Visual Abstract

Glass fiber for improved behavior of light expanded clay aggregate concrete beams: an experimental study

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ABSTRACT. Concrete developed from light expanded clay aggregate (LECA) and glass fiber has good performance, durability, and sustainability. Towards this, the experimental investigation was designed to study cubes, cylinders, and simply supported beams. Four mixtures had LECA volume of 0%, 75%, 85%, and 95% as coarse aggregate replacement and glass fiber content volume of 2% (N, L75, L85, and L95), and the other two mixtures had 75% LECA and glass fiber content of 1% and 1.5% (L75-F1 and L75-F1.5). Results compared to normal concrete showed the weight reduction of samples while adding more glass fiber caused slump reduction in contrast to LECA. Increasing glass fiber volume in the mixture had a negative influence on tensile strength while causing compressive strength enhancement. Moment resistance and energy absorption capacity of L85 were enhanced by 7.5% and 10.3%, respectively. For L75-F1 specimens, the beam stiffness and ductility were enhanced by 14.8% and 14.3%, respectively. Finally, using more glass fibers did not necessarily result in improved mechanical properties. More ideal properties can be obtained by controlling the LECA content and glass fibers ratio. After conducting tests, narrowing down the glass fiber content range up to 2%, along with LECA content of 75% and 85%, is highly recommended for obtaining the best behavior of glass fiber-reinforced LECA concrete.

KEYWORDS. Energy absorption, Glass fiber, LECA, LWC, Mechanical properties, Strength.

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INTRODUCTION

The use of lightweight concrete (LWC) in the construction industry is gaining popularity due to an increase in the demand for sustainable buildings and a reduction in transportation-related greenhouse gas emissions [1]. To produce lightweight concrete there are many techniques like no fines, aerated, and lightweight aggregate concrete. Such aggregates have two sources to get, natural like scoria, pumice, coconut shells, and oil palm shells, or artificial like expanded clay, and expanded slate [2,3]. One of the most promising materials for this purpose is fiber-reinforced lightweight aggregate

composites. Composite structures made of light expanded clay aggregate (LECA) are extremely durable, fire-resistant, sound isolation, and lightweight [4,5]. However, a major drawback of concrete made from these materials is that they have a high brittleness that limits their application to thin cross-sections only. One possible solution to this problem is the use of fibers as a replacement material to improve the mechanical properties of fiber-reinforced polymer composites. The addition of fibers makes the concrete more homogeneous and isotropic, transforming it from a brittle to a ductile material. Fiber-reinforced lightweight aggregate can improve the durability and strength of concrete while reducing construction costs and carbon emissions. When concrete cracks, the randomly oriented fibers limit crack propagation, resulting in increased strength and ductility [6]. Therefore, the present study investigates the effect of adding LECA to the matrix of glass fiber-reinforced polymer composites on the performance of the resulting structural beams.
LECA is a round artificial lightweight aggregate. It is manufactured by subjecting its raw material to high temperatures of up to 1300 C° in a horizontal rotary furnace. High temperatures cause gas emissions and expand to six times their original size [7]. Vijayalakshmi and Ramanagopal reported that LECA can be used to produce structural lightweight concrete with compressive strengths ranging from 30 MPa to 60 MPa and densities ranging from 1290-2044 kg\m³ [8]. Sajedi and Shafigh demonstrated experimentally that high-strength LWC can be produced from 28.2 MPa to 55.1 MPa by using LECA aggregate with various pellet sizes and silica fume [9]. Vinoth and Vinod Kumar showed that using LECA concrete by 0-20% as a coarse aggregate replacement resulted in compressive strength ranging from 42 MPa to 45 MPa. The 15% LECA replacement mixture has higher compressive and splitting tensile strengths than the normal control mixture [10]. Because lightweight concrete has lower mechanical properties than conventional cement, its structural application was limited. Meanwhile, LWC is widely used in the construction industry as non-structural wall panels and architectural exterior finishing. With the rapid development of high-rise buildings and structures with extremely long spans, concrete density has become as important as strength, making it necessary to improve the mechanical properties of lightweight concrete for use in structural fields. Adding fibers is one method used to improve concrete behavior. Glass fiber, among other polymeric, metallic, and natural fibers, is one of the most commonly used fibers to improve concrete properties. The failure mode changed from brittle to ductile when PVA (polyvinyl alcohol) powder was added to glass fiber-reinforced concrete [11].
For ultra-lightweight concrete with a 30-65% decrease in weight, excellent ductility (50-150% increase over plain lightweight concrete) can be sustained at the expense of flexural strength (50-250% increase) using PVA fiber-reinforced lightweight concrete [12]. According to Zaid et al., increasing the percentage of glass fibers increases the mechanical properties of coconut shell concrete such as compressive, flexural, and split tensile strength. At 28 days, the concrete compressive strength and split tensile strength increase by about 20% and 22%, respectively, when 45% crushed aggregate is replaced with coconut shell aggregate and 1.5% glass fiber and 15% silica fume are added [13]. Ahmed et al. added glass, and nylon fiber to peach shell lightweight concrete by 2, 4, 6, and 8% from cement weight. the highest weight reduction was obtained equal 6.6% at 6% of glass fiber. Although, compressive strength, splitting tensile strength, and flexural strength were increased by 10.2%, 60.1%, and 63.49%, respectively. The findings confirmed that incorporating fibers into lightweight concrete improved mechanical properties such as modulus of elasticity and post-failure toughness [14]. Wu et al. found that incorporating glass fiber was more effective than incorporating polypropylene fiber in improving the mechanical properties and post-failure toughness of peach shell concrete. Although the addition of fibers increased water absorption and porosity slightly, adding 0.75% glass fiber improved the mechanical properties of peach shell lightweight concrete. Compressive, splitting tensile, and flexural strength were increased by 19.1%, 54.3%, and 38.6%, respectively, while density was reduced by up to 6.1% [15]. Amani et al. mentioned that the use of glass fiber increased the flexural strength of LECA concrete by 18% [16].
Previous studies show that glass fibers can be used in lightweight aggregate concrete to improve its mechanical and durability properties, resulting in sustainable concrete with acceptable strength and ease. However, there are few kinds of literature on the comparison of glass fiber-reinforced LECA lightweight concrete. The current study presents an experimental investigation conducted to explore the effect of various ratios of glass fiber content on the behavior of lightweight concrete. Standard 18 cubes, 18 cylinders, and 18 simply supported four loading samples were used to measure the physical and mechanical properties of mixes such as density, slump, compressive strength, and split tensile strength. Finally, the structural behavior of six simply supported three loading beams composed of LECA and glass fiber was investigated by studying the crack pattern, moment resistance, stiffness, ductility, and energy absorption capacity.

MATERIALS AND METHODS

The research program is divided into two sets; the first one consists of four mixtures with a glass fiber content of 2% and LECA aggregate by ratios (0%, 75%, 85%, and 95%) as a replacement for coarse aggregate volume. The second one consists of two mixtures with LECA aggregate by 75% replacement with a glass fiber content of 1% and 1.5%.

Triplicate standard cubes 150 mm × 150 mm × 150 mm, cylindrical samples 150 mm × 300 mm, and standard four-point loading beams were used to measure physical and mechanical properties for mixes such as density, slump, compressive strength, and tensile strength. Flexural strength was determined by testing six beams at two points of loading at one-third of the beam length. To determine the total applied load and the mid-span displacement of specimens, a load cell and a linear variable displacement transformer (LVDT) were used as shown in Fig. 1.

