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Research Article

Performance of eco-friendly masonry units made with limestone calcined clay cement (LC^3)

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Abstract

This paper aims to evaluate the performance of masonry units manufactured in a plant for the first-time using limestone calcined clay cement (LC^3). Locally available raw materials in Iraq were employed to produce the masonry blocks by using an automated block maker in a local plant. In addition to the control ordinary Portland cement (OPC) blocks, two types of LC^3 masonry blocks were produced to evaluate their performance. These two types were LC^3 blocks made by replacing 25% and 50% of OPC with calcined clay and limestone, namely, LC^3-75 and LC^3-50 blocks, respectively. Following the production, the performance of the blocks was assessed through compressive strength, absorption, and density tests. The results showed that the values of compressive strength for LC^3-75 and LC^3-50 blocks, at 28 days, were 94% and 82% of OPC blocks, respectively. According to the American Society for Testing and Materials, the compressive strength of LC^3-75 blocks satisfied the requirements of loadbearing units, whereas that of LC^3-50 blocks fulfilled the requirements of non-loadbearing units, in terms of compressive strength and absorption. Compared with OPC blocks, the estimated reductions in embodied carbon by utilizing LC^3-75 and LC^3-50 blocks were 18% and 36%, while the reductions in mass were 0.9% and 1.7%, respectively.

1. Introduction

Concrete blocks are among the most commonly used masonry units due to their ease of manufacturing, affordability, durability, and many other benefits. Thus, they are utilized in numerous applications such as bearing walls, partitions, fences, and other constructions. The masonry unit is termed as a brick when its length, width, and height do not exceed 337.5 mm, 225 mm, and 112.5 mm, respectively, while it is called a block when any of these dimensions exceeds the corresponding values [1]. Concrete blocks are generally produced as solid, cellular, or hollow units [2, 3]. A hollow block has one or more voids, called cores or cells, that completely extend through the full height of the unit [4] with a net cross-sectional area less than 75% of the gross area in each plane parallel to the bearing surface [2]. Accordingly, a solid block has no voids, or has a cross-sectional area equal to or greater than 75% of the gross area in each plane parallel to the bearing surface [5]. Cellular blocks are units having one or more voids which do not penetrate their full height [4]. Cellular units can be laid on a full bed mortar during the construction of the masonry [6], preventing the waste of mortar, compared with hollow blocks in which mortar losses occur due to dropping into open holes during the construction [7]. However, concrete blocks can also be produced in other different shapes and dimensions depending on manufacturers and the standards in a region. The modern concrete blocks are manufactured by casting their mixed components (cement, aggregate, and water) by an automated block maker (vibro-compression machine).

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Due to the global urban development, massive quantities of cement are needed in the concrete block industry worldwide. The huge quantities of produced cement result in large emissions of carbon dioxide (CO_2) [8], as manufacturing one ton of cement emits approximately one ton of CO_2 [9], resulting in a negative impact on the global environment [10]. Additionally, the large consumption of natural aggregate is another aspect in which the concrete blocks industry contributes negatively to the planet. Therefore, researchers around the world have focused on employing alternative materials in an attempt to make the masonry blocks ecologically friendly. Accordingly, studies have examined various methods in the way of producing sustainable masonry units with main aspects of partial or full replacements of aggregate, and/or partial or full replacements of cement.

The replacement of aggregate by sustainable materials is one of the major approaches in producing eco-friendly masonry units. In this approach, the substitution of different ratios of fine aggregate by olive wood wastes was investigated to produce masonry blocks [11]. The results demonstrated that the replacement ratios 25% and 50% leveled up the flexure strength of the blocks, compared with the reference concrete blocks, whereas the compressive strength satisfied the requirements of masonry non-loadbearing units according to ASTM. The performance of hollow blocks was also evaluated by replacing a part of coarse aggregate with high density polyethylene (HDPE), low density polyethylene (LDPE), and crumb rubber (CR) wastes [12]. The outputs indicated that HDPE and LDPE concrete blocks satisfied the minimum requirements of compressive strength for nonloadbearing masonry units according to ASTM specifications, while the CR concrete blocks failed to give acceptable strength. Furthermore, experimental tests were carried out by [13] to evaluate the suitability of replacing the fine aggregate in concrete blocks with quarry dust (the waste of industrial stone crushing). The findings showed a comparable performance of the proposed units with the conventional concrete loadbearing units, whereas the replacement ratio of 30% led to better performance than the conventional loadbearing blocks. In addition, multiple techniques were employed to develop energy efficient concrete hollow blocks by replacing aggregate with various materials [14]. An expanded perlite (heated volcanic rock), an expanded vermiculite (heated hydrated magnesium aluminum silicate), an expanded polystyrene (industrial processed polystyrene), and a scoria (volcanic basalt rock) were used separately to substitute 30% by weight of fine aggregate, 5% by weight of fine aggregate, 14% by volume of coarse aggregate, and 100% of coarse aggregate, respectively. The results proved that all blocks satisfied the requirements of compressive strength and absorption for non-loadbearing masonry units based on ASTM, and could reduce 53% of energy consumption compared with the conventional blocks.

The partial replacement of cement is also an important approach which has been examined by researchers around the world. Melted plastic wastes were utilized as a binder to produce masonry blocks [15]. The wastes of high-density polyethylene (HDPE) and low-density polyethylene (LDPE) were melted and mixed with a river sand with plastic to sand ratios of 1:1.5, 1:2, and 1:2.5. The study revealed that the ratio of 1:1.5 of plastic (100% HDPE or 100% LDPE) was the best ratio to achieve the optimal results of compressive strength and absorption. The authors recommended using these blocks as non-loadbearing masonry units and to improve the process of melting and manufacturing as a result of the higher cost of manufacturing compared with the commercial blocks. Another researcher [16] evaluated the mechanical properties of eco-friendly hollow blocks produced by replacing 10% of cement by fly ash, 20% by volume of aggregate by chipped PET bottle wastes, and 40% by volume of aggregate by chipped wood wastes. In addition, Polyester fibers by-products 30 mm- long were used as reinforcement for the block. The outputs revealed a reduction in compressive strength and enhancement in tensile strength of the hollow blocks. The assessment for the influence of replacing specific parts of cement and sand by wood ash and glass waste in concrete blocks was carried out by [17]. The study found that the compressive strength of the block enhanced for 15% and 10% replacement of cement and sand by wood ash and glass waste, respectively. The challenge of this study was the availability of waste materials, especially the wood ash to manufacture large quantity of masonry blocks. The partial replacement of cement was also investigated by [18] to explore the performance of concrete blocks. A part of both the cement and the fine aggregate were substituted with steel slag (by-product of steel manufacturing industry). It was proven that incorporating 10% of steel slag as a binder and 35% as fine aggregate into block mixtures did not degrade the general performance of the blocks, whereas the flexure strength increased compared with control mix except for the mix of substituting 10% of cement by EAF-oxidizing slag.

