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MECHANICAL PROPERTIES OF LIGHTWEIGHT EXPANDED CLAY AGGREGATE (LECA) CONCRETE

Key words: lightweight concrete, mechanical properties, lightweight expanded clay aggregate, LECA concrete

Introduction

The self-weight of concrete construction accounts for a major amount of the total load on the structure. Therefore, decreasing the density of concrete has obvious advantages. Lightweight concrete (LWC) has become one of the most essential materials in construction today, because of its practical and economic advantages (American Concrete Institute [ACI], 2014b). The self-weight of normal concrete is about 2,400–2,500 kg·m^{-3}, this makes it very heavy, and the size of structural members increases as a result of the overall dead load. The LWC is a form of concrete that contains either lightweight aggregate (LWA) or an expanding agent. The dry density of LWC ranges from 300 to 1,840 kg·m^{-3}, and it weighs 23–80% less than conventional weight concrete. When compared to conventional weight concrete, which has a unit weight of 2,400 kg·m^{-3}, the unit weight of LWC for structural usage ranged between 1,400 and 2,000 kg·m^{-3} (Agrawal, Gupta, Sharma, Panwar & Siddique, 2021). Lightweight aggregate has many advantages when used in producing the concrete such as reducing a dead load of a structure elements that may result in reduced foundation size and large area availability due to reduction in the dimensions size of columns, slabs, and beams, high thermal and sound insulation, enhanced fire resistance (El-Sayed, Heniegal, Ali & Abdelsalam, 2013). For structural LWC applications, the 28-day compressive strength should be greater than 17 MPa (Abdulrazzaq & Khadhim, 2019; Ahmad, Chen & Shah, 2019). Nowadays, many types of LWA can be utilized to make lightweight concrete such as expanded

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clays, slate, shale, pumice, etc. (Agrawal et al., 2021). One of the LWA types that are utilized in structure construction is light expanded clay aggregate (LECA), which is a kind of artificially produced LWA that is created by expanding the natural clay at a high temperature of around 1,200°C (2,190°F) in a horizontal rotary kiln. Thousands of tiny bubbles are formed during the heating process, expands the clay about 5–6 times about its original volume, forming a honeycomb structure. The LECA has a spherical or potato shape appearance because of the circular movement in the kiln with they have a secured and barely porous external surface as compared to internal structure that is black in the color and highly porous (Ahmad et al., 2019). For the production of LWC, the use of increasing amounts of cement becomes even more important. However, increasing the cement content for constant water content has generally improved the workability of these mixes, allowing for lower w/c ratios. Water content is reduced by using a superplasticizer. The use of a higher cement content paired with a lower w/c ratio may have contributed to the improved quality of the LWC matrix. Silica fume has risen in popularity in recent years as a result of its high reactivity potential, which is boosted by its large specific surface area. It works as a pozzolan when it reacts with the lime that is released during the hydration of Portland cement. There needs to be a lot of research done on the role of silica fume as well as the effects of aggregate on mechanical properties and durability (Mahdy, 2016). Dilli, Atahan and Şengül (2015) worked on different mixes of LWC using LECA with different unit weights 1,640 and 2,050 kg·m^{-3} to investigate the compressive strength, modulus of elasticity (MOE), Poisson's ratio, and the ductility of LWC to compare them with mixes of normal concrete (NC). The results showed that the compressive strength of LWC mixtures varied between 20 and 70 MPa. As well, LWC mixtures changed significantly in terms of elastic properties and ductility compared with NC mixtures. When compared to NC mixes, LWC mixtures showed a significant decrease in MOE and more brittle behavior throughout the same compressive strength range. Sonia et al. (2016) studied the properties of lightweight aggregate concrete (LWAC) using LECA as coarse aggregate with different ratios such as 20, 40, 60, 80, and 100% and compared them with NWC using fly ash ratios such as 15, 20 and 25% as a partial substitute for cement in concrete. The LWAC has shown a reduction in compressive strength and split tensile strength from 34.60–21.77 and 3.20–1.57 MPa, respectively, with an increase in LECA content from 0 to 100%. The values obtained for the LECA concrete when substituted with 40 and 60% of coarse aggregate showed better results when compared to NWC. Similarly, they found out that the replacement of cement with 15% fly ash gives better results. With various mix proportions, the use of fly ash and LECA, at 15 and 40%, shows higher compressive strength and tensile strength and thus can be recommended for structural purposes. Patel, Shah and Desai (2019) investigated the effect of partially replacing coarse aggregate with (LECA) on concrete mechanical properties. The percentage of replacement of normal aggregate ranges from 0–100% with an increment of 25%. The results show that the compressive strength decreased as the LECA content increased. The compressive strength, split tensile strength, and flexural strength decreased by 16.87, 17.20, and 13.29%, respectively, after 28 days of curing, along with a reduction in weight of about 28% with 100% LECA replacement of normal aggregate. Nevertheless, with 25% LECA replacement, negligible loss of strength is noted. To improve the mechanical properties of concrete containing LECA, materials such as silica fume, fly ash, slag, steel fiber, and polypropylene fiber can be used to increase its strength.