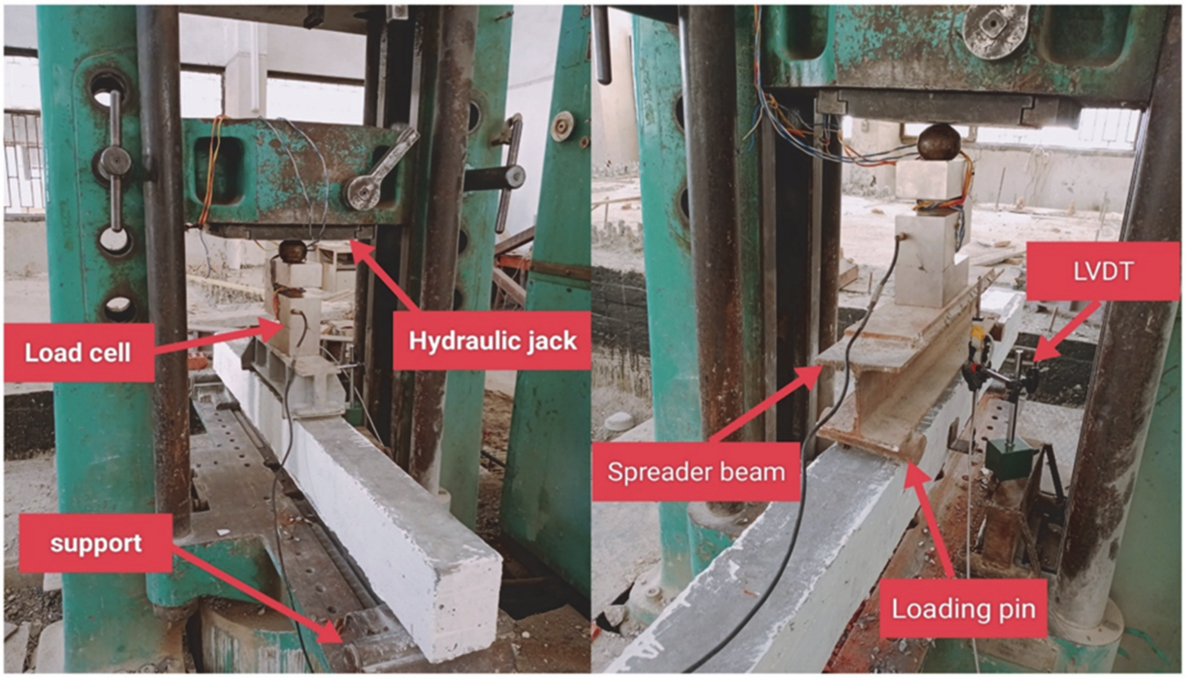


Figure 1: Components of beams testing machine and instruments.

Materials

The materials used in concrete mixtures include fine, normal coarse, lightweight coarse aggregates, hydraulic cement, Silica fume, super plasticizing admixture, tap water, and glass fiber. Natural siliceous sand had a fineness modulus of 2.72 and a bulk density of 1738 kg/m^3. Sieve analysis is shown in Tab. 1. Locally available crushed dolomite was used as a normal coarse aggregate. Normal coarse aggregate with a maximum nominal size 14 mm, bulk density 1570 kg/m^3, specific gravity 2.62, and water absorption ratio 2.35% is used. Sieve analysis of normal coarse aggregates is shown in Tab. 2. In this study the coarse lightweight aggregate, expanded clay aggregate type LECA, which is locally produced by ALEX Hydroponics company for the hydroponics clay industry, is shown in Fig. 2.a. LECA brown pellets were applied in a rotary kiln at a temperature 950-1100 C$^\circ$. LECA's maximum nominal size is 20 mm, specific gravity =1.6, bulk density =1000 kg/m^3, and water absorption ratio =16.69 %. Sieve analysis of LECA is shown in Tab. 3. In this study, LECA pre-soaked in water before mixing for 24 hours to make sure that all inside voids were filled with water and were taken out from the water an hour before usage. LECA chemical components are shown in Tab. 4.

Sieve size (mm)	5	2.36	1.18	0.6	0.3	0.15
Passing %	99.4	95	78.4	44.4	8.6	2

Table 1: Sand sieve analysis.

Sieve size (mm)	14	10	5
Passing %	99.167	77.67	12.5

Table 2: Normal coarse aggregate sieve analysis.

Sieve size (mm)	20	14	10
Passing %	95.9	19.7	0

Table 3: LECA sieve analysis.

Components	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	LOSS
LECA	61.12	18.77	14.21	1.78	2.37	0.4

Table 4: LECA chemical components (Wt%).

The specimens were made using ordinary Portland cement with a grade of 42.5 as a binder. Portland cement used was type I (CEMI 42.5N), following Egyptian standards ES 4756-2 / 2020 [17]. It is produced locally in EGYPT by Suez Cement Company. Tab. 5 lists the physical and chemical properties of cement. The specific gravity of cement was taken to equal 3.15. Sika fume - HR was a chemical from Sika Egypt for construction chemicals. Fig. 2.b shows a grey powder Sika fume with a density of 0.65±0.1 kg/L. Silica fume is usually used by 2-10% of the cement weight and is added directly to the cement before adding water. In this experiment, Sika fume was used at a rate of 8% of the cement weight. A high range water reducing super plasticizing admixture from Master Builders Solutions Construction Chemicals Egypt was used, MasterRheobuild1100. MasterRheobuild1100 is a chloride-free product; its basic components are synthetic polymers, which allow for significant reductions in mixing water and increases in concrete strength, particularly at early ages. It satisfies the requirements for superplasticizers specified by American standards ASTM C-494 type A&F and British standards BS 5075 Part 3. MasterRheobuild1100 can be used at a rate of 1-3 L/100 kg of cement, and it is used at 2.2% in this experiment. Tab. 6 lists the mechanical and physical properties of MasterRheobuild1100.

Properties	Initial setting time (min)	Soundness (expansion) mm	Compressive strength 2D (MPa)	Sulfate (SO_3)	Chloride content (CL^-)
Value	≥ 60	≤ 10	≥ 10	≤ 3.5 %	≤ 0.1 %

Table 5: Physical & chemical properties of cement.

Properties	Value
Colour	Dark brown liquid
Specific Gravity at 25°C	1.19-1.26
Air-entrainment	Maximum 1%
PH	6-11

Table 6: Typical properties of MasterRheobuild1100.

Glass fiber is manufactured in Egypt by the Egyptian European Steel Fiber company. Fig. 2.c shows a glass fiber of type E that has been coated with silane to improve initial dispersion and bonding. The fiber has a length of 12 mm, a diameter of 13 microns, and a tensile strength of 500-600 N/mm². Finally, two types of locally produced reinforcing bars were used. The first was tensile longitudinal reinforcement made of strength steel (f_y /f_{ult} = 40/60). The second was stirrups and upper longitudinal reinforcement made of ordinary mild steel (f_y /f_{ult} = 24/35).

