as compressive strength, tensile strength, modulus of rupture, density, and thermal conductivity, were investigated at ages 7, 14, and 28 days. All tests were conducted in accordance with standard specifications.

4. Results and discussion

4.1. Concrete test results

4.1.1 Density

The dry and fresh densities of concrete mixtures studied are mentioned in Table 7. For the mix without LECA (M1), the fresh density (1 day) was 2390 kg/m^3, which decreased to 2250 kg/m^3 at 28 days. Simultaneously, both densities of the mixture with LECA decreased with LECA incorporation. This is because the void percentage increases with increasing LECA content. Moreover, all densities range from 2000 kg/m^3 to 1650 kg/m^3; hence, it can be characterized as a lightweight concrete [28]. Fig. 3 illustrates the relationship between fresh and dry densities at 28 days for concrete mixtures with and without LECA.

Figure 2. Molds and concrete hollow specimens.

Table 7. Density of concrete specimen.

Density (kg/m^3)	M1	M2	M3
Dry density	2250	1850	1650
Fresh density	2390	2000	1820

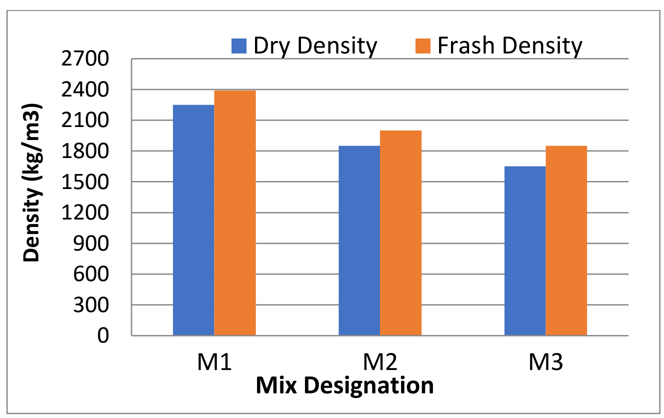

Figure 3. Density of concrete specimens.

4.1.2. Compressive strength

Table 8 presents the cube's compressive strength for the M1 mix in the absence of LECA and for 50% and 75% LECA at curing ages of 7, 14, and 28 days. According to Fig. 4, the 28-day compressive strengths are apparently higher than those at 7 and 14 days for all mixes. This is self-evident because strength increases with the formation of cement hydration products with age.

Table 8. Compressive strength test value.

Mix designation	LECA %	Compressive strength (MPa)		
		7 days	14 days	28 days
M1	0	6.95	13.72	17.79
M2	50	6.45	11.68	13.9
M3	75	5.9	10.77	11.25

Compared with 50% LECA in the reference mix, compressive strength decreases by 7.19%, 14.86%, and 21.86% at ages 7, 14, and 28 days, respectively. The percentage decrease in compressive strength with 75% LECA was 15.1%, 21.5%, and 36.76% at ages 7, 14, and 28 days, respectively. The percentage decrease in strength becomes greater as the LECA-to-coarse aggregate replacement ratio increases. This behavior aligns with findings reported by researchers [15], [29]. LECA's physical properties were responsible for this decrease. When compared with natural aggregates such as gravel, LECA exhibits high porosity and lower particle crushing strength, thereby reducing the strength of LECA lightweight aggregate concrete. The spherical shape of LECA, resulting from the rotary kiln effect, led to reduced mechanical interlocking with the cement matrix, unlike gravel. As a result, cracking typically initiates in the LECA aggregate due to its porosity. As noted earlier, the density decreases with the inclusion of LECA; consequently, compressive strength also declines. Fig. 5 shows the compressive strength-density relationship.

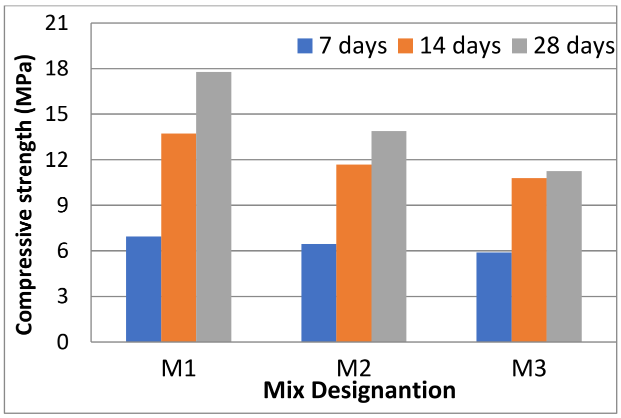

Figure 4. Compressive strength of concrete specimens.