The aim of this work is to present an experimental study of the mechanical properties of LECA concrete. An effort was made in this study to examine the impact of adding silica fume (SF) to the structural LWC as an attempt to enhance strength performance. It's commonly used in concrete constructions that demand high strength or low water permeability as a partial replacement for cement. It is also known to be very reactive. Because of this, it is used in small amounts to improve the microstructure of concrete. The percentage of replacement of LECA (100%) instead of coarse aggregate. In addition, two kinds of concrete admixtures were used in this research; silica fume with a percentage of 8% of cement weight and superplasticizer with a percentage of 0.95% of cementitious materials (cement and silica fume).

Material properties

The materials used in this study are: Portland cement, fine aggregate (sand), light expanded clay aggregate (LECA) as a full replacement for the coarse aggregate, silica fume, superplasticizer.

Cement

Portland cement was utilized in the current study. Tables 1 and 2 show the chemical and physical properties of Portland cement, respectively. The properties of cement meet the requirements of ASTM C150/C150M-21 (ASTM International [ASTM], 2021).

Fine aggregate

The available natural fine aggregate (sand) that has a maximum size of 4.75 mm was used for the LWC mixture. The test

TABLE 1. Chemical properties of cement

Chemical properties	SiO_2	CaO	MgO	Fe_2O_3	Al_2O_3	SO_3	Loss on ignition	Insoluble residue	Lime saturated factor	C_3A
Tested cement [%]	21.67	57.3	2.83	3.8	3.5	2.25	3.9	1.42	0.83	2.9
ASTM C150/C150M-21	–	–	≤ 5	–	–	≤ 2.8	≤ 4	≤ 1.5	0.66–1.02	≤ 5

TABLE 2. Physical properties of cement

Physical properties	Tested cement	ASTM C150/C150M-21
Vicat initial time of setting [min]	156	not less than 45 min
Vicat final time of setting [min]	226	not more than 375 min
Average compressive strength, age (3 days) [MPa]	18.9	≥ 8
Average compressive strength, age (7 days) [MPa]	23.8	≥ 15

TABLE 3. Sand gradation and sulphate content

Specification	Sieve size [mm]							Pan	Sulphate
	9.5	4.75	2.36	1.18	0.6	0.3	0.15		
Cumulative passing [%]	100	98	90	77	56	20	1	–	0.4
Passing [%] (acc. ASTM C33/C33M-13)	100	90–100	80–100	50–85	25–60	5–30	0–10	–	< 0.5