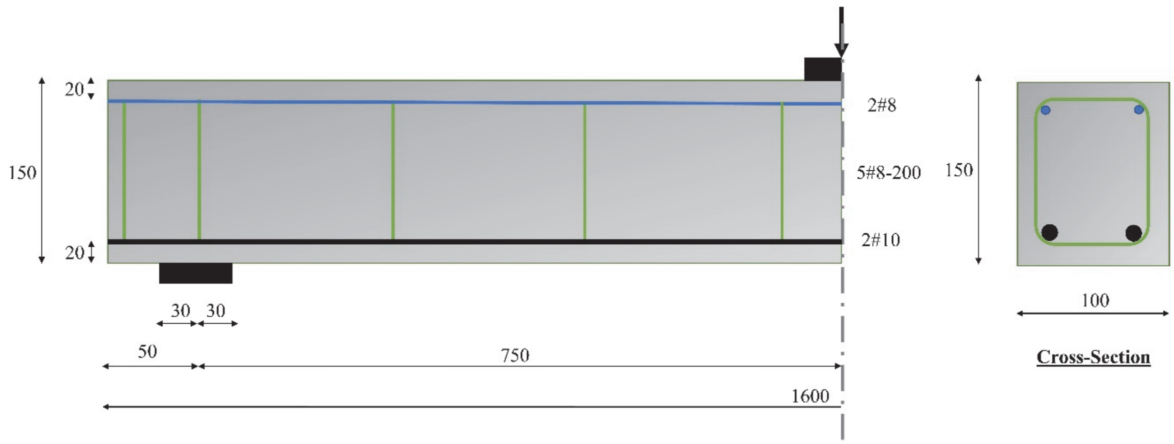
(a) (b) (c)

Figure 2: Materials of research (a) LECA. (b) silica fume. (c) glass fiber.

Specimens

The experimental program consists of simply supported normal and lightweight concrete beams, cubes, and cylinders. Beams have a rectangular cross-section (10 cm ×15 cm), a total length of 160 cm, and a clear span of 150 cm. Fig. 3 shows the reinforcing detailing of test specimens. The bars used for tensile longitudinal reinforcement were 10 mm in diameter.

Bars with a diameter of 8 mm were used for upper reinforcement and stirrups. Specimens were divided into two sets, the first of which included four beams (N, L75, L85, and L95) with LECA aggregate by ratio 0%, 75%, 85%, and 95%, respectively, and 2% glass fiber content. N specimen is a normal control sample concrete used as a reference to evaluate the effect of LECA aggregate and fiber added to the mixtures. The second is composed of two beams (L75-F1 and L75-F1.5) that contain glass fiber by a ratio of 1% and 1.5%, respectively, and 75% LECA replacement. To measure the compressive and splitting tensile strength of concrete, standard cubes 150 mm in size and cylinders 150 mm in diameter and 300 mm in length were prepared. At 28 days, compressive and tensile strength were measured as an average. Tab. 7 summarizes the variables for each specimen.



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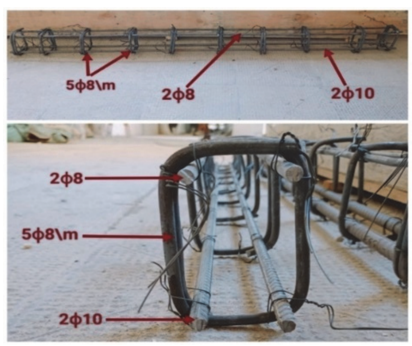

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Figure 3: (a) Beam and cross-section details. (b) Reinforcing detailing of test specimens. All dimensions are in mm.

Sample ID	Input variables	
	LECA replacement %	Glass Fiber content %
N	0	2
L75	75%	2
L85	85%	2
L95	95%	2
L75-F1	75%	1
L75-F1.5	75%	1.5

Table 7: variables of tested specimens.

Test methods

A total of six concrete mixtures in this study, the normal and lightweight concrete with glass fiber were proportioned for 1 m^3 as summarized in Tab. 8 and with a constant water-to-cement ratio w/c of 0.39. Silica fume was used at a constant rate of 8 % from cement weight in all mixes to improve strength, durability, stability of fresh concrete, and abrasion resistance. Within the high range water reducer (HRWR) was used at a constant rate of 2.2 L\ 100 kg cement to reduce mixing water and increase concrete strength.

Mix ID	Cement	SF*	Water	HRWR**	Aggregate			Glass Fiber (% of volume)
					Sand	Normal	LECA	
N	500	40	195	11	574.4	1004.8	0	2%
L75						248.9	484.5	
L85						149.34	549.1	
L95						49.78	613.7	
L75-F1						248.9	484.5	1.5%
L75-F1.5						248.9	484.5	1%

*SF=Silica Fume, **HRWR=High Range Water Reducer

Table 8: Concrete mixtures for research samples (kg\m^3).

The mixing procedure was carried out in several steps by using a laboratory mixer with a capacity of 0.05 m^3 as shown in Fig. 4. First, sand, coarse aggregate, LECA aggregate, silica fume, and cement were mixed in dry conditions for 2 min to ensure uniformity of the mix. Half of the mixing water was added gradually during mixing and followed by the remaining water with HRWR and mixed for two minutes. Fibers were slowly and gradually sprinkled into the concrete mixture to ensure better homogeneous distribution. Finally, to ensure the concrete is homogeneous hand mixing was performed. Mixing process. After 24 hours specimens were marked and put in a water curing tank for 28 days to have the same curing conditions.

Figure 4: Mixing process.

Results and discussion

The mean and standard deviation (SD) of the density, compressive, and splitting tensile strengths after 28 days are displayed in Tab. 9 with SD below 35%. The sample results for slump and flexural tensile strengths after 28 days for each concrete mixture are also presented in Tab. 9. Fig. 5 represents the relationship between these physical and mechanical properties of concrete and LECA or fiber content.