To get benefits from the recycled materials, the researchers [19] designed a mix of agro-industrial rejects, bio-briquette ash (BBA), and fly ash (FA) with alkaline activator solutions of sodium silicate and sodium hydroxide to form a masonry block. It was concluded that BBA/FA of 1 and sodium silicate to sodium hydroxide of 2 gives the maximum compressive strength (31 MPa) with absorption of 1.5% and average density of 1841 kg/m^3. A New technique was also presented by [20] to produce masonry blocks made once with polypropylene (PP) and the second time with high density polyethylene (HDPE) by using the rotational molding process (rotation and heating of the polymer particles). The results showed that the performance of HDPE blocks is better than that of PP blocks, and the authors concluded that HDPE blocks can be used in civil constructions provided they pass the flammability test. An innovative mixture for developing masonry blocks based on a combination of metakaolin with basalt, volcanic rock, powder is presented by [21]. The study proved that the increase in basalt content significantly improved the compressive strength and reduced the absorption, and that the ratio of 60:40 (metakaolin to basalt) provides the optimal performance regarding the strength, durability and microstructure of the developed blocks. Recently, a locally available pozzolana in Morocco was investigated to produce eco-friendly compressed earth blocks [22]. Various percentages of pure pozzolana or in a combination with conventional cement were examined as stabilizers for soil to evaluate the performance of the proposed blocks. The study demonstrated that the natural pozzolana could be used as a potential green stabilizer for compressed earth blocks in masonry constructions under low loads.

The earlier studies in the field of producing eco-friendly masonry units indicates that the proposed approaches generally have shortcomings or limitations when used in practical application. Regarding the alternative binders, there is a lack in worldwide availability of these binders which makes a difficulty to sustain the process of cement replacement under the global massive demand of the masonry components. When it concerns to the replacement of aggregate, despite the generally positive outputs of this option, the shortage of some materials (such as plastic and wood wastes) and the cost of supplying others may affect the continued productivity of masonry units by using these materials. However, the environmental and cost assessments of employing such alternative materials are necessary to determine the feasibility of using them.

This study focuses on the trend of replacing the conventional cement with a cementitious material that is less carbon footprint to produce environmentally friendly masonry units. Due to its promising features in terms of strength, economic, and environmental aspects, limestone calcined clay cement (LC^3), was selected in this study to be investigated in producing masonry units. Limestone calcined clay cement (LC^3) is a potential environmentally friendly cement as it decreases carbon dioxide (CO_2) emissions up to 40% by decreasing the clinker content and the fuel consumption in the process of cement production [23, 24], and reducing costs due to the natural availability of clay [25]. To obtain the calcined clay, the clay is thermally activated generally from 600 ºC up to 900 ºC in order to transfer its minerals from the inactive state to the amorphous (active) phase [26]. LC^3 is generally produced by mixing three main constituents; calcined clay, limestone, and cement/clinker, with water, in an appropriate proportion. Gypsum can also be added to LC^3 components for the purpose of balancing the sulfate and maintaining the ettringite formation by providing calcium [27]. In the last few years there has been a considerable interest by researchers to investigate the properties and behavior of this modern substance. Previous studies, e.g., [28-34], revealed that LC^3 systems (paste, mortar, or concrete) exhibit a promising performance in terms of strength and/or durability. Further, studies in LC^3 field reported that the strength of LC^3 blends, made with calcined clay containing a kaolinite of 40% or more, may exceed those made with ordinary Portland cement (OPC) [31, 35]. Since LC^3 is a new construction material, research in this field is still limited to investigating its characteristics without moving toward assessing its performance when used in structural components such as masonry constructions. As a result, there are no previous studies that have examined the properties of plant-scale masonry units made with LC^3 binder, nor even have investigated the possibility of manufacturing LC^3-based masonry units in practice. The only study that came close to this field was the attempt presented recently by [36] to simulate the manufacturing of LC^3 units by producing specimens of hollow blocks in the laboratory. The study has utilized LC^3-50 and LC^3-35 binders to investigate the feasibility of producing low-carbon units. The results showed that the values of compressive strength for LC^3-based blocks satisfied ASTM specifications for non-loadbearing masonry units. However, because LC^3-based blocks were produced by hand in the laboratory, the study lacked both a sufficient methodology for manufacturing them in practice, and the real performance of LC^3-based blocks. Therefore, there is a clear lack in the feasibility and applicability of LC^3 blends in producing a sustainable binder for manufacturing masonry units in practice.

This study is a part of series of experimental studies concerned with the production of environmentally friendly LC^3 binder and its applications in civil engineering practice. The significance of this research stems from it being the first study to explore the production and performance of plant-scale masonry units made with LC^3 binder. Manufacturing the blocks in a plant reveals the actual properties of the proposed material under factory conditions such as pressing, molding, and transformation, in addition to post-manufacturing conditions. Furthermore, this study presents the first attempt of producing LC^3 blocks by using locally available raw materials sourced from Iraq. This study contributes to closing the gap between the theory and practice, and promote the idea of practical manufacturing for LC^3 masonry units by using available raw materials. In addition, it paves the way for further studies in other regions worldwide to focus on producing LC^3 blocks in markets. These outcomes will support the global sustainable development and offer an economical solution to the increasing demand for masonry units due to globally urban development. The objectives of this work include investigating the viability of producing LC^3 blocks by using automated block maker in a plant, and then to evaluate the performance of the blocks through compressive strength, absorption, and density. The study is driven by the need to supply ecological and economically feasible masonry units instead of the existing OPC-based units which are manufactured worldwide in huge quantities, leading to negative impact on the environment. The work was started by collecting the locally available raw materials and preparing them to produce LC^3 binder. Then blocks were manufactured in a nearby plant to assess the applicability of molding this new material in vibro-compression machine. Finally, the experimental tests were carried out on the block specimens to evaluate their performance through the compressive strength, absorption, and density characteristics.

2. Materials and Methods

2.1 Materials

The raw materials utilized for producing LC^3 binder were clay, limestone, and commercial cement, which were utilized in a preceding study [37]. The clay was sourced from Ramadi in central Iraq, while the limestone was taken from Mosul in northern Iraq, and the cement was an ordinary Portland cement provided from Al-Mass factory in Iraq. The chemical compositions for the clay, limestone, and cement have been measured previously by using x-ray fluorescence (XRF) test, while the mineralogical composition for the clay has been evaluated by x-ray diffraction (XRD) test [37], as illustrated in Table 1 and Table 2, respectively. The values of specific gravity for clay and limestone were 2.61 and 2.66, respectively, while their particle size distribution curves are shown in Fig. 1. The clay was a low-grade clay, with a zero-kaolinite content and a thermogravimetric analysis (TGA) graph as shown in Fig. 2 [37]. Following [38, 39], the concept of strength activity index (SAI), which represents the percentage ratio of LC^3 to OPC values of compressive strength for mortars, has been adopted to verify the clay activation [37]. As can be seen in Fig. 3, the ratios of SAI for the clay used in this study have been varied with the change of calcination temperature, verifying the clay activation. Although the clay was a low-grade with null kaolinite, it yielded a successful activation and a promising strength for LC^3 mortars [37]. The cement was (Type I) ordinary Portland cement satisfied the Iraqi specifications [40], with a Blaine fineness over 250 m^2/kg. The aggregate employed in producing the blocks was a mix of crushed gravel and a river sand mined from Samarra, in central Iraq, with a physical property as given in Table 3. The sieve analysis for the aggregate was performed according to ASTM C33 [41], with a distribution as reported in Table 4. Tap water was used in both mixing and curing processes.