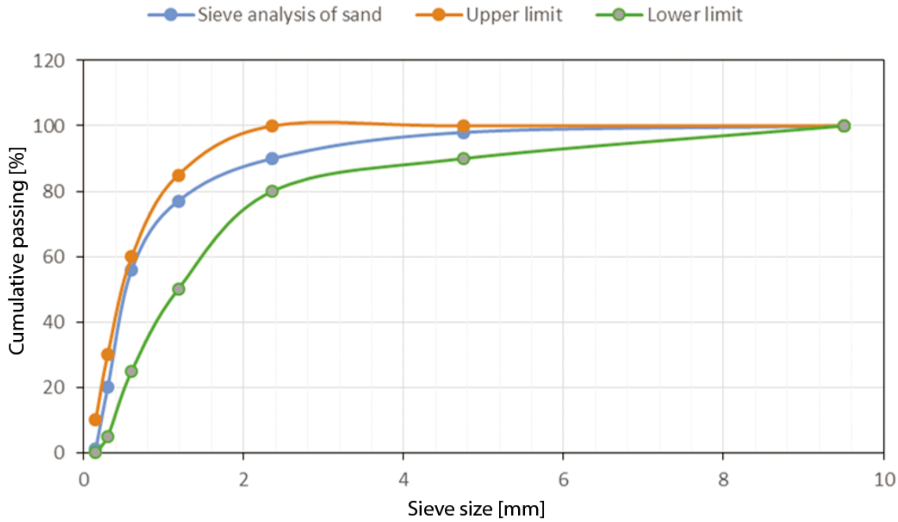

FIGURE 1. Sieve analysis of fine aggregate

results meet the requirements of ASTM C33/C33M-13 (ASTM, 2013a). The sand gradation and sulphate are presented in Table 3 and Figure 1.

Lightweight expanded clay aggregate (LECA)

The LECA was used in this study at a maximum size of 10 mm as a lightweight aggregate in all LWC mixtures. In this study, expanded clay aggregate, as shown in Figure 2, was used as a full replacement for the coarse aggregate. The test results meet the requirements of ASTM C330/ /C330M-17A (ASTM, 2017). The gradation

FIGURE 2. Shows lightweight expanded clay aggregate (LECA) used in the current study

TABLE 4. Lightweight expanded clay aggregate (LECA) gradation results

Specification	Sieve size [mm]				
	12.5	9.5	4.75	2.36	1.18
Cumulative passing [%]	100	88	9	3	1
Passing [%] (acc. ASTM C330/C330M-17A)	100	80–100	5–40	0–20	0–10

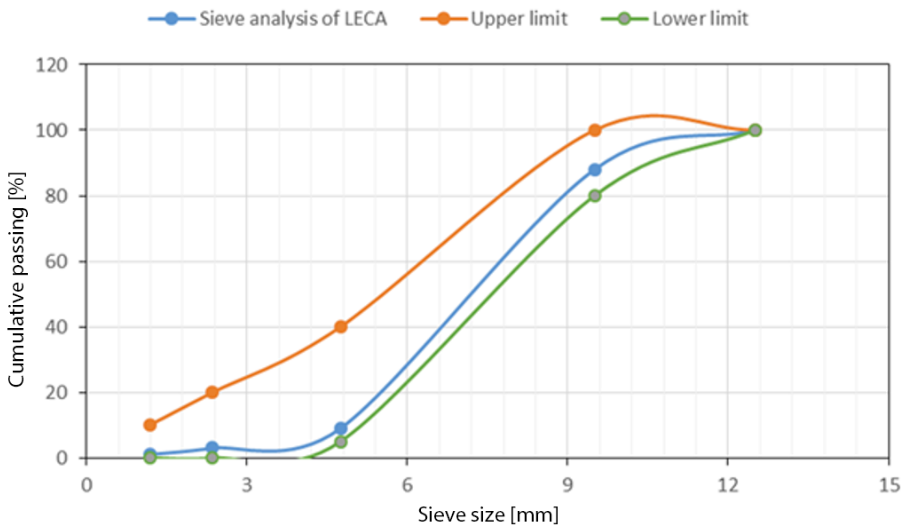

FIGURE 3. Sieve analysis of lightweight expanded clay aggregate (LECA)

TABLE 5. Physical properties of lightweight expanded clay aggregate (LECA)

Physical properties	Dry density [$kg \cdot m^{-3}$]	Absorption [%]	Specific gravity	Maximum size [mm]
Value	415	20	0.62	10

and physical properties of test results of LECA are listed in Table 4 with Figure 3 and Table 5, respectively.

