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Mechanical Properties of Structural Lightweight Aggregate Concrete Using Light Expanded Clay (LECA) with Steel Fiber

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Abstract

This study investigated the mechanical and physical properties of lightweight coarse aggregate concrete LWAC utilizing LECA as a lightweight aggregate with steel fibers. A total of thirteen LWAC mixes were casted; seven were trial mixes, carried out to investigate the effects of the LECA/Gravel replacement ratio on equilibrium density and compressive strength and nominate the mix that has the highest compressive strength. After that, six mixes of LWAC with variable contents (0, 0.5, 0.75, 1, and 1.5) % of hooked end steel fiber SF and 1% of corrugated, and straight SF were prepared to study the influence of SF's content and types on the mechanical characteristics of LWAC mix. For each mix, six cubic specimens (150×150×150) mm, six cylinders (150×300) mm, and one prism (150×150×500) mm were casted to investigate compressive strength, split tensile strength, equilibrium density, modulus of elasticity, and modulus of rupture, respectively. The result showed that the specimens of trail mix have an equilibrium density of 1435–1949 kg/m^3 with a compressive strength ranging between (25.9 - 30.77) MPa, while specimens of steel fiber lightweight aggregate concrete SFLWAC have a compressive strength ranging between (25.9 - 34.41) MPa. It was concluded that the presence of steel fibers reduced the workability of the LWAC mixes and improved the split tensile strength and modulus of rupture of LWAC with a slight increase in compressive strength. Hooked end steel fiber exhibits the highest flexural performance at 1.5% SF volume compared to straight and corrugated types.

Keywords: Lightweight aggregate concrete, LECA, Steel Fiber.

1. Introduction

Weight can be mentioned as one of the most important construction design principles. Construction weight increases with rising concrete density due to the materials used in concrete production. Hence the need to use a type of concrete with a lower density than normal, termed "lightweight aggregate concrete" (LWAC). ACI 318-19 [1] defines LWAC as concrete containing lightweight aggregate LA and possessing an equilibrium density as measured according to ASTM C567 [2] within 1440 - 2160 kg/m^3. LWAC has a low modulus of elasticity and is highly brittle in nature; due to the low modulus of elasticity of its components (fine and coarse aggregate), it causes a faster rate of crack development in reinforced concrete members. These issues can be, to some extent, addressed by the incorporation of discrete fibers like hooked end steel fibers into the concrete in order to control crack development due to its ability to restrict the growth of cracks and thus change the brittle mode of concrete. The main advantage of steel fibers is their ability to distribute stresses across cracks, enhancing the toughness and ductility of the concrete and its absorption capacity under impact.

2. Literature Review

Gao et al. (1997) [3] observed that the compressive strength of high-strength lightweight concrete was slightly enhanced with the presence of steel fiber. However, flexural strength and splitting tensile were largely improved. It was concluded that the modulus of elasticity of steel fiber-reinforced, high-strength, lightweight concrete was lower than that of steel fiber reinforced normal concrete.

Alaa M. Rashad (2018) [4]concluded that addition LECA into the mixture produced increased workability, decreased density, decreased chloride penetration, increased water absorption, decreased shrinkage, decreased freeze/thaw resistance, higher segregation resistance, fire resistance and thermal insulation. Although the mechanical behaviour of lightweight concrete depends on the type of lightweight aggregate, the addition of LECA into the matrix decreased mechanical strength.

Hamoodi et al. 2021 [5] carried out an experimental study to investigate the influence of fibers on the behavior of normal-strength concrete. It was concluded that steel fibers improved compressive strength, splitting tensile strength, and flexural strength. The gain in strength was highest in splitting tensile strength. Also, it was deduced that steel fibers could significantly improve the tensile strength of concrete characteristics.

3. Experimental Plan

The experimental work provides data and features for materials, machines and instruments that are used in testing. The experimental work was carried out at the Construction Materials Laboratory of civil Engineering Department in the College of Engineering, University of Basrah.

3.1 Materials

3.1.1 Cement

Falcon, an Iraqi ordinary Portland cement was used in this study in casting all the specimens. Tables (3.1) and (3.2) show the physical properties and chemical composition test results for the utilized cement, respectively. They conform to the Standard Iraqi specification limits (IQS N05 1984)[6] for ordinary Portland cement.

3.1.2 Aggregate

3.1.2.1 Fine Aggregate (Sand)

The natural sand from Al-Zubair area in Basrah city was used as fine aggregate in all concrete mixes in this research. It was 4.75mm in maximum size with a fineness modulus of (2.93). Fig. (3-1) and Table (3.3) show the physical properties and the fine aggregate grading test results respectively. They conformed to Iraqi specification (IQ.S No. 45/1984)[7].