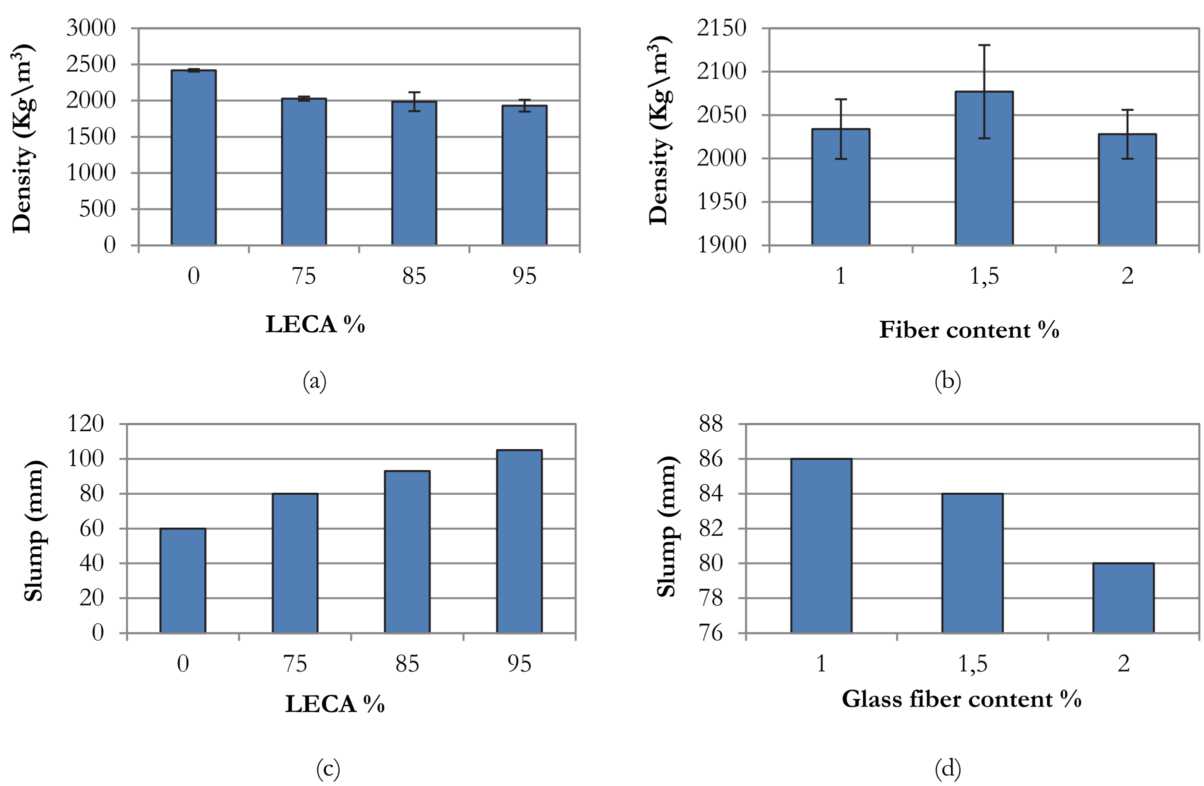
Density

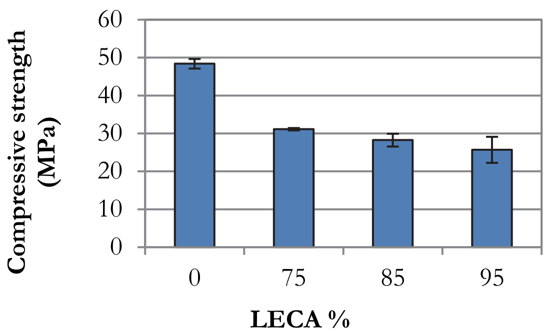
As shown in Tab. 9, the hardened density result for a mixture with 95% LECA content was reduced by about 20%, while mixtures with 75% and 85% LECA reduced bulk density by about 16% and 18%, respectively, when compared to normal concrete weight 2419 kg\m^3. Fig. 5.a and Fig. 5.b represent the relationship between bulk density, LECA content, and glass fiber content. Using various glass fiber content showed a very low effect on the weight of LECA concrete. Compared to concrete with 75% LECA content + 2% glass fiber, using 1.5% glass fiber content caused a weight increase by 2.02% to reach 2077 kg\m^3 from 2028 kg\m^3 while using 1% glass fiber content slightly caused no effect on bulk density (increasing by 0.25%) to reach 2034 kg\m³. The decrease in the weight of fiber-reinforced samples can be attributed to the increased number of voids due to the incorporation of more fibers in the matrix.

As a result of the low-density LECA introduced into the mixes, increasing LECA volume fraction leads to the gradually increased loss in densities. In a previous study [14,15], the incorporation of lightweight shell aggregate and glass fiber resulted in a density decrease of up to 6.6%, a greater result now of LECA concrete confirmed by this study. When the unit weight and compressive strength values are considered together, LECA mixtures can be classified as structural lightweight concrete. L85 and L95 density values complied with the European specification for structural lightweight concrete of density not exceeding 2000 kg/m³ but not met the ACI specification of 1850 kg/m³ [18]. ACI Committee definition states that the compressive strength of structural lightweight concrete at 28 days should be higher than 15–17 MPa [19]. It was seen from the experimental results (see Tab. 9) that, the compressive strength values of all LECA mixtures were found to be satisfactory.

Sample ID	**Density**			**Slump**		**Compressive strength**			**Splitting tensile strength**			**Flexural tensile strength**	
	Mean kg/m³	**SD**	**%**	**mm**	**%**	**Mean MPa**	**SD**	**%**	**Mean MPa**	**SD**	**%**	**MPa**	**%**
N	2419.05	17.03	-	60	-	48.41	1.26	-	3.40	0.28	-	22.73	-
L75	2028.63	28.16	-16.14	80	+33.33	31.13	0.31	-35.7	1.58	0.18	-53.52	22.24	-2.19
L85	1986.66	130.4	-17.87	93	+55	28.21	1.67	-41.63	1.82	0.15	-46.54	24.43	+7.46
L95	1930.78	81.74	-20.19	105	+75	25.68	3.43	-46.94	2.03	0.08	-40.5	21.80	-4.09
L75-F1	2034.56	34.34	-15.89	86	+43.33	23.56	5.94	-51.32	2.36	0.59	-30.48	22.93	+0.89
L75-F1.5	2077.43	53.73	-14.12	84	+40	29.30	1.38	-39.46	2.02	0.16	-40.5	24.24	+6.65

Table 9: Physical and mechanical properties of concrete mixes.





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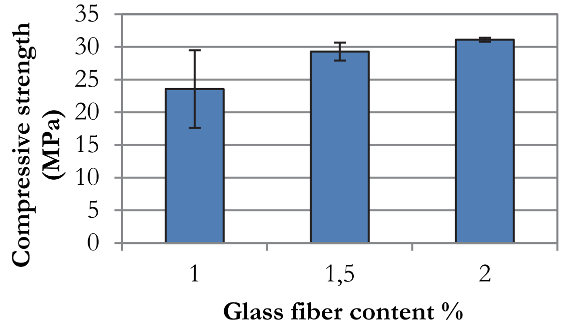

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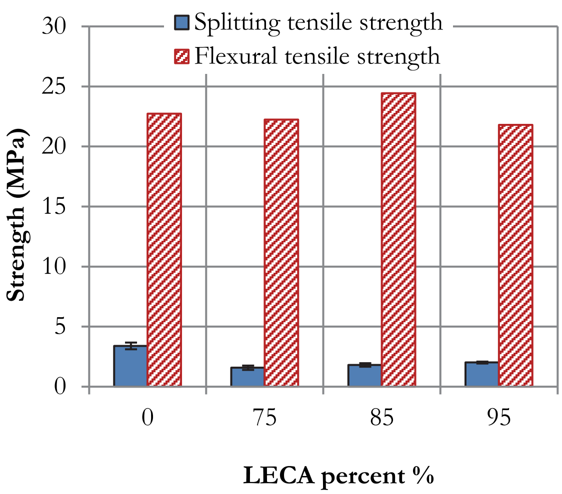

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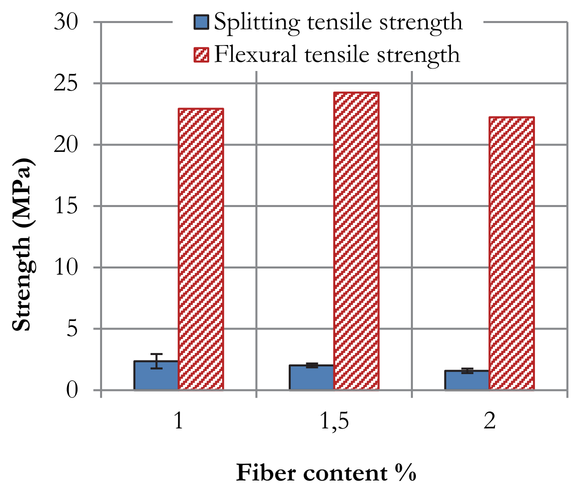


(h)

Figure 5: Relation between; (a) bulk density and LECA content. (b) bulk density and fiber content. (c) slump and LECA content. (d) slump and fiber content. (e) compressive strength and LECA content. (f) compressive strength and fiber content. (g) tensile strengths and LECA content. (h) tensile strengths and fiber content.