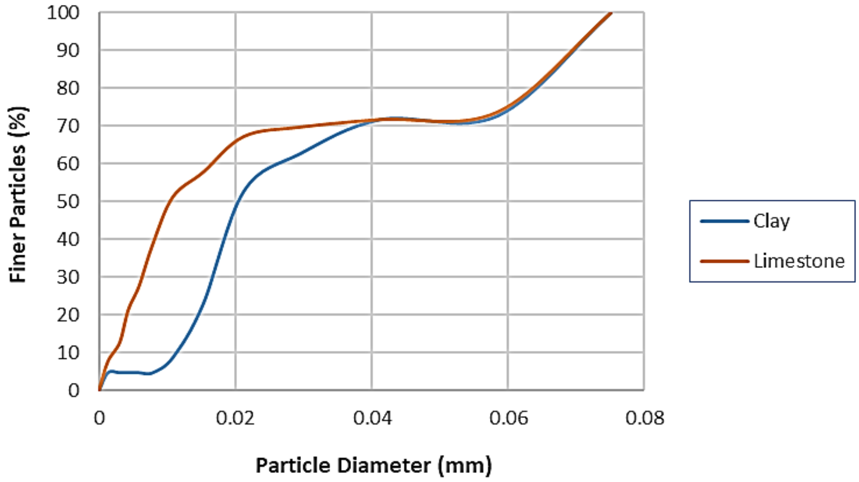


Fig. 1. Particle size distribution for clay and limestone

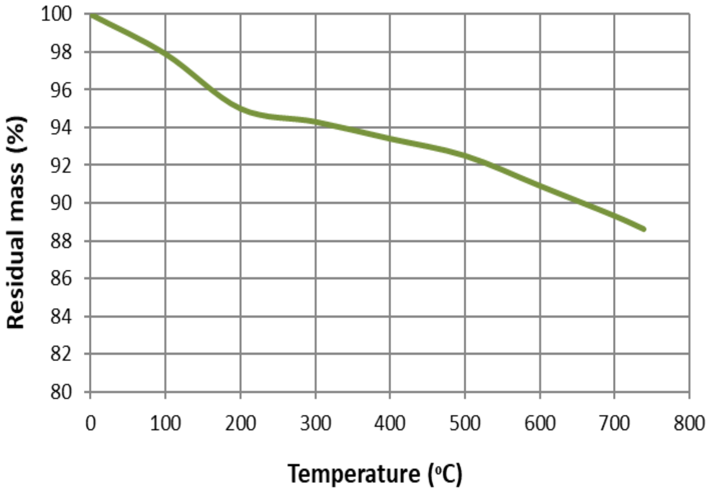


Fig. 2. TGA graph for the clay sample [37]

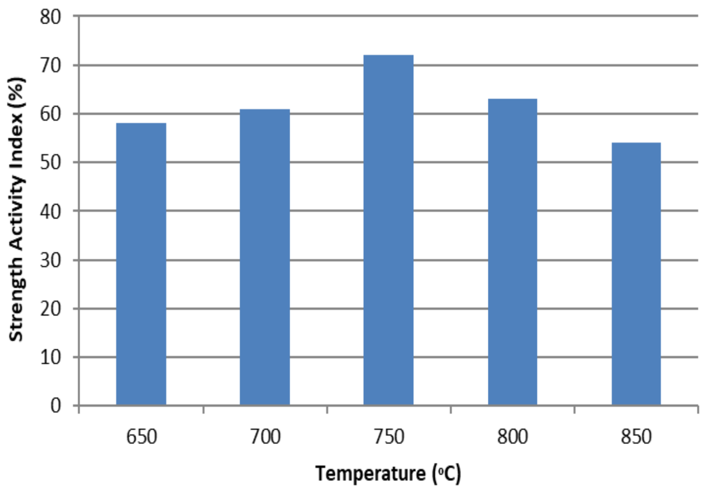


Fig. 3. Strength activity index of LC^3-70 mortars at 7 days [37]

Table 1. Chemical compositions (oxides) for the raw materials [37]

Oxides	Clay (%)	Limestone (%)	Cement (%)
CaO	24.2	50.8	60.1
SiO_2	37.8	2.0	16.2
Al_2O_3	9.1	1.8	4.9
Fe_2O_3	6.6	0.4	4.4
MgO	5.1	4.2	2.1
SO_3	1.7	0.1	3.4
LOI	11.1	39.1	5.9

Table 2. Mineralogical composition for the clay [37]

Mineral	Quartz	Calcite	Dolomite	Illite	Chlorite
Content (%)	45.5	28.7	10.9	8.2	5.3

Table 3. Physical properties for the aggregate

Property	Value
Specific gravity	2.67
Water absorption	2.5 %
Fineness modulus	3.6

Table 4. Sieve analysis for the aggregate

Sieve size	9.5 mm	4.75 mm	2.36 mm	1.18 mm	0.6 mm	0.3 mm	0.15 mm
Passing percentage	100%	84%	58%	40%	30%	23%	8%

2.2 Preparation of LC^3 Binder

The extracted clay and limestone were initially smoothed out by using a metal rod in order to reduce the clumps to be suitable for the grinding machine. Then, the clay and limestone were ground separately by using a grinding machine. The fineness was controlled by sieving the obtained powders to achieve a particle size of 75 µm (or passing through a 75 µm sieve). A static calcination of 750 ºC, with 10 ºC/min heating rate, for 30 minutes residence time in a laboratory furnace was adopted.

(a) (b)

Fig. 4. Ground raw materials for LC^3 mixes (a) Calcined clay (b) limestone

The proportion 2:1 (two parts of calcined clay to a one part of limestone) was chosen to be added to the cement, then the three ingredients were mixed drily in a drum mixer to obtain a homogenous LC^3 binder, and were finally sealed into airtight bags. The values of fineness, calcination temperature, residence time, and proportions were taken from the previous study [37], which have been concluded after a thorough parametric study carried out on the same raw materials used in the current work. Fig. 4 shows the calcined clay and limestone powders utilized in LC^3 mixes in the current study.

2.3 Block Mixtures

The design of block mixtures manufactured in a plant differs significantly from laboratory-based design, as the plant conditions and parameters could not be controlled in the same way as they are in the laboratory. The design of each batch of masonry units in a plant requires costly and excessive tests [42] because it is affected by numerous factors, such as variation in moisture content of the provided aggregate, changes in air temperature and humidity during the production, alteration in compaction energy, consuming the production time, etc. Therefore, taking benefits from prior experiences in block manufacturing as well as from the reported proportions in literature was a helpful guidance in this work. It has been stated that the cement to aggregate ratios of 1:8 to 1:12 are typically used in block manufacturing [43], while the ratios 1:7, 1:9, and 1:11 are commonly employed in the market of producing the structural masonry units [42]. Accordingly, the ratio 1:11 (1 binder portion to 11 aggregate portions) was adopted in this work, following [42, 43], especially the manufacture plant was also programmed with this proportion. At this ratio, each cellular block contained about 2 kg of binder. Regarding the water content of the mixes, there is no fixed water content for all block mixes produced in the plant because it varies with the water content of aggregate in a given supplied batch, Therefore, the water content of the mixes in this study was designed after making trial mixes along with examining the quality of the produced blocks in the plant, and reviewing the practical values that utilized in previous works [12, 42-45]. Accordingly, the water-to-binder ratio (w/b) of 0.82, based on oven-dry aggregate, was adopted in this work. This ratio led to a required water of 54 kg for each batch, based on 6.1% water content of moist aggregate state at the time of mixing.