Table (3.1) Physical Properties for Cement*

Physical property	**Specific surface area (Fineness) (m^2/kg)**	**Setting time (hr:min) (Vicat apparatus)**		**Compressive strength *MPa***	
		Initial	Final	3-day	7-day
Test results	325	2:15	4:40	19	27
IQS No. 5/1984	*230 (Min.)*	*00:45 (Min.)*	*10:00 (Max.)*	*15 (Min.)*	*23 (Min.)*

* Construction materials laboratory of the College of Engineering, Basrah University

Table (3.2) Chemical analysis and main compounds of cement*

Compound composition of Cement									
CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	I.R	LOI
62.80	20.25	6.30	3.5	4.53	0.22	0.63	2.10	0.55	0.75

Main Components of Cement			
C_3S	C_2S	C_3A	C_4AF
40.75	27.90	11.20	10.30

* Chemical tests lab. in the College of Eng. University of Basrah.

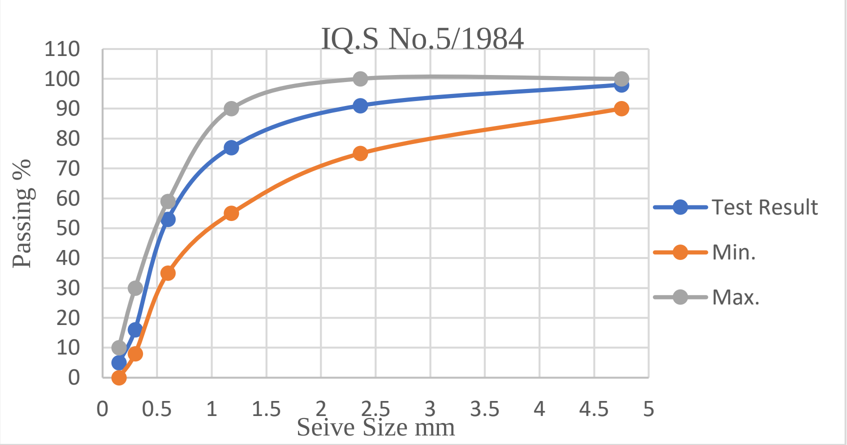


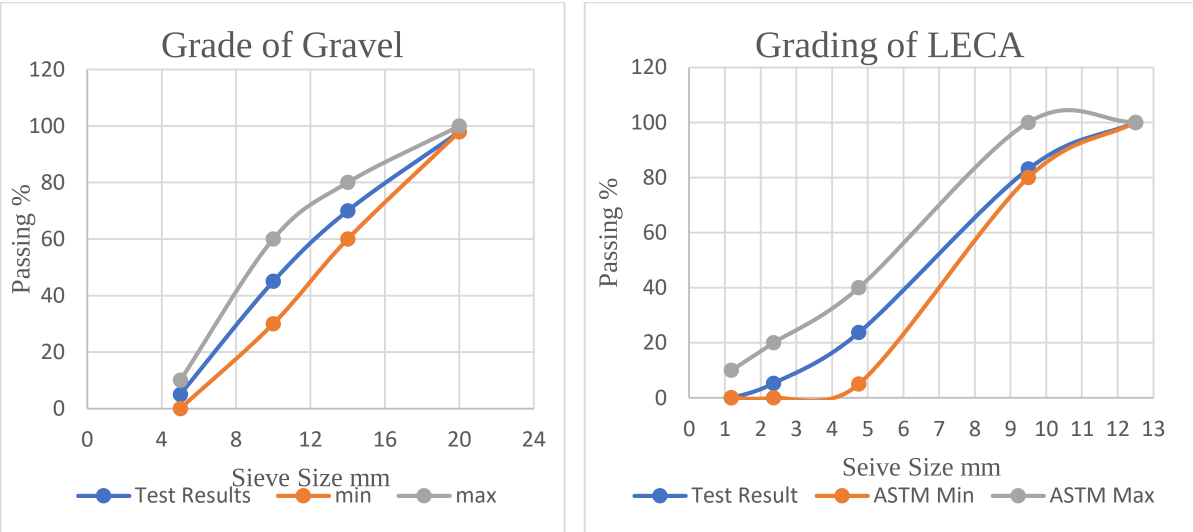
Fig. (3-1) Grading of fine aggregate with IQ. S No.5/198 limits

3.1.2.2 Coarse Aggregate (Gravel)

Two types of coarse aggregate were used in this study, natural coarse aggregate NCA and lightweight expanded clay aggregate LECA. Crushed gravel from Jabal Sanam at south of Basrah governorate was used as natural coarse aggregate with a max size of 19.5 mm. The LECA was formed in a rotating kiln at a very high temperature via a pyroclastic process, it was imported from Iran and utilized at size (4-10) mm. The coarse aggregate grading and the physical properties of coarse aggregate are shown in Fig. (3-2), Table (3.4), respectively, they satisfied the limits of Iraqi standard IQ.S No.45/1984[7] requirements.