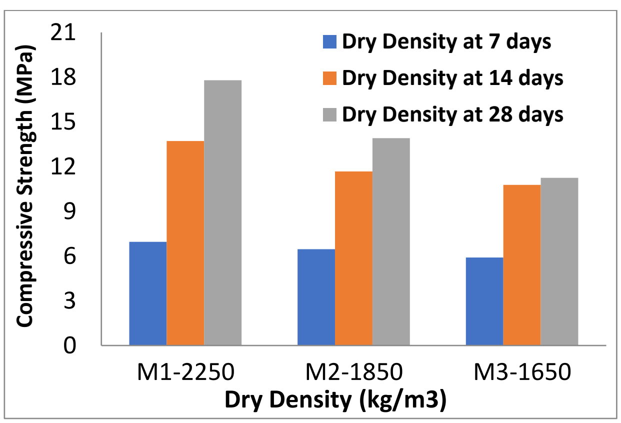

Figure 5. Relation of density versus compressive strength at ages 7, 14, and 28 days.

4.1.3. Split tensile strength

Results for the tensile strength of concrete mixtures for ages 7, 14, and 28 days are presented in Table 9. Tensile strength decreases with increasing LECA replacement percentage. According to Fig. 6, the rate of strength decrease becomes greater when the increase ratio of LECA used as a substitute for coarse aggregate. The tensile strength decreases with an increase in LECA from 50% to 75%. Compared with 50% LECA in the reference mix, tensile strength decreases by 3.2%, 4.1%, and 5% at ages 7, 14, and 28 days, respectively. The percentage reduction in tensile strength with 75% LECA was 8.1%, 9.7%, and 10.4% at ages 7, 14, and 28 days, respectively. This decrease in tensile strength was slightly smaller than the corresponding decrease in compressive strength over the ages.

Table 9. Tensile strength test value.

Mix designation	LECA %	Tensile strength (MPa) 7days	14day	28days
M1	0	1.24	1.44	2.4
M2	50	1.20	1.38	2.28
M3	75	1.14	1.3	2.15

4.2. Block test results

4.2.1. Density of blocks

The test results for block concrete show that concrete with 75% LECA has a lower density than concrete with 50%, which in turn has a lower density than concrete without LECA at 28 days. ASTM C129 [30] defined normal weight concrete block as a block with a density of more than 2000 kg/m3, while blocks that have densities between 1680-2000 kg/m3 are medium weight concrete blocks, and blocks whose densities are less than 1680 kg/m^3 fall within a category of light-weight concrete blocks. Therefore, according to this specification, the two types of blocks (M2 and M3) are classified as lightweight blocks, whereas control blocks (M1) are normal-weight blocks. An important consideration in measuring the concrete block density is the following: reducing weight improves operating conditions, facilitates handling, significantly affects the structure's dead load, and also affects the total construction cost.

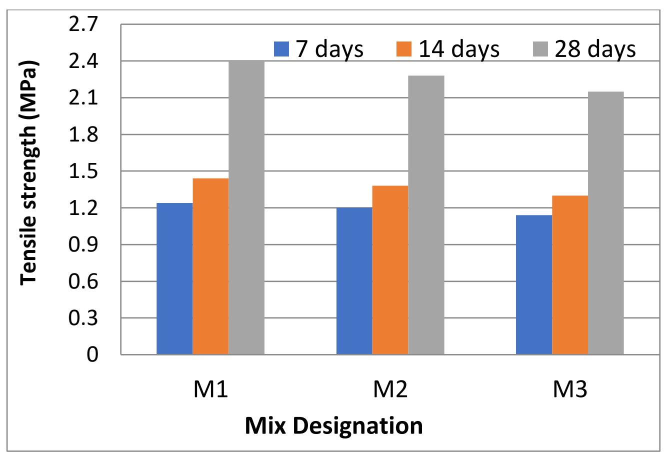

Figure 6. Tensile strength for concrete specimens.