Silica fume (SF)

Silica fume is a very fine pozzolanic material produced in electric arc furnaces for silicon or alloys containing silicon, with particles around 100 times less than an average cement grain (Holland, 2005). Silica fume was used in this study with three values (4, 8 and 12%) as a partial replacement of cement weight to choose the best ratio to be added to the LWC mixture. Figure 4 shows the type of SF used. Tables 6 and 7 show the physical and chemical characteristics of SF, respectively, according to the manufacturers specifications, which conform to ASTM C1240-05 requirements (ASTM, 2005).

FIGURE 4. Sample of silica fume used in the current study

TABLE 6. Physical characteristics of silica fume (SF)

Physical characteristics	Tested SF	ASTM C1240-05 requirements
Max, % percentage retained on a 45 m (No 325) sieve	2	< 10
Index of accelerated pozzolanic strength activity	105	< 105
Specific surface [$m^2 \cdot g^{-1}$]	24	< 15

TABLE 7. Chemical characteristics of silica fume (SF)

Chemical characteristics	SiO_2	CaO	SO_3	Cl	Loss on ignition
Tested cement [%]	90	0.8	0.2	0.035	4
ASTM C1240-05	≥ 85	–	–	–	≤ 6

Superplasticizer (SP)

In this study, the Sika Visco Crete 5930 IQ with a ratio of 0.95% of cement weight was used, which meets the specification described in ASTM C494/C494M-19 (ASTM, 2019). The SP is also called high range water--reducing admixtures (HRWRA). This type of SP reduces the quantity of water while improving the workability and working to prevent the segregation issue. The properties of this type are shown in Table 8 according to the manufacturer's specifications.

TABLE 8. Properties of superplasticizer

Property	Specific gravity	Chloride content	Appearance	Recommended dosage	Storage life
Description	1.085	nil	turbid liquid	0.8–2% by weight of binder for flowing concrete	up to 1 year in closed containers

Water

Potable water was used throughout the experimental work necessary to produce the concrete mixes, while tap water provided in the university site was used in curing all specimens.

Mix design

Structural lightweight aggregate concrete has a density of less than 2,000 kg·m^{-3} and a cylinder compressive strength of greater than 17 MPa at 28 days. According to previous researches, and based on ACI 211.2-04 (ACI, 2004), which is used as a design guide for lightweight concrete mixtures, many trial mixes were made to select the proportion of the mixture ingredients that satisfied the required compressive strength and density for lightweight concrete. Because of the LECA's high water absorption capacity, more water was added (approximately 20% of the LECA weight over the amount of water used in the control mix) to keep the slump within the 20–100 mm range. In order to ensure the adequacy of the trial mixtures for the compressive strength, three concrete cubes with a dimension of 150 × 150 × 150 mm were cast for each trial mix. After 24 h, concrete cubes were demold and then cured at ambient temperature for 7 days. After 7 days of curing, concrete cubes were left to dry in fresh air for 4 h prior to the concrete compressive strength test. A digital compression machine with a maximum capacity of 2,000 kN was used to test the concrete cube's compressive strength at the Civil Engineering Structural Laboratory at the University of Thi-Qar in Iraq. Mix proportion (by weight), slump, weight of specimen, hardened density, and compressive strength of the trail mixes are illustrated in Table 9. Figure 5 shows some trial mixes and their compression tests.