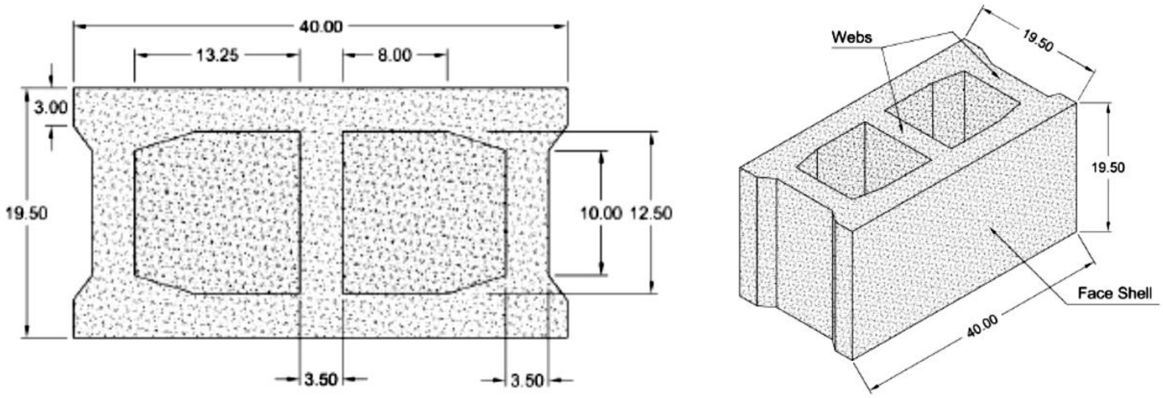
Three mixes were prepared to produce three main batches of cellular blocks (each batch has 60 blocks). This number of blocks was selected to cover the required units for conducting the required experimental tests of this study and for further studies in this field. The first mix was the conventional concrete blocks made with the ordinary Portland cement to act as a control mix, identified as (OPC). The other two mixes were prepared by replacing 25% and 50% of cement by limestone and calcined clay (with calcined clay to limestone ratio of 2:1), identified as (LC^3-75) and (LC^3-50), respectively. The detailed proportions of the mixes are presented in Table 5.

Table 5. Proportions of the block mixes for the three batches (each batch produces 60 cellular blocks)

Mix	Ingredients (kg)				
	Cement	Calcined Clay	Limestone	Water	Aggregate
OPC	120	0	0	54	1320
LC^3-75	90	20	10	54	1320
LC^3-50	60	40	20	54	1320

2.4 Block Geometry

The produced cellular blocks were stretcher-shaped masonry units which are commonly used in Iraqi market. The nominal outside dimensions of the unit were 40 cm (length) × 20 cm (height) × 20 cm (thickness). The actual outside dimensions were 40 cm (length) × 19.5 cm (height) × 19.5 cm (thickness), representing the average dimensions of three specimens for each type, measured according to ASTM C140 [46]. Each unit has two cores (cavities) closed at one end by a thin shell of about 2 cm thickness, covering the entire area of the base. The closed end of the block has been earlier designed by manufacturers mainly to facilitate laying mortar and reducing its wastage during the construction. The average net cross-sectional area for the unit was calculated according to ASTM C140 [46], by dividing the volume of the block's solid material by the height of the block. The volume of the block's solid material was determined experimentally based on Archimedes principle (the volume of submerged block is equal to the volume of displaced water). The value of block's solid material for each type of blocks (OPC, LC^3-75, and LC^3-50 blocks) was taken as the average value of three specimens for each type. The detailed dimensions of the unit are shown in Fig. 5.



(a)

Fig. 5. The geometry of the cellular block in this study (a) Top view, (b) 3D view (All dimensions are in cm)

2.5 Block Production

The blocks were manufactured in the plant of Haj Muthanna, shown in Fig. 6, which is located in Samarra. All the production parameters were fixed except the binder type, namely, OPC, LC^3-75, and LC^3-50. The process of production for each batch was started by dry-mixing the aggregate with the binder (OPC or LC^3) in a rotary mixer, then water was added within about two minutes to the dry mix while it was rotating to complete the wet mixing within additional two minutes. After that, the fresh mix, which was in a uniform consistency for each type of units, was poured into conveyer forklift, then transported to the automatic block maker. To ensure a uniform quality for all types of units, the blocks were finally molded on a horizontal fair pavement by a combination of compression hammering pressure and a vibration, as shown in Fig. 7(a). The compression pressure of block maker machine was 28 kPa, with an average of 10 hammer strikes. The vibration was applied by two vibrator motors (fixed at the upper punch and lower mold of the machine), each one had a power of 3 hp, with 3000 rpm and 50 Hz frequency, applied for around 6 seconds. Following the molding of blocks, a curing process was carried out after the hardening of blocks by water spraying, as shown in Fig. 8, for 7 days (6 days in the plant and 1 day in the laboratory) to maintain their moisture. The curing was carried out at air temperature ranging from 15 ºC to 30 ºC, and a humidity of around 30%.

Fig. 6. The plant of Haj Muthanna for producing concrete blocks in Samarra

The seven-days curing time was adopted as it is the least curing period according to ACI 301-16 [47], and to be near to the practical curing period in the market which has been considered by [42]. At the age of six days, the blocks were collected and lifted successfully from the plant by a forklift truck as shown in Fig. 7(b), then transported by a truck to the laboratory yard. A period of six days was chosen after ensuring visually that the produced units had acquired the appropriate strength, as it was the first time of producing LC³ blocks.

(a) (b)

Fig. 7. (a) Molding LC³ blocks by automated block maker (b) Lifting LC³ blocks by a forklift