Concrete blocks without substitution have a higher density than lightweight blocks because the ordinary aggregate is denser than the lightweight aggregate. Based on Table 10 and Fig. 7, the density decreases gradually with increasing LECA percentage. The reduction in fresh density at 28 days reaches 19.9% and 29.4% for 50% and 75% replacement of LECA, respectively. The decrease in dry density at 28 days is 22.3% and 31.5% for gravel replacement by LECA at 50% and 75%, respectively.

Table 10. Density of blocks.

Density (kg/m^3)	M1	M2	M3
Dry density	2152	1648	1473
Fresh density	2272	1818	1603

4.2.2. Compressive strength of blocks

After a curing period of 28 days, three blocks of each mix type were tested for compressive strength in accordance with ASTM C140 [31]. Fig. 8 illustrates the 28-day compressive strength of blocks for all mixtures. It's clear from the figure that the compressive strength decreases with the use of LECA. This is due to gravel being replaced by lightweight aggregate (LECA), which has a lower specific gravity (0.5) and lower strength. The most significant decrease in compressive strength was observed at a 75% replacement ratio, corresponding to 37.2. In contrast, the decrease was 22.6% at a replacement rate of 50%. As the compression test progresses on blocks, cracks form horizontally along the larger face of the block. These cracks appeared to be of a crushing type, leading to gradual spilling. All block types have a 28-day compressive strength greater than 4.14 MPa. Therefore, they all satisfied the requirement of specification ASTM C129 [30], which mentioned that the minimum compressive strength is 3.45 MPa for individual blocks, and more than 4.14 MPa for the mean of three blocks for non-load bearing blocks.

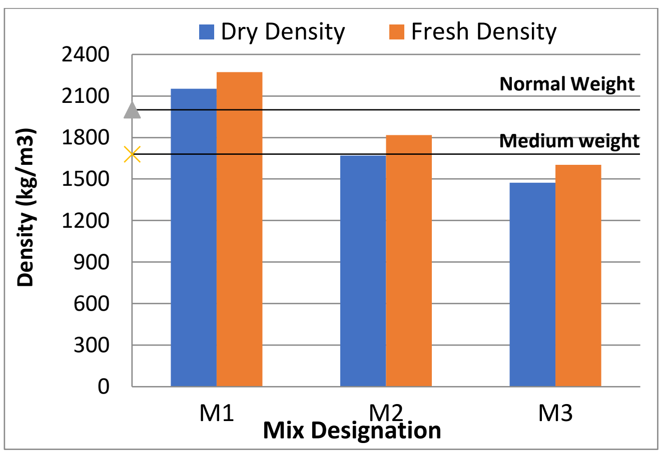

Figure 7. Density of concrete blocks.

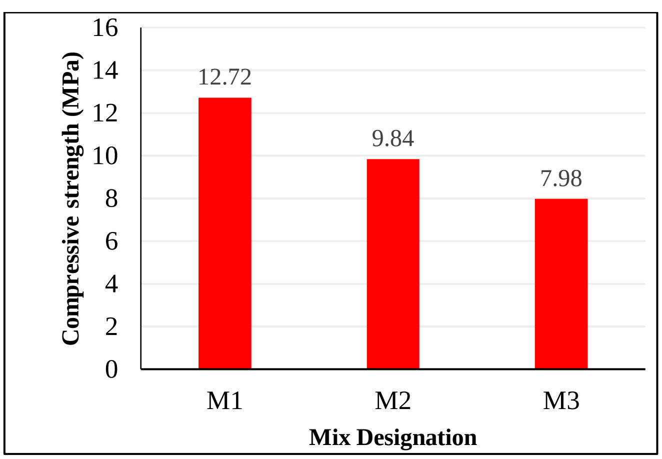

Figure 8. Compressive strength of concrete blocks at age 28 days.

4.2.3. Modulus of rupture of blocks

The three blocks were subjected to the modulus of rupture test in accordance with Iraqi Standard I.Q.S. No. 1107 [32]. Flexural strength for light-weight concrete block is lower than that of normal-weight concrete block. Fig. 9 shows the flexural strength of the three block types at 28 days. Based on the figure, an increase in the LECA replacement percentage caused a decrease in flexural strength; the recorded values were 2.57 and 2.12 N/mm2 for LECA percentages of 50% and 75%, respectively. The reduction in flexural strength was linear. It can be attributed to the globular shape and soft surface of LECA, which contains several cavities that weaken the block structure.