TABLE 9. Trial mixes proportions

Trail mix (T.M)	T.M (1)	T.M (2)	T.M (3)	T.M (4)	T.M (5) selected	T.M (6)
Cement [kg·m^{-3}]	500	500	500	480	460	440
Silica fume [%]	–	4	–	4	8	12
Fine aggregate [kg·m^{-3}]	872	872	936	936	936	936
Lightweight expanded clay aggregate [kg·m^{-3}]	230	230	180	180	180	180
Superplasticizer [%]	0.8	0.8	0.95	0.95	0.95	0.95
Water [kg·m^{-3}]	180	187	190	190	190	190
w/c or b/c	0.36	0.36	0.38	0.38	0.38	0.38
Slump [mm]	33	30	80	90	90	90
Weight of specimen [g]	5 933	5 924	6 168	6 149	6 152	6 155
Cube compressive strength [MPa]	18	20	23	25	27.8	30.5
Density [kg·m^{-3}]	1 760	1 757	1 833	1 828	1 821	1 824

FIGURE 5. Some trial mixes and their compression tests

Casting of LWC test specimens

Steel cubes with standard dimensions of 150 × 150 × 150 mm were used in the current study to cast the concrete cube specimens to determine the concrete compressive strength of the LWC specimens. In addition, steel cylinders with dimensions of 150 × 300 mm (diameter × height) were used to cast and test concrete cylinders for indirect splitting tensile strength and to draw a stress–strain relationship. As well, steel prisms with standard dimensions of 100 × 100 × 500 mm were used to determine the modulus of rupture of LWC. Table 10 presents the mixing proportions from the trail mixes for the casting of the test specimens in the presence of an admixture, which meets the specifications of ASTM C494/C494M-19 – Type F (ASTM, 2019). According to BS 1881-116 (BSI, 1991), a cube compressive design strength of 30 MPa was specified for the reference concrete mix. In general, six cubes, three cylinders, and three prisms were cast. To avoid moisture loss, all specimens (concrete cubes, cylinders, and prisms) were covered with plastic bags. All specimens were kept moist for 36 h, after which the formwork was stripped and cured under identical conditions for 28 days.

TABLE 10. Lightweight concrete (LWC) mix proportions

Mix type	Cement [kg·m^{-3}]	Silica fume [kg·m^{-3}]	Light expanded clay aggregate [kg·m^{-3}]	Fine aggregates [kg·m^{-3}]	Superplasticizer [kg·m^{-3}]	Water [kg·m^{-3}]
LWC	460	40	180	936	4.75	190

Testing methods

Test of fresh concrete (slump test)

The workability of the LWC mix was checked immediately after mixing using the slump test, as stated in ASTM C143/ /C143M-15 (ASTM, 2015b). The procedure of the test consists of filling the concrete to the slump cone in three equivalent layers. Each layer is tamped with a tamping rod about 25 times. The excess concrete is removed from the top edge of the cone by the tamping rod. The cone is raised vertically and quickly and the amount is measured by the slumps of the concrete sample. The slump value is gotten from the distance between the highest point on the surface of the slumped concrete sample and the underside of the round tamping bar. The slump value was 90 mm. The type of slump is recorded as a “true slump”, as shown in Figure 6.

Mechanical properties of the hardened samples of LWC

At the age of 28 days, each sample of hardened concrete contains five main properties. These properties are compressive strength (f_{cu}), splitting tensile strength (f_{ct}), modulus of rupture (f_r), static modulus of elasticity (E_c), and density (D).

Compressive strength (f_{cu})

The compressive strength of hardened concrete is performed after 7 and 28 days of curing, in accordance with BS 1881-116 (BSI, 1991) using a digital compression