Figure 6: Steps of slump cone test.

Slump

The slump of concrete mixtures was determined using a cone test after mixing, as shown in Fig. 6. Tab. 9 summarizes slump behavior for concrete mixtures in which the slump increased by 33.33-75% by adding more LECA aggregate to reach 105 mm for 95% LECA replacement compared to 60 mm for normal concrete. When using different fiber content for a 75% LECA replacement mixture, the slump increased by 6.66% and 10% for 75% LECA mixtures with a fiber content of 1.5%

and 1%, respectively, when compared to 75% LECA content +2% glass fiber content. The graphs in Fig. 5.c and Fig. 5.d illustrate the relationships between slump, LECA content, and glass fiber content. The results showed that as the glass fiber content increased, the slump decreased. However, the value of reduction is less than 10%. While a larger slump for concrete is desirable to aid in placement and consolidation, the workability of LECA mixes achieves a gradual increase in a slump with increasing LECA content at the same HRWR dosage.

Compressive strength

Compression tests on standard cubes were performed according to British standards BS EN 12390-3 [20]. Three cubes were tested for each mixture under constant rate-increasing loading, as shown in Fig. 7. Fracture at normal concrete cubes after testing compressive strength was beside normal aggregate pellets through concrete, while in LECA concrete fracture was through LECA pellets which means normal aggregate is stronger than LECA pellets. The average compressive strength of normal concrete (N) was 48.40 MPa, which was reduced to 31.12, 28.25, and 25.68 MPa for 75%, 85%, and 95% LECA replacement, respectively. As shown in Tab. 9, this resulted in a large strength reduction of 36%, 42%, and 47% for 75%, 85%, and 95% LECA replacement, respectively. Also, there was a reduction in compressive strength of about 51%, and 40% of LECA specimens with a glass fiber content of 1 and 1.5%, respectively, compared to the LECA sample with a fiber content of 2%. The compressive strength reduced to reach 29.3 and 23.56 MPa for 1.5%, and 1% fiber content, respectively, compared to 31.12 MPa for 2% fiber content.

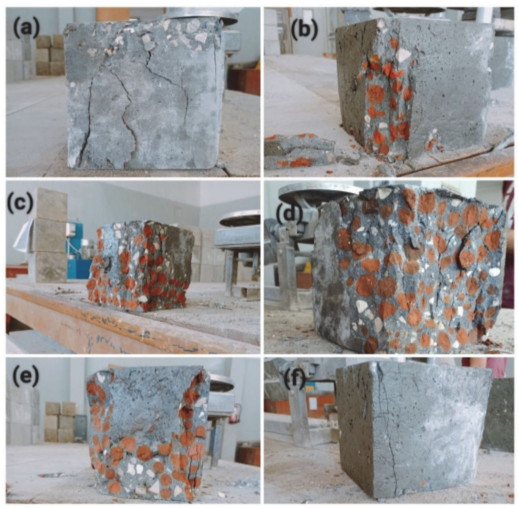


Figure 7: Samples after compressive strength test; (a) Normal concrete +2% glass fiber. (b) 75% LECA +2% glass fiber. (c) 85% LECA +2% glass fiber. (d) 95% LECA + 2% glass fiber. (e) 75% LECA +1% glass fiber. (f) 75% LECA + 1.5% glass fiber.

The relationship between compressive strength, LECA content, and fiber content is represented in Fig. 5.e and Fig. 5.f. The compressive strength decreased significantly when the LECA volume fraction was increased to 95%. However, as the glass fiber content increased, the compressive strength increased gradually. The fiber volume fraction increases, resulting in a larger surface area that tends to pack tightly into the pores of the matrix. As a result, the stress required to achieve a given deformation increases, as does the specimens' compressive strength. When comparing 75% LECA content +2% glass fiber content to 75% LECA content +1% and 1.5% fiber content, the compressive strength increased by 15% and 4%, respectively. The previous study showed that the glass fiber addition resulted in an increase of lightweight aggregate concrete compressive strength up to 19%, a lower result now confirmed by this study for LECA concrete [14,15].

Tensile strength

The indirect splitting tensile strength was determined per British standards BS EN 12390-6 [21]. The load was applied diametrically in the transverse directions of standard cylindrical specimens at a constant rate. Fig. 8 represents splitting tensile strength specimens after testing. Also, flexural tensile strength was determined by four points loading due to ASTM C78/C78M-16 as shown in Fig. 9 [22]. Flexural strength of 18 simply supported beams was determined from the equation; [(p×L)/(b×d2)], where p is the maximum load applied on the beam, L is the supported beam length, b is the width of beam cross-section, and d is beam depth. All these values were considered as the ASTM standards recommend.

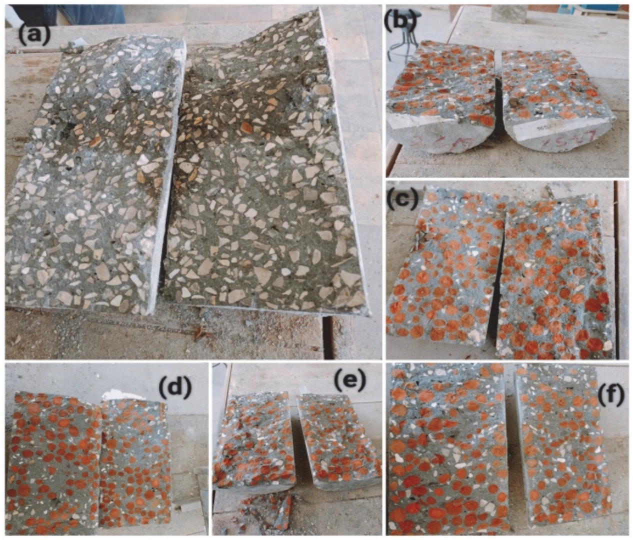


Figure 8: Cylinders after testing splitting tensile strength; (a) Normal concrete +2% glass fiber. (b) 75% LECA +2% glass fiber. (c) 85% LECA +2% glass fiber. (d) 95% LECA + 2% glass fiber. (e) 75% LECA +1% glass fiber. (f) 75% LECA + 1.5% glass fiber.

Figure 9: Four points loading applied to beam specimens.

Fig. 5.g and Fig. 5.h show the relation between tensile strengths, LECA content, and fiber content. Firstly, the splitting tensile strength of normal concrete was 3.395 MPa, which decreased by 53%, 46%, and 40% for 75%, 85%, and 95% LECA mixtures to reach 1.578, 1.815, and 2.02 MPa, respectively. While the splitting tensile strength increased in LECA mixtures with 1% and 1.5% glass fiber, it decreased in LECA mixtures with 2% glass fiber content. Splitting tensile strength increased by 30.5% and 40.5% for 1% and 1.5% fiber content to reach 2.36 MPa and 2.02 MPa, respectively.