Fig. 8. Curing of manufactured blocks in the plant by water spraying

2.6 Experimental Tests

To provide a general assessment of LC³ cellular blocks, three key experimental tests; namely, compressive strength, absorption, and density, were conducted for the produced blocks. Based on ASTM C140 [46], compressive strength testing of the units was carried out at 3, 7, and 28 days to investigate the strength and its growth for each type of blocks. As the 28-days compressive strength is an essential factor for the strength of masonry units, three specimens were tested for each type of units (OPC, LC³-75, and LC³-50). Furthermore, due to the limited number of LC³ units, two specimens were tested at 7 days, for each type of units, and one specimen was tested at 3 days, for LC³-75, and LC³-50 units, while three specimens were tested for OPC units. The compressive strength tests were conducted at 3 and 7 days to take a general insight about the strength development at early ages. The blocks were prepared before conducting the compressive strength test by removing protrusions from the upper and lower surfaces to ensure a uniform loading distribution. Next, a capping by using a thick steel loading plate was carried out to distribute the compression load uniformly on the entire area of the specimen. Prior to pressing, each block was placed so that its cores (cavities) were directed vertically. The loading rate was implemented by applying an initial loading at any convenient rate, up to one-half of the expected maximum load, then applying the remaining loading at a uniform speed for a duration of 1 to 2 minutes. The value of compressive strength for each unit was calculated by dividing the maximum compressive load by the net cross-sectional area of the unit. The net cross-sectional area of the unit was determined according to ASTM C140 [46], by dividing the volume of the unit's solid material by its height. The volume of the block's solid material was determined experimentally based on Archimedes principle (the volume of submerged block is equal to the volume of displaced water). In addition, to compare with Iraqi specifications [48], the values of compressive strength were also computed based on loaded gross area for each specimen. The strength index, which represents the maximum compressive strength of a given unit to that of OPC unit, was employed to evaluate LC^3 blocks with respect to OPC blocks. Fig. 9 shows a set of cellular blocks taken randomly from the units that were tested for compressive strength at 3, 7, and 28 days. The compressive strength tests were conducted using 2000 kN compression machine, as shown in Fig. 10, at the laboratories of Department of Civil Engineering, University of Samarra.

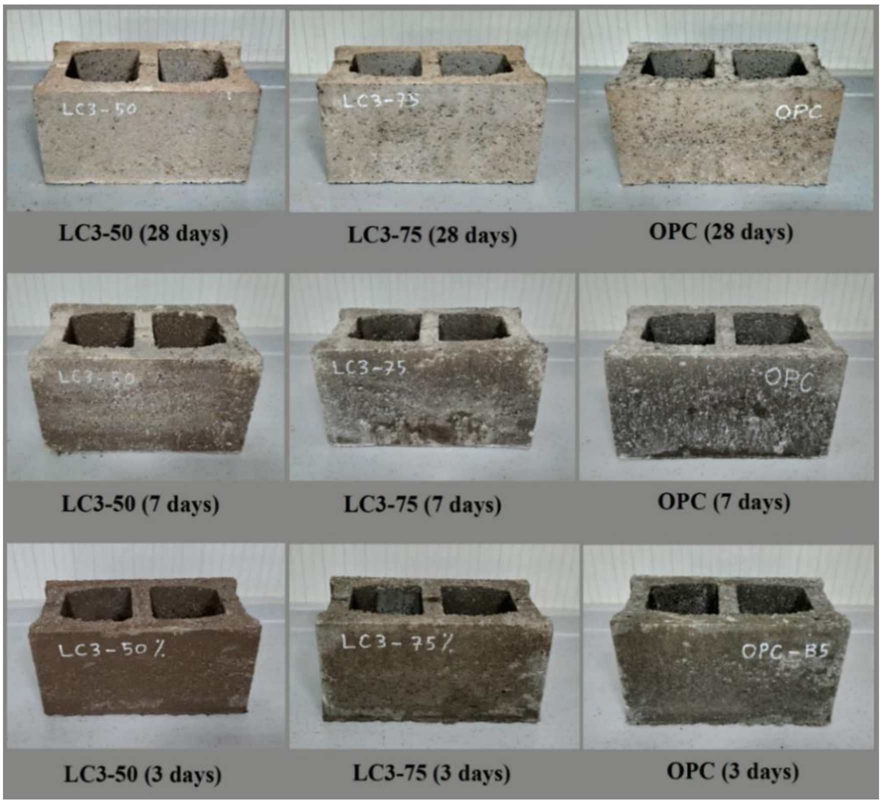


Fig. 9. Blocks taken randomly before testing the compressive strength

(a) (b) (c)

Fig. 10. Compressive strength test (a) OPC blocks (b) LC^3-75 blocks (c) LC^3-50 blocks

The absorption was determined, after 28 days, by testing three specimens from each type of units according to ASTM C642 [49]. Each selected specimen was dried in an oven at a temperature of 100 ºC to 110 ºC for at least 24 hours to compute its oven-dry mass (W_d). Next, the specimen was submerged in a water, for not less than 48 hours, the surface moisture removed before weighting the specimen to obtain its saturated surface-dry mass (W_s). The absorption was finally calculated by taking the percentage ratio of the difference between two masses (W_s - W_d) divided by the oven-dry mass (W_d). The specimens used in absorption tests were also used to evaluate the oven-dry density for the blocks in each type, after 28 days. According to ASTM C140 [46], the mass of each submerged specimen (W_i) was obtained from the previous absorption test. Next, the value of oven-dry density was calculated by multiplying the density of water (1000 kg/m^3) by the ratio of (W_d) to (W_s – W_i), as stated by ASTM C140 [46]. It is worth noting that the same specimens that were used in evaluating the absorption and density were also used in the calculations of aforementioned net cross-sectional area.

2.7 Estimation of Environmental Benefits

The calculations of the reductions in embodied carbon due to utilizing LC^3 substances are beyond the scope of this study. Precise information regarding the calcination outputs of clay and non-clay minerals, the methods of extraction, transportation, grinding, calcination, and others, are all necessary for conducting accurate environmental analysis for CO_2 emissions. However, the preliminary reduction in embodied-carbon by using LC^3 blocks could be estimated simply based on the quantity of cement in a mixture, following the computations of CO_2 emissions that have been reported in literature.

The value of embodied carbon due to producing LC^3-75 and LC^3-50 binders in this work were estimated by computing the summations of the emitted CO_2 for the cement, calcined clay, and the calcite after calcination. For the cement, the calculations were established on the basis that producing one tonne of OPC releases about one tonne of CO_2 [9] [50]. Regarding calcined clay, the computations were based on the assumption that manufacturing one tonne of calcined clay liberates about 0.3 tonne of CO_2 emissions, which has been stated by [50]. Furthermore, CO_2 emissions due to the presence of calcite in clay were also considered because calcite ($CaCO_3$) releases CO_2 due to decarbonization in calcination process between 600 ºC and 800 ºC [51]. The emissions of calcite were computed based on its percentage in clay, provided that each one tonne of calcite releases about 0.44 tonne of CO_2 emissions, due to the calcination of calcium carbonate [52]. The overall emissions of LC^3 binders were then compared with those liberated from OPC binder to estimate the reductions in embodied carbon of utilizing LC^3-75 and LC^3-50 products in this work.

3. Results and Discussion

3.1 Cross-Sectional Area, Density, and Absorption

The gross and net cross-sectional areas are basic parameters in computing the mechanical properties for the masonry units. On the other hand, density gives an indication for the quality and soundness of the masonry units, while absorption gives an indication of the performance and durability [53-55] along with the bond strength of the units [8]. The average values of the physical properties; gross (total) and net cross-sectional areas, dry density, and absorption for the manufactured blocks in this work are illustrated in Table 6.