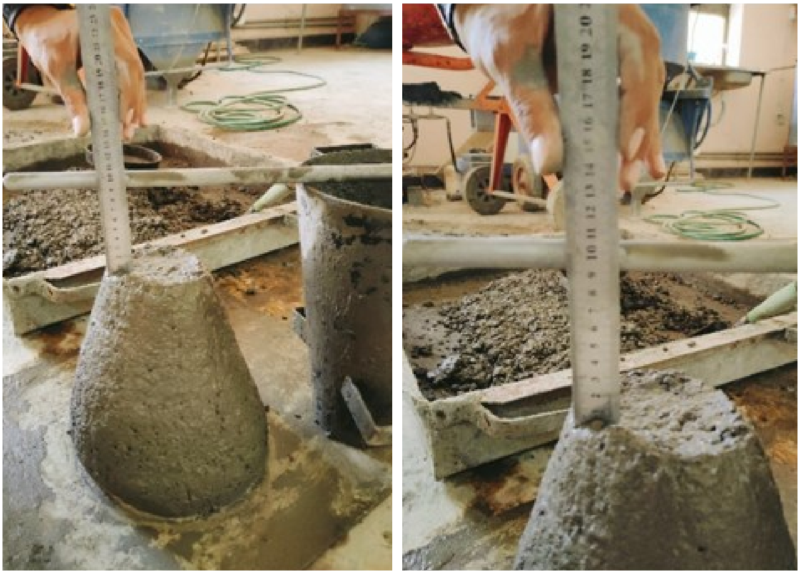

FIGURE 6. Slump test

machine with a capacity of 2,000 kN, as illustrated in Figure 7a. Cubes of 150 × 150 × 150 mm were used to determine the concrete's compressive strength. The tests were conducted at ages 7 and 28 days, and three specimens were tested at each age. The specimen is aligned carefully at the center of thrust of the higher bearing block and loading is applied continuously until failure. The average value of three specimens was taken; it is 28 MPa at age 7 days and 32 MPa at age 28 days. Figure 7b illustrates the compressive strength test failure shape.

Splitting tensile strength (f_{ct})

The splitting tensile strength (indirect tensile strength) tests are executed on three cylindrical samples of LWC in accordance with ASTM C496/C496M-11

FIGURE 7. Compressive strength test: a – testing machine; b – the cubes after failure

(ASTM, 2004). The splitting-tension test calculates the concrete tensile strength. In this test, a concrete cylinder (150 × × 300 mm) is exposed to a compressive loading along the vertical diameter till failure by using a thin strip of plywood which is placed between the sample and the upper bearing blocks of the testing machine. The average value of three cylinders is considered, according to the equation:

$$f_{ct} = \frac{2P}{\pi DL}, \qquad (1)$$

where:
f_{ct} – splitting tensile strength [MPa],
P – load up on failure [N],
D – cylinder's diameter [mm],
L – cylinder's length [mm].

Table 11 presents the splitting tensile strength test results for LWC samples and the values obtained by the equation of ACI 318M-14 (ACI, 2014a) equal to $\lambda 0.56\sqrt{f'_c}$ MPa (where λ symbolize reduction factor equals 0.85 for LWC, and f'_c means cylinder compressive strength measured in MPa), which showed good agreement with the test results. Figure 8 shows the stages of test and mode of failure for LWC samples.

TABLE 11. Splitting tensile strength of tested lightweight concrete (LWC) specimens

Tested sample	Measuring f_{ct} [MPa]	Predicted f_{ct} [MPa]
LWC	2.95	2.26

Modulus of rupture (f_r)

The LWC samples are subjected to flexural strength (modulus of rupture) tests in accordance with ASTM C78/C78M--15A (ASTM, 2015a). The flexural strength tests are performed on three prism samples 100 × 100 × 500 mm with four points of loading, as shown in Figure 9. A comparison between the theoretical values determined by ACI 318M-14 (ACI, 2014a) equal to $\lambda 0.62\sqrt{f'_c}$ MPa and the experimental results of modulus of rupture is presented in Table 12. The estimation of flexural strength is given in the following equation:

$$f_r = \frac{PL}{bd^2}, \qquad (2)$$

where:
f_r – modulus of rupture [MPa],
P – maximum applied load (failure load) [N],
L – distance between the center of one support to the center of the other [mm],
b – prism width [mm],
d – prism depth [mm].