Secondly, the flexural strength of normal concrete was 22.734 MPa. Using LECA aggregate at rates of 75% and 95% caused a small reduction in flexural strength at rates of 2% and 4% to be 22.236 and 21.802 MPa, respectively. While using LECA aggregate at a rate of 85% achieved flexural strength more than normal concrete by about 7.5%. At the same time using 1.5% and 1% fiber content increased flexural strength by rates of 7% and 0.9% to reach 24.245 and 22.937 MPa, respectively, compared to 22.236 MPa for LECA concrete with 2% fiber content.

Amani et al. mentioned that the increased strength of LECA concrete directly depends on the content, length, and thickness of the used fiber. Glass and Polyolefin fiber enhance the flexural strength of LECA concrete by around 18% and 45%, respectively [16]. This finding is consistent with that of the current study.

Fig. 10 shows that all concrete samples had a splitting tensile to compressive strength ratio in the 5-10% range. When compared to normal concrete, using LECA and glass fiber increased the ratio between splitting tensile strength and compressive strength by about 42% and 13% for samples L75-F1 and L95, respectively. The concrete with 75% LECA content + 1% glass fiber (L75-F1) had the highest splitting tensile to compressive strength ratio of 10%. While the concrete sample with 75% LECA content + 2% glass fiber (L75) had the lowest ratio of all samples with splitting tensile strength equaling 5% compressive strength. Concrete is used as a structural building material that holds compressive stresses, while the tensile stresses-to-strain ratio should never develop. As a result, the highest splitting tensile to compressive strength ratio is advantageous to avoid the major drawback of concrete, which is its inability to withstand significant tension.

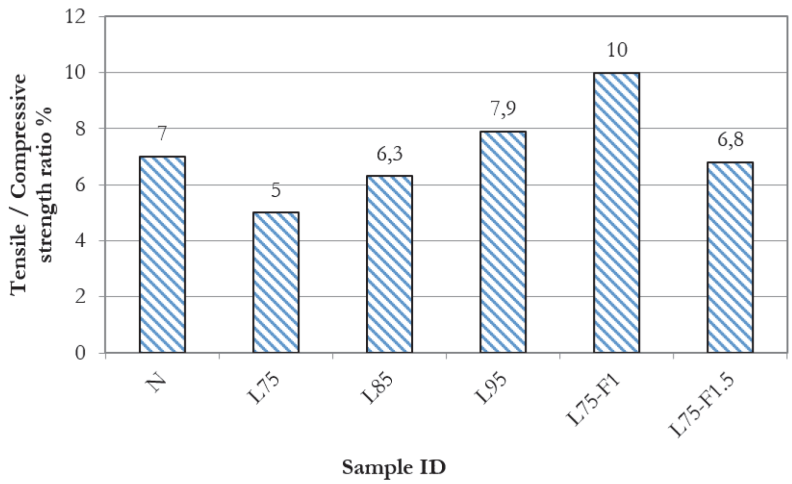
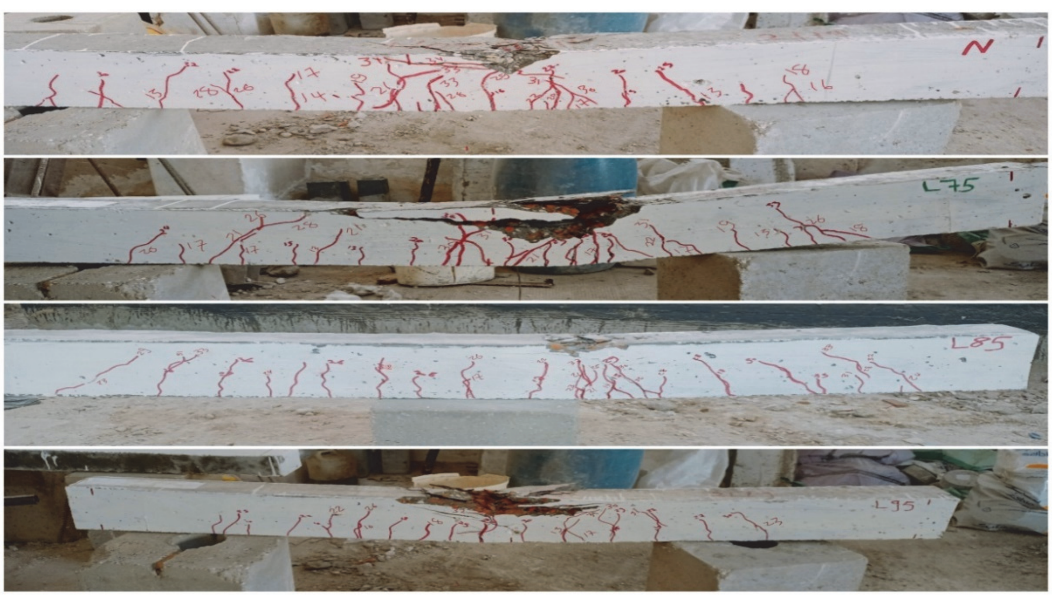


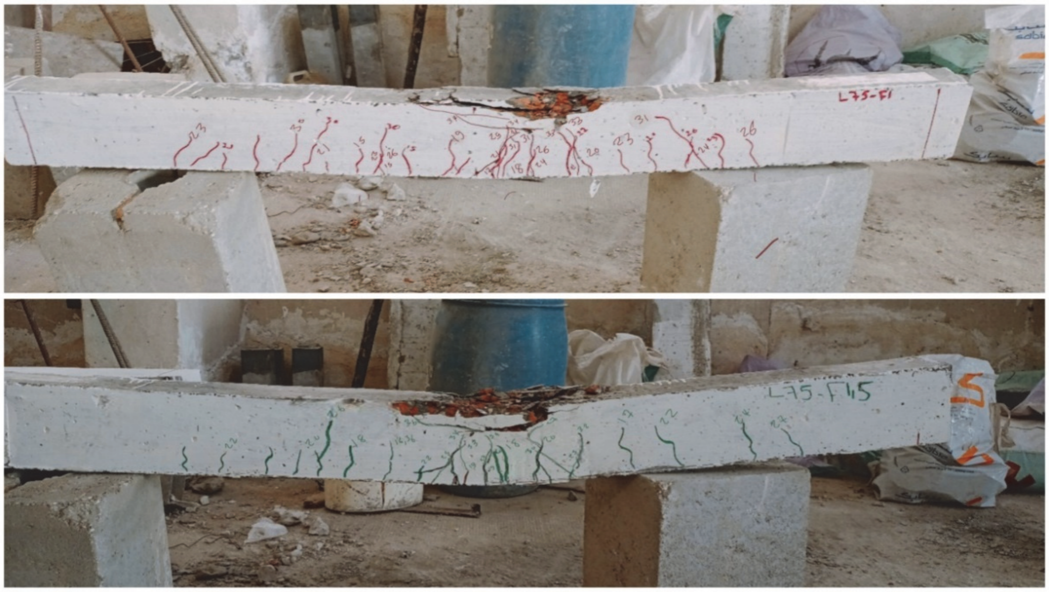
Figure 10: Ratio between splitting tensile strength and compressive strength for different samples.