It can be seen from Table 6 that the percentage of the net cross-sectional area for all types of blocks were less than 75%. This percentage puts the blocks closed to the classification of hollow masonry units based on Canadian standard [2], which defines the hollow masonry unit as a unit with a net cross-sectional area less than 75% of the gross area in each plane parallel to the bearing surface. Table 6 also shows that the values of the dry density for LC^3 blocks were slightly less than the value of the dry density for OPC blocks, and they were decreased as the cement replacement increased. The results indicated reductions value of 0.9% and 1.7% in density for LC^3-75 and LC^3-50 blocks, respectively. The slight decrease in the density of LC^3 blocks could be attributed to the larger volume of micro voids in LC^3 as opposed to OPC blends, as recorded by [34], lower density of calcined clay and limestone, and lesser development of hydration products, compared with conventional cement [56]. Furthermore, the values of the density for both OPC and LC^3 blocks were identified as normal weight densities according to ASTM C90 [5], which classifies the value equals or greater than 2000 kg/m^3 as a normal weight density. It is worth noting that the decrease in density for LC^3 blocks led to slightly lighter weights for these blocks, compared to OPC blocks, as shown in Table 5. The achieved reduction in the density for LC^3 blocks has many benefits, including lowering the weight of the masonry units, resulting in a lighter construction, compared with those built with OPC units. Further, the lighter blocks make the handling and construction faster and more comfortable for the workers in the site. In addition, light-weight blocks reduce the overall cost and the emissions caused by trucks' transportation.

Table 6. Average values for the computed physical properties of the blocks

Property	Type of Block		
	OPC	LC^3-75	LC^3-50
Length (mm)	400	400	400
Width (mm)	195	195	195
Height (mm)	195	195	195
Gross Area (mm^2)	78000	78000	78000
Net Area (mm^2)	52596	52147	51720
Net Area / Gross Area (%)	67.4	66.9	66.3
Dry Density (kg/m^3)	2162.5	2144.0	2126.4
Mass (kg)	22.18	21.80	21.45
Absorption% (COV)	5.88 (9.0%)	7.12 (2.6%)	7.72 (4.2%)
Absorption in kg/m^3 (COV)	127.14 (9.0%)	152.73 (2.6%)	164.08 (4.2%)

Regarding the absorption, it is illustrated in Table 6 that the values of absorption for LC^3 blocks were higher than those for OPC blocks, and they were increased as the cement replacement increased. The increase in absorption for LC^3-75 and LC^3-50 blocks were 21% and 31%, compared to OPC blocks, respectively. Numerous earlier studies have revealed that LC^3 systems exhibit lower absorption characteristics compared with OPC systems due to the positive contribution of pozzolanic and filler effects of LC^3 blends [57] [58]. The increase in absorption values for LC^3 blocks could be attributed to the large surface area of unreacted calcined clay in LC^3 blends, as reported by [32], and/or to the low content of kaolinite in raw clay [59]. Therefore, for LC^3 blocks in this study, the recorded higher absorption could be linked mostly to the null content of kaolinite in the clay utilized in developing LC^3 binder, or might be related to other parameters, which need further excessive investigations. However, the obtained values of absorption for both types of LC^3 units (7.12% and 7.72%) satisfied the Iraqi standard specifications for the grade A of loadbearing blocks, which requires a maximum absorption ratio of 15% [48]. Additionally, the values of absorption capacity for LC^3-75 and LC^3-50 blocks were 152.73 kg/m^3 and 164.08 kg/m^3, respectively. These values conformed to the minimum requirements of ASTM C90 for the loadbearing masonry units [5], which stipulates, for normal weight density, a maximum of 208 kg/m^3 for three units and 240 kg/m^3 for individual units.

3.2 Compressive Strength

The compressive strength is a crucial characteristic that can provide an indication for the mechanical properties of the blocks [12], and develops a perception of its strength to support the applied loads within the masonry. In the present work, the compressive strength experiments for three groups of masonry units (OPC, LC^3-75, and LC^3-50 blocks) were conducted to examine the ability of the proposed LC^3 units to withstand loading compared with the conventional cement blocks. The results of the compressive strength (C.S.), based on gross area calculations, along with the values of strength index (S.I.) for the OPC, LC^3-75, and LC^3-50 blocks at 3, 7, and 28 days are reported in Table 7, and represented graphically in Fig. 11. These values of compressive strength were calculated based on gross cross-sectional area of the blocks (total loaded area), following the Iraqi standards [48]. The values of the coefficient of variation (COV) are also presented in Table 7, in which the abbreviation (N/A) is associated with a single tested specimen.

As can be shown from Fig. 11 that the OPC blocks achieved the highest values of compressive strength at all ages as LC³ blends were made with low grade calcined clay, which usually leads to lower values of compressive strength due to the lower reactivity of calcined clay and limestone compared with OPC [60], [33]. Additionally, it can be noticed from Fig. 11 that the growth of compressive strength of LC³ systems, especially LC³-50, at early ages (3 and 7 days) was less than OPC's, but it boosted at later age (28 days). These results are aligned with previous studies [30], [61], and they were attributed to the various proportions of tricalcium silicate (C_3S) and dicalcium silicate (C_2S) components in OPC and LC³ mixes, which control the development of strength at early and late ages, respectively [30]. The slow growth of compressive strength for LC³ systems with high contents of CC and LS can be proven from the values of strength index for the blocks made with LC³-50, which were 32% and 54% at 3 and 7 days, respectively, while the value was raised significantly to 82% at 28 days, as illustrated in Table 7. It is important to note that although the values of compressive strength at 3 and 7 days provide useful insights, the small number of tested blocks at these early ages limits the generalization of these results. Therefore, these outputs can be considered as preliminary observations, while larger number of specimens is recommended for future works to validate these findings.

Table 7. Values of compressive strength (C.S.), based on gross area calculations, and strength index (S.I.) for the blocks

Type of Block	3 days		7 days		28 days	
	C.S. (MPa) (COV)	S.I.	C.S. (MPa) (COV)	S.I.	C.S. (MPa) (COV)	S.I.
OPC	6.28 (4.5%)	100%	6.80 (2.6%)	100%	9.86 (7.9%)	100%
LC³-75	4.63 (N/A)	74%	6.18 (10.0%)	91%	9.29 (0.6%)	94%
LC³-50	2.02 (N/A)	32%	3.69 (N/A)*	54%	8.06 (0.2%)	82%

** The result for one of the specimens was discarded due to technical error.*

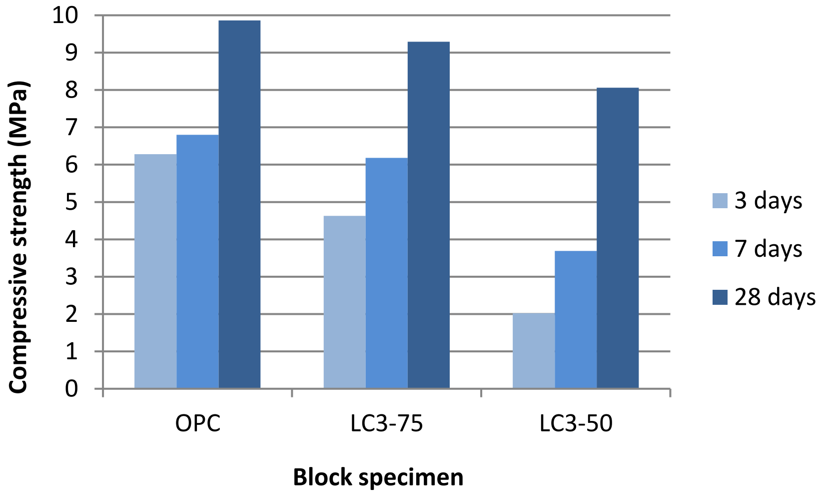


Fig. 11. Compressive strength of the blocks, based on gross area calculations

Furthermore, it can be observed from the values of compressive strength in Table 7 that, at the age of 28 days, the compressive strength of OPC blocks reached 9.86 MPa, while those of LC³-75 and LC³-50 were 9.29 MPa and 8.06 MPa with remarkable strength index values of 94% and 82%, respectively. These obtained values of compressive strength for both systems of LC³ blocks at 28 days satisfied the minimum requirements of the Iraqi standard specifications for the grade A of loadbearing blocks, which stipulates a minimum average value of 7 MPa based on the total loading area of the unit, provided that the value for each unit is not less than 6 MPa [48].