FIGURE 8. Splitting tensile test

TABLE 12. Flexural strength value (f_r) of tested lightweight concrete (LWC) specimens

Tested sample	Measuring f_r [MPa]	Predicted f_r [MPa]
LWC	3.66	2.50

Static modulus of elasticity of LWC (E_c)

This test technique offers a ratio of stress to strain value for standard hardened concrete cylindrical specimens. The modulus of elasticity is the degree of resistance of the material to deformation. The modulus of elasticity for lightweight strength is measured according to ASTM C469/C469M-10 (ASTM, 2010) using three cylindrical specimens with dimensions 150 × 300 mm, tested in the laboratory under the uniaxial compression load. An average of three cylinders was used. The following expression is used to compute the static modulus of elasticity:

$$E_c = \frac{(S_2 - S_1)}{(\varepsilon_2 - 0.00005)}, \tag{3}$$

where:
E_c – static modulus of elasticity [MPa],
S_2 – stress corresponds to 40% of ultimate load [MPa],
S_1 – stress corresponds to longitudinal strain (0.00005) [MPa],
ε_2 – longitudinal strain induced by the stress S_2.

TABLE 13. Static modulus of elasticity (E_c) value of tested lightweight concrete (LWC) specimens

Tested sample	Measuring E_c [MPa]	Predicted E_c [MPa]
LWC	12 506	15 893

FIGURE 9. Set-up of modulus of rupture test

FIGURE 10. Modulus of elasticity test and mode of failure for samples

Table 13 presents the static modulus of elasticity from test results for LWC samples and the values obtained by the equation of ACI 318M-14 (ACI, 2014) equal to $0.043(W_c)^{1.5}\sqrt{f_c'}$ MPa (where W_c symbolize unit weight measured in kg·m^{-3}). Figure 10 shows the stages of test and mode of failure for LWC samples. In addition, cone and split-type failures occurred in the LWC cylinders, as shown in Figure 10.

Density (D)

Density was calculated using three (150 mm) cubes on average, as specified by ASTM C642-13 (ASTM, 2013b), and the result was 1,823 kg·m^{-3}. The density of the specimen was determined by weighing it after modelling and drying. The following equation can be used to find the density of the specimen:

$$D = \frac{M}{V}, \tag{4}$$

where:
D – density [kg·m^{-3}],
M – weight of specimen [kg],
V – volume [m^3].

Results and discussion

Hardened LWC samples' mechanical properties

The mechanical properties of LWC (compressive strength, flexural strength, splitting tensile strength, density, and modu-lus of elasticity) were tested after 28 days; the results are listed in Table 14. The cubes, cylinders, and prisms were used in dimensions of 150 × 150 × 150, 150 × 150 × 300, and 100 × 100 × 500 mm, respectively. An average of three specimens is considered for the mix. The results show that the ratio of strength-to-density or strength-to-weight is efficient in structural elements. The strength capacity can generally be increased by reducing the maximum size of the coarse aggregate. The LWC in this work uses LECA as coarse aggregate. According to ASTM C330/C330M-17A (ASTM, 2017), structural lightweight aggregate concrete must have a splitting tensile strength of 2 MPa or higher. From the test, the LECA concrete is 47% more than the minimum requirement of ASTM C330/C330M-17A. The LECA concrete has a splitting tensile to compressive strength ratio of around 13%. A decreased flexural/ /compressive strength ratio was also observed for the LWC in comparison to the normal weight concrete (NWC).

Stress–strain curve

Figure 11 shows the stress–strain curve for the LWC specimen. The modulus of elasticity of concrete is based on the modulus of each component and how they are mixed together. The NWC has a higher modulus of elasticity than the LWC because the moduli of sand, stone, and gravel are greater than the moduli of lightweight constituents. Several expressions for the modulus of elasticity of concrete have been developed over the years.