4.2.4. Thermal conductivity of blocks

A Quick Thermal Conductivity Meter (QTM-500) [33] was used to measure the thermal conductivity of all blocks produced. Fig. 10 illustrates the thermal conductivity for the three block types. The lightweight block concrete (M2 and M3) has a lower k-value than the standard concrete block (M1). Given that aggregates with low thermal conductivity produce lower thermal conductivity concrete [34], LECA effectively reduced the thermal conductivity of concrete blocks. When observing the effect of LECA percentages used in block production, it appears that increasing LECA decreases thermal conductivity. The difference in LECA content was observed in the K-value, which decreased from (1.4) W/m^2.K for control blocks, to (0.83) and (0.6) for blocks with 50% and 75% LECA, respectively. The thermal insulation properties of LECA were excellent, indicating the potential to develop concrete blocks with high thermal insulation performance.

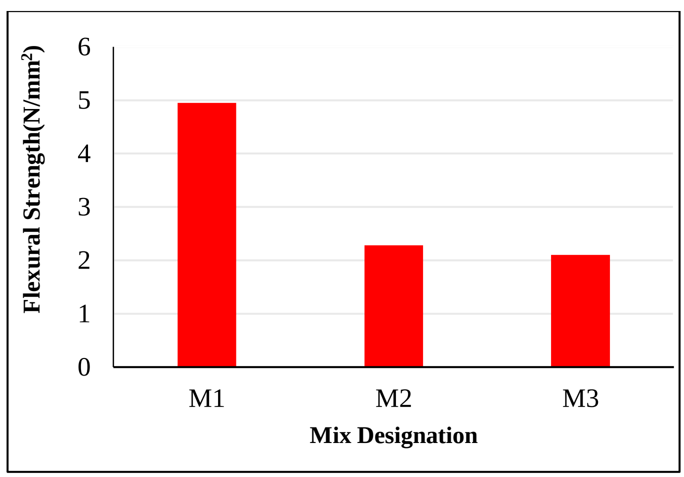

Figure 9. Modulus of rupture for concrete blocks at age 28 days.

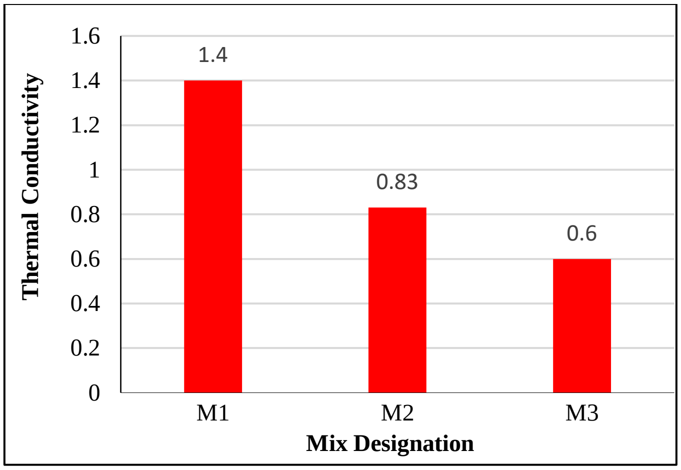

Figure10. Thermal conductivity of concrete blocks at 28 days.

5. Conclusions

Use of LECA at two volumetric ratios (50, 75%) instead of ordinary coarse aggregate reduces the dry density and the compressive and tensile strengths of the reference mix. The compressive and splitting tensile strengths of all mixes increase with time. Good thermal conductivity can be achieved with LECA, reducing the thermal conductivity of the reference block by approximately half. Additionally, increasing the volumetric ratio of LECA substitution reduces thermal conductivity. Its low thermal conductivity and weight, as well as its ability to be cast into any desired shape, qualify this type of concrete as an appropriate material for manufacturing various thermally insulated elements and masonry units.

Acknowledgements

The authors would like to thank Mustansiriyah University, Baghdad, Iraq (www.uomustansiriyah.edu.iq) for its support in the present work.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

All authors discussed the results and contributed to the final version of the manuscript.

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