Table (3.4) Physical properties of fine aggregate.

Physical properties	Test result	Limits of IQ.S No.45/1984
Specific Gravity	2.65	-
Sulphate content	0.36	≤ 0.5
Absorption	1.07	-
Loose bulk density (Kg/m³)	1635	-



a **b**

Fig. (3-2) (a) Grading of Natural coarse aggregate with IQ. S No.5/198 limits.

(b)Grading of LECA with ASTM C330 Limits.

3.1.3 Mix Water

In this research, ordinary tap water was used in concrete mix, casting and curing all the specimens, cubes, cylinders, and prisms.

Table (3.6) Physical properties of Coarse aggregate.

Physical properties	Test results		IQ. S No. 45/1984
	Gravel	LECA	
Specific gravity	2.65	0.6	-
Sulphate content SO_3	0.08	0.048	≤ 0.1 %
Chloride content CI	0.091	0.02	≤ 0.1%
Absorption	0.66	24	-
Loose bulk density kg/m³	1670	370	-

3.1.4 Steel Fiber

The steel fiber types used in this research were Corrugated, hooked end, and straight steel fibers as shown in Fig. (3-3). The used steel fiber were conforming to ASTM A820M[8]. The mechanical properties of steel fibers types that used in this study are tabulated in Table (3.7)

(a) (b) (c)

Fig. (3-3) Steel fiber

a. Hook end b. Straight c. Corrugate

3.1.5 Superplasizetizer

A powerful superplasticizer, Sika ViscoCrete-180 GS, shown in Fig. (3.11), was used in this research. It satisfied the ASTM C494 [9] requirements.

Table (3.7) The mechanical properties of Hooked end steel fibers*

Properties	Hooked end	Straight	Corrugated
Density kg/m³	7860	7860	7860
Tensile strength (f_t) MPa.	≥ 1000	2850	≥ 700
Fiber length (L) mm.	30	14	30
Fiber diameter (D) mm.	0.5	0.25	0.55
Aspect Ratio (*l/d*)	60	56	55
Modulus of elasticity (E_c)	2×10^5	2×10^5	2×10^5

∗ According to manufacturer's data sheet

Fig. (3-4) Sika ViscoCrete-180 GS

3.1.6 Silica fume

The silica fume that used in this study was MegaAdd MS shown in Fig. (3-12). The typical properties of silica fume used in this investigation are shown in Table (3.16), and it was conformed to the requirements of ASTM C1240[10].

Table (3.8) Silica fume properties ∗

Property	Value
Color	Grey to medium grey
Specific Gravity	2.10 - 2.40
Bulk Density kg/m³	500 - 700

∗ According to manufacturer data sheet

Fig. (3-5) Silica fume powder

3.2 <u>Concrete Mix Proportions</u>

3.2.1 NWC Mix proportions

For normal weight concrete NWC, one trail mix was carried out. Its quantities and proportion stated in Table (3.9).

Table (3.9) Mix proportion of NWC

Mix proportion (by weight *Kg.*) 1:1.44:2.15					Density Kg/m^3	f_c at 28 days MPa	Slump *mm*
Cement	Sand	Gravel	Water	w/c			
486	697.7	1047	170	0.35	2400	34.02	80

3.2.2 LWAC Mix Proportions

A total of seven trial mixes were cast and tested to select which mixes were to be used in this study, designed according to ACI 211.2-98[11]. Trail mixes included LECA as a partial replacement of natural coarse aggregate. The replacement ratios were (0, 55%, 60%, 65%, 70%, 75%, and 80%). Ingredients and proportions of trail mixes are presented in Table (3.18). According to the result that shown in Table (3.10), it was chosen (LW5), which uses 60% LECA as a partial replacement for natural gravel, got the highest compressive strength 30.08 MPa with a unit weight density of 1904.7 kg/m^3, and equilibrium density of 1943 kg/m^3 satisfied ACI 318-19 requirements[1] .

Table (3.10) Proportions and ingredients of trail mix of LWAC

Materials	Mix						
	LW0	**LW1**	**LW2**	**LW3**	**LW4**	**LW5**	**LW6**
Cement *Kg.*	400	447	447	447	447	447	447
W/C	0.45	0.39	0.39	0.33	0.49	0.44	0.4
Water *Kg.*	180	175	175	147.5	220	195	182.5
Sand *Kg.*	680	697.7	697.7	697.7	697.7	697.7	697.7
LECA/Gravel	