TABLE 14. Mechanical properties of tested lightweight concrete (LWC) specimens

Tested sample	f_{cu} [MPa]	$f'c$ [MPa]	$\frac{f'c}{f_{cu}}$	f_{sp} [MPa]	f_r [MPa]	Density (d) [kg·m^{-3}]	E_c [MPa]
LWC	32	22.55	0.7	2.95	3.66	1 823	12 506

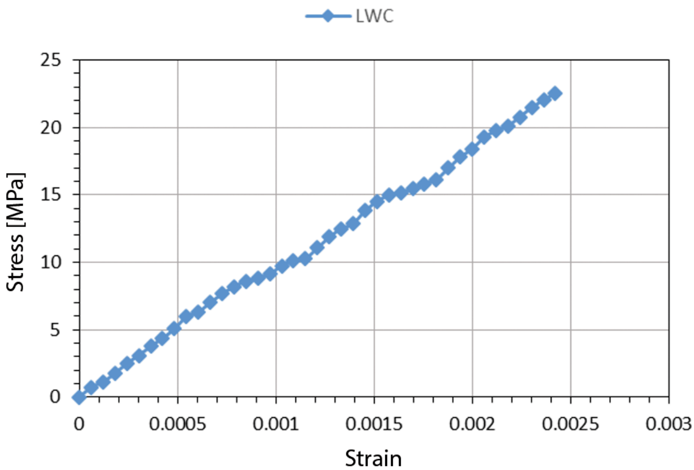

FIGURE 11. Experimental stress–strain curve for lightweight concrete (LWC)

However, the increased use of lightweight and higher-strength concrete has led to a need for a more precise expression. The results demonstrate a 27% variation in the modulus of elasticity between the calculated and tested values. It is clear from the figure that the stress–strain curve exhibits more extended linear and elastic behavior. Furthermore, the strain at failure is approximately 0.0024 for LWC. In addition, a cone and split failure mode occurred in the cylinders of LWC, as shown in Figure 10.

Conclusions

Based on the findings acquired from the laboratory tests performed in this study, it can be inferred that the concrete produced can be categorized as LWC. In the case of LECA, it has been discovered that it is ideal for usage in structural elements due to its qualities, which include being lightweight and having sufficient strength when compared to other lightweight aggregates. This type of LWC, with a compressive strength of 32 MPa and a density of 1,823 kg·m^{-3}, could be used in the structural and non-structural elements. The results show that the reduction in the strength of LWAC was found to be higher in the concrete with an estimated compressive strength of 32 MPa due to the lower strength of the LWA (expanded clay). The mechanical properties of LWC are significantly improved by adding SF by improving the microstructure of the concrete. In comparison to ASTM C33/C33M-13 (ASTM, 2013a), LECA concrete has a splitting tensile strength that is 47% higher. The LECA concrete has a splitting tensile to compressive strength ratio of around 13%. A decreased flexural/ /compressive strength ratio was also observed for the LWC.

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Summary

Mechanical properties of lightweight expanded clay aggregate (LECA) concrete. The construction activities are based on structural concrete, which is one of the most commonly used materials. The fundamental aim of using lightweight concrete (LWC) was to reduce the concrete self-weight of the structure parts. As a result, LWC has been used successfully in a variety of installations for several years. In this paper, the mechanical properties of concrete made with lightweight expanded clay aggregate (LECA) as a full replacement for coarse aggregate are studied. The experimental program shows that LECA with a 32 MPa cube compressive strength and an 1,823 kg·m^{-3} dry density can be used to make structural lightweight aggregate concrete (SLWC). The results show that the reduction in the strength of lightweight aggregate concrete (LWAC) was found to be higher in the concrete with an estimated compressive strength of 32 MPa due to the lower strength of the LWA (expanded clay). According to the test results, the mechanical properties of LWC were greatly improved by adding silica fume (SF). Furthermore, LECA concrete has a splitting tensile strength that is 47% higher than the ASTM C330/C330M-17A minimum requirement. The LECA concrete has a splitting tensile strength to compressive strength ratio of approximately 13%. Additionally, the results demonstrate a 27% difference in the modulus of elasticity between the calculated and tested values.