Crack pattern and failure modes

The crack pattern and failure modes of tested specimens are presented in Fig. 11. Flexural cracks were observed in the mid-span region of normal concrete specimens at the initial loading level. Minor diagonal cracks appeared as the loading level increased. Diagonal cracks destined for loading points. Flexural cracks overlapped at the final loading level until the concrete crushed at the compression region, resulting in flexural-compression failure mode for sample N. Samples L75 and L95, similar to sample N, had the same failure mode (flexural-compression) and crack pattern, with only difference being that as the load increased, more diagonal cracks destined to loading points appeared. For specimen L85, flexural cracks were observed in the mid-span region at the initial loading level. The diagonal cracks appeared as the loading level increased. Finally, at the failure stage, some shear diagonal cracks emerged roughly 45º from the support region, and the sample failed due to concrete crushing at the compression region, resulting in flexural-compression failure. Adding fiber at a rate of 1% did not affect the crack pattern and failure mode of sample L75-F1 compared to sample L75 with 2% fiber content. Sample L75-F1.5 had the same crack propagation and failure mode as the other tested samples, but it had the least diagonal crack propagation.



(a)



(b)

Figure 11: Crack propagation and failure pattern of specimens; (a) N, L75, L85, and L95. (b) L75-F1 and L75-F1.5.

Flexural strength and displacement

Tab. 10 compares quantitatively the initial cracking and maximum (peak) loads, as well as moment resistance and deflection at both load stages. The first cracking load for normal concrete specimens was 15 kN, whereas the first cracking load for LECA L75, L85, and L95 specimens with 2% glass fiber content decreased by 13.33%, 6.66%, and 33.33% to reach 13, 14, and 10 kN, respectively. The first cracking load for the specimen with 1% glass fiber content was 15 kN, similar to the normal concrete specimen, while the specimen with 1.5% fiber content increased by 6.66% to reach 16 kN. The change in moment resistance of the tested specimens was remarkably similar to the maximum load, ranging from 8.1 kN.m to 9.16 kN.m. Moment resistance for specimens L85 and L75-F1.5 increased from 8.5 kN.m for normal concrete specimens by 7.5% and 6.65% to reach 9.16 and 9 kN.m, respectively, while moment capacity for specimen L75-F1 increased slightly by 0.9% to be 8.6 kN.m. However, the moment capacity for specimens L75 and L95 decreased by 2.2% and 4% to reach 8.3 and 8.1, respectively.

Sample ID	Cracking stage						Maximum stage					
	Cracking load		Cracking moment		Displacement at cracking load Δ_{cr}		Maximum load		Maximum moment		Displacement at maximum load Δ_{max}	
	kN	%	kN.m	%	mm	%	kN	%	kN.m	%	mm	%
N	15	-	3.75	-	3.271	-	34.101	-	8.525	-	20.968	-
L75	13	-13.33	3.25	-13.33	2.818	-13.85	33.354	-2.19	8.338	-2.19	10.341	-50.68
L85	14	-6.66	3.5	-6.66	3.224	-1.44	36.65	+7.47	9.16	+7.47	15.25	-27.27
L95	10	-33.33	2.5	-33.33	2.206	-32.56	32.704	-4.09	8.176	-4.09	15.192	-27.55
L75-F1	15	0.0	3.75	0.0	2.988	-8.65	34.405	+0.89	8.6	+0.89	10.705	-48.95
L75-F1.5	16	+6.66	4	+6.66	3.191	-2.45	36.368	+6.65	9.092	+6.65	13.054	-37.74

Table 10: Load, moment resistance capacity, and displacement of test specimens.

Fig. 12 plots the envelopes of load-deflection curves for normal concrete, LECA concrete with (75%, 85%, and 95%) replacement, and 75% LECA concrete with (1% and 1.5%) glass fiber ratios. The results revealed that the deflection corresponded to the maximum load recorded the highest value for normal concrete and decreased by about 50%, 27%, and 27.5% when LECA was added for samples L75, L85, and L95, respectively. Compared to normal concrete, the initial linear part rapidly reached the boundary of elasticity in the case of 85% LECA concrete and 75% LECA concrete with a glass fiber ratio of 1% and 1.5% (L85, L75-F1, and L75-F1.5). As a result, the addition of LECA and glass fiber affected the crack initiation and improved the post-cracking and ductile behavior of beams. The relationship between deflection, LECA content, and glass fiber content was illustrated in Fig. 13. For 75% LECA concrete with different fiber contents (1%, 1.5%, and 2%), the sample with a fiber content of 1.5% (L75-F1.5) recorded the highest deflection corresponding to the maximum load.

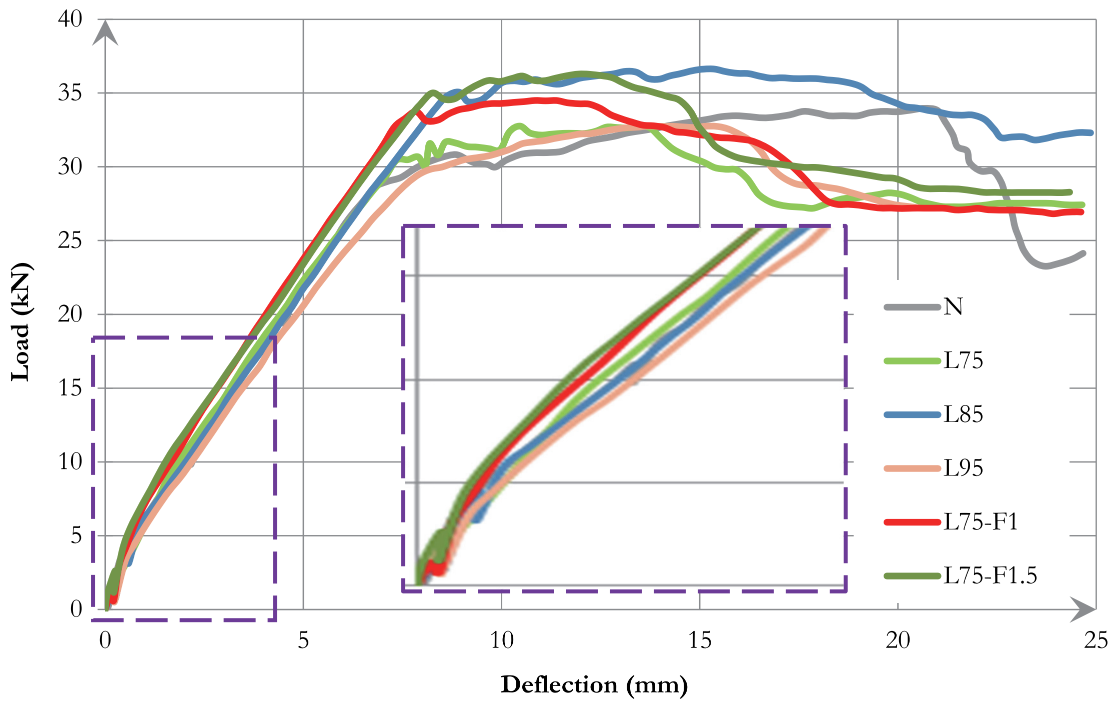


Figure 12: Load-displacement behavior of specimens.