It is noteworthy to point out that the value of strength index for LC^3-50 block at 28 days (82%) was higher than the strength index for LC^3-50 mortar at 28 day (72%), which has been presented in [37], by using the same characteristics of calcined clay and limestone and the same proportion (2:1 of CC to LS ratio). The increase in strength index could be attributed to the positive effect of the compaction of block maker machine by applying both vibration and compression.

To compare with the requirements of ASTM C90 [5], the average values of compressive strength for OPC, LC^3-75, and LC^3-50 blocks, based on net area calculations, at 28 days are illustrated in Table 8. In addition, the minimum recorded values of compressive strength for the specimens in each type of blocks are also given in Table 8. According to these values, LC^3-75 blocks reported a net area compressive strength of 13.89 MPa, conforming to the minimum requirements for the loadbearing units of ASTM C90, which obliges a minimum value of 13.8 MPa for three units and 12 MPa for individual units, based on net area calculations. On the other hand, the net area compressive strength of LC^3-50 was 12.15 MPa, which did not meet the minimum requirements for the loadbearing units of ASTM C90 [5], but it satisfied the requirements of nonloadbearing units, which stipulates a minimum average value of 4.14 MPa based on the net area of the unit, provided that the value for each unit is not less than 3.45 MPa.

Table 8. Values of compressive strength, based on net area calculations, for the blocks

Type of Block	Average Compressive Strength at 28 days in MPa (COV)	Minimum Recorded Compressive Strength at 28 days (MPa)
OPC	14.63 (7.9%)	13.27
LC^3-75	13.89 (0.6%)	12.95
LC^3-50	12.15 (0.2%)	11.44

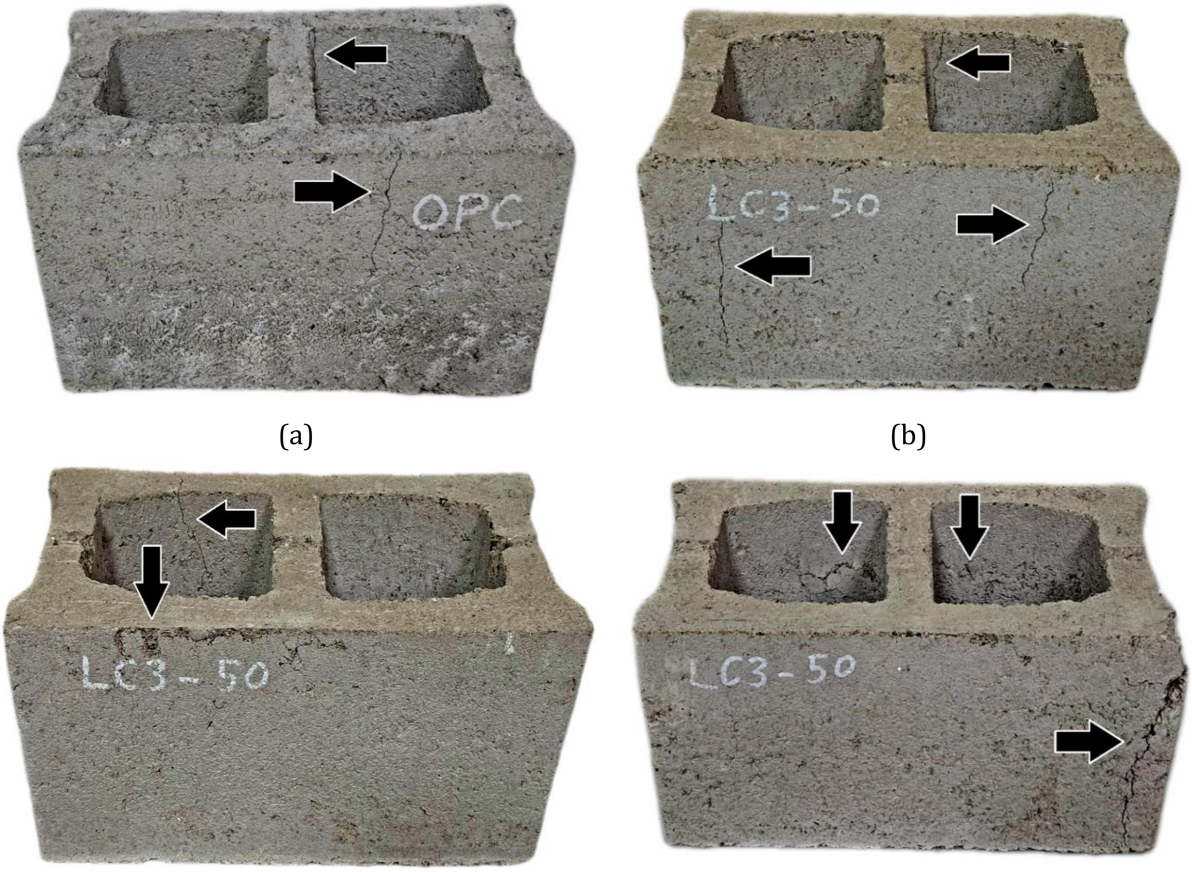
3.3 Failure Modes

In order to deepen the understanding of behavior for LC^3 blocks under compression and compare it with those of OPC blocks, the failure modes under compression for the blocks were investigated. The primary failure mode observed was the splitting of the units, characterized by vertical cracks in the webs across all block types, as shown in Fig. 12.

(a) (b) (c)

Fig. 12. Splitting failure mode in webs (a) OPC block (b) LC^3-75 block (c) LC^3-50 block

The splitting is caused by the lateral expansion of the unit during the compressive loading, which induces horizontal tensile forces in the webs, leading to vertical cracks in the material which has a poor tensile strength. This failure mode with its interpretation was also proven by previous studies for concrete blocks within prisms under compression [62], [63]. In addition to web splitting, other failure modes were recognized in the face shells of OPC and LC^3 blocks, which were inclined cracks in the face shell, and vertical cracks at the connection between the central web and the face shell, as shown in Fig. 13(a) and Fig. 13(b). The inclined cracks could be attributed to the combined effects of the vertical compressive force and the tension induced due to the expansion of the unit, while the vertical cracks could be linked to the high tensile stresses at the connection plane. Furthermore, LC^3-50 blocks showed inclined cracks and local spalls at the face shells, as shown in Fig. 13(c) and Fig. 13(d). The local spalling of material could be related to the loss of bearing under high compressive stress.



(a) (b)

(c) (d)

Fig. 13. Failure modes (a) cracks in face shells of OPC block (b) cracks in face shells of LC^3-50 block (c) cracks and spalling in face shells of LC^3-50 block (d) spalling in face shells of LC^3-50 block

3.4 Estimated Reductions in Embodied Carbon

Strength is not the only important consideration in the production of masonry units; the environmental advantages are also crucial in order to lessen the ecological damage that the cement industry causes, especially that the concrete units consume an extensive amount of cement. The calculations of reductions in embodied carbon for using LC^3 blocks of this study were carried out by using simple estimations of CO_2 emissions limited to the quantities of OPC, calcined clay, and calcite in block mixtures. The quantity of cement in LC^3-50 binder was 50% of the total substance, while clay formed two-thirds of the remaining 50%, as the ratio of calcined clay to limestone was 2:1. Similarly, the quantity of cement in LC^3-75 binder was 75% of the total substance, while the clay was formed two thirds of the remaining 25%. The emissions related to OPC and calcined clay were calculated based on each one tonne of OPC liberates about one tonne of CO_2, and each one tonne of calcined clay releases 0.3 tonne of CO_2, respectively. The additional emissions caused by the calcination of calcite were calculated by multiplying its content in mixture (28.7% of clay content in a given mixture) by its approximated CO_2 emissions (0.44 tonne per 1 tonne of calcite). The emissions due to the limestone were neglected because the limestone is utilized in LC^3 systems without calcination. Table 9 summarizes the values of CO_2 emissions and the achieved preliminary reductions in embodied carbon by using LC^3 blocks. It can be seen from this table that the maximum estimated carbon reduction was 36% associated with utilizing the proposed LC^3-50 blocks. As stated before, LC^3 could reduce CO_2 emissions up to 40% [23] [24]. For the clay employed in this work, the presence of calcite with a considerable content increased CO_2 emissions for the clay, and consequently decreased the embodied carbon reduction to 36%. This contribution of calcite in CO_2 emissions has been proven by [51]. Regarding LC^3-75 blocks, it can be noticed from Table 9 that their higher cement content, compared with those of LC^3-50, led to a half carbon reduction (18%) compared with LC^3-50 blocks.

The above-mentioned outputs, which represent preliminary embodied carbon estimates, demonstrate the environmental benefits that can be achieved through the use of LC^3-50 and LC^3-75 blocks manufactured in this work. According to United States Green Building Council (USGBC), the sustainable (eco-friendly) design and construction can be defined as the practice which eliminates or reduces the negative impact of the building on the environment and on the building's occupants as well [64]. Consequently, LC^3-50 and LC^3-75 blocks presented in this study could be considered as eco-friendly masonry units because they are able to reduce the negative ecological impacts resulted from CO_2 emissions, compared with the conventional OPC units.

Table 9. Estimated CO_2 emissions and reductions in embodied carbon for LC^3 products in this study

LC^3 Product	CO_2 Emissions (per tonne of LC^3)	Reduction in Embodied Carbon (compared with OPC)
LC^3-50 blocks	0.64 tonne	36%
LC^3-75 blocks	0.82 tonne	18%

4. Conclusions

This study examined the viability of employing limestone calcined clay cement (LC^3) to produce new eco-friendly blocks. The produced blocks were assessed through a number of essential features, namely, the applicability of manufacturing LC^3-based masonry units in a plant, by using the block maker machine, compressive strength, density, and absorption. Based on the results of this work, the following conclusions can be drawn:

- The production process of LC^3-75 and LC^3-50 cellular blocks in a market plant by using the automated block maker machine proceeded successfully, similar to the manufacturing process of conventional OPC blocks. Also, the produced LC^3 blocks were collected and lifted normally by a forklift truck after six days of casting.
- Locally available raw materials in Iraq, especially low-grade clay, can be used to manufacture LC^3 masonry units with a promising performance. The results of compressive strength and absorption for the produced LC^3-75 cellular blocks satisfied the corresponding values of loadbearing units, while those of LC^3-50 cellular blocks fulfilled the relevant values of nonloadbearing walls. The compressive strength at 28 days of LC^3-75 and LC^3-50 blocks achieved strength index values of 94% and 82%, compared with OPC blocks, respectively. The achieved values of compressive strength satisfied the requirements of the Iraqi standard specifications for the grade A of loadbearing blocks. In addition, by comparison with ASTM standards, these values for LC^3-75 blocks fulfilled the requirements of loadbearing masonry units, while the values of LC^3-50 blocks satisfied only the requirements of nonloadbearing masonry units. Regarding the absorption, LC^3-75 and LC^3-50 blocks recorded an increase in absorption of 21% and 31%, compared with OPC blocks, respectively. However, the reported absorption values also satisfied the requirements of the Iraqi standard specifications for the grade A of loadbearing blocks and the requirements of ASTM for loadbearing masonry units as well.
- The produced LC^3 blocks provided slightly lighter weights of masonry units, which can offer many constructions, economic, and environmental benefits, compared with those manufactured with the conventional cement. The values of density for LC^3-75 and LC^3-50 blocks reported 2144 kg/m^3 and 2126 kg/m^3, with reductions of 0.9% and 1.7%,

respectively, compared with OPC blocks. According to ASTM standards, these blocks are considered as normal weight masonry units.

- The manufactured LC^3 blocks could be considered as low-carbon masonry units because their preliminary reductions in embodied carbon were 18% and 36% for LC^3-75 and LC^3-50 units, respectively, compared with the commercial cement units.

5. Limitations of Study

While the experimental work of this study provides significant contribution to the field of eco-friendly masonry structures, it is important to identify the limitations of this study to understand the boundaries of its applications, and to improve the future studies in this line. One of the major limitations is the variation in mineralogical composition for the clay, which affects the selection of calcination technology and the obtained characteristics of the calcined clay. Achieving a unique optimum calcination process for a clay deposit in a region requires a longer time to collect suitable number of clay samples and conducting a series of optimization process for all the variables. In addition, satisfying the uniformity of calcination technology is difficult to be controlled by using a laboratory static calcination. Regarding the production of masonry units, the homogeneity of produced blocks in plant cannot be guaranteed in a high level of accuracy as a result of combined effects due to many factors related to materials, production, and curing conditions. Moreover, testing masonry units inherently involves a high scatter in outputs due to impacts of non-uniformity. To reduce the impact of these factors, a larger number of specimens and more laboratory resources would be useful to obtain more accurate results. Finally, further studies are recommended to develop deeper knowledge for the benefits of LC^3 cellular blocks. These studies could be conducted in shrinkage, freeze-thaw and wetting-drying resistance, carbonation, chloride ingress, sulfate resistance, efflorescence, long-term strength beyond 28 days, field validation, LC^3-based masonry behavior, thermal conductivity, and full environmental assessment. These studies will promote the present concrete block manufacturing to the point where the eco-friendly units, proposed in this study, are adopted in practice in order to enhance the global sustainable development.

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