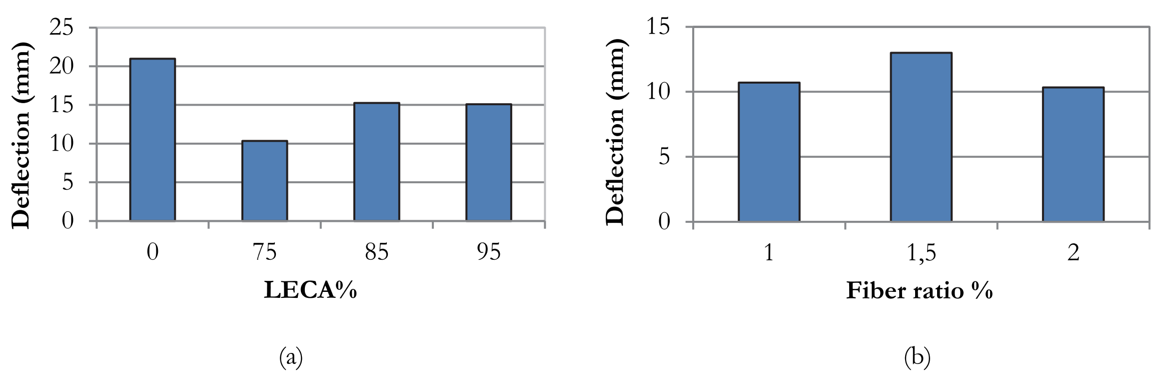


Figure 13: Relation between specimen deflection and; (a) LECA content. (b) glass fiber content.

Stiffness, ductility, and energy absorption capacity

However, load-deflection curves were nearly identical in this study, the beam stiffness was evaluated based on the concept of secant stiffness defined in the ACI 318M-19 code as the slope of the line connecting 45% of the peak load point to the origin. Tab. 11 summarizes the stiffness values for the tested beams. Only the L75-F1, L75-F1.5, and L75 beams had a significant increase in stiffness by 14.8%, 13.6%, and 3.9%, respectively. Due to the cracks formed and the nonlinear behavior of the constituent materials, the stiffness of the beam degraded by increasing LECA content.

In the seismic design of reinforced concrete structures, energy absorption, and displacement ductility capacities are important. As a result, ductility prediction should be as precise as possible to present a structure's ability to withstand inelastic deformations while retaining its loading capacity. The displacement ductility ratio, μ, is defined as Δ_u/Δ_y, where Δ_u and Δ_y represent the ultimate and yield displacements, respectively. Δ_u and Δ_y were calculated by fitting a beam's actual load-displacement response to an equal idealized bilinear curve. As proposed in ASTM E2126-11, the bilinear and original curves should intersect at a point equal to 40% of the actual curve's peak load [23].

Tab. 11 summarizes the ductility and dissipated energy values for the tested beams. It is necessary to allow for relatively high ductility so that seismic energy is absorbed without shear failure or concrete strength degradation, even after reinforcing steel yielding. Only the L75-F1, L75, and L75-F1.5 samples had significant enhancement in displacement ductility by 14.3%, 4.7%, and 4.27%, respectively. The area covered by a load-displacement curve is defined as energy absorption capacity. Only beams L85 and L75-F1.5 had significant increases in energy absorption capacities of about 10.3% and 2.1%, respectively, compared to normal concrete beams. Finally, no direct relations could be established between the LECA or glass fiber content and either a test specimen's energy absorption capacity or ductility. This behavior can be attributed primarily to the intense rocking behavior at a specific combination of LECA and glass fiber content.

Sample ID	Stiffness		Displacement ductility				Energy absorption capacity	
	kN/mm	%	Ultimate displacement Δ_y	Yield displacement Δ_u	Ductility ratio μ		kN.mm	%
			mm	mm	-	%		
N	4.57	-	27.17	5.81	4.68	-	662	-
L75	4.75	+3.94	26.50	5.41	4.90	+4.70	635	-4.07
L85	4.51	-1.31	28.06	6.33	4.43	-5.34	730	+10.27
L95	4.36	-4.59	22.77	5.94	3.83	-18.16	518	-21.75
L75-F1	5.25	+14.88	26.57	4.97	5.35	+14.32	663	-0.15
L75-F1.5	5.19	+13.56	25.88	5.30	4.88	+4.27	676	+2.11

Table 11: Ductility and energy absorption capacity of test specimens.

CONCLUSIONS

The effects of LECA and glass fiber content were investigated on the physical and structural behavior of lightweight concrete. For this purpose, 18 concrete cubes, 18 cylinders, and 24 beams were tested under incremental load. Through experiments the major conclusions are as follows:

- LECA aggregate could be used as lightweight aggregate, as using LECA as a coarse aggregate replacement at a ratio of 75-95% and increasing by 10% for each mixture resulted in weight reductions ranging from 16% to 20% compared to normal concrete weight. Glass fiber content almost has a minor effect on LECA concrete density. Compared to the LECA mixture with 2% fiber content, using glass fiber ratios 1 and 1.5 increased the density value by 2.1 and 2.4%, respectively.
- The relationship between LECA content and density is inverse, with increasing LECA content lowering density to 1930 kg/m^3 at 95% LECA content mixture. Despite the weight reduction, the density of only L85 and L95 concrete samples was within the range of structural lightweight concrete according to the European specification by 17.8% and 20% weight reduction compared to normal concrete, indicating that LECA can be used to produce structural lightweight concrete.
- The slump of concrete increased by adding more LECA to the mixture by 33-75% compared to normal concrete while adding more glass fiber to the LECA mixture caused slump reduction as a result of fiber absorption of mixing water. The 95% LECA content +2% glass fiber mixture (L95) had the highest slump value compared to all mixtures
- Adding more LECA to the concrete mixture decreased compressive strength while increasing glass fiber content improved compressive strength. The 75% LECA content +2% glass fiber mixture (L75) was the optimum LECA mixture, which recorded the highest compressive strength 31 MPa. Normal concrete had a compressive strength of 48.4 MPa which is in the range of high-strength concrete, while LECA mixtures had a compressive strength of 23.5-31 MPa, which is out of range, so LECA concrete can't be used to get high-strength concrete.
- For the same LECA mixture, increasing glass fiber volume had a negative influence on splitting tensile strength, while increasing LECA content improve the splitting tensile strength of LECA concrete by 13% for 95% LECA content +2% glass fiber mixture (L95) compared to 75% LECA content +2% glass fiber mixture (L75). Among all samples, 75% LECA content +1% glass fiber mixture (L75-F1) is the best lightweight mixture for splitting tensile strength. As a result, the splitting tensile strength reduction influence of glass fiber had more significance than the enhancement effect of increasing LECA content.

- All the tested specimens failed in flexural-compression cracks and a greater number of cracks were observed for lightweight fiber-reinforced concrete beams as compared to normal-weight concrete specimens at the same loading level. The addition of LECA and glass fiber affected the crack response at similar loads and improved the post-cracking and ductile behavior of beams.
- The behavior of load-deflection response curves for lightweight fiber-reinforced concrete beams is quite similar to that of normal-weight concrete beams. The percentage improvement of flexural resistance was affected by fiber and LECA content.
- The degree of influence of the LECA and glass fiber content on the test beam's behavior including stiffness, energy absorption capacity, and ductility was confirmed with this study. Beam named L75-F1 had the highest significant increase in stiffness and ductility by about 14.8% and 14.3%, respectively. However, the beam with 85% LECA +2% glass fiber (L85) achieved the best increase in energy absorption capacity by about 10.3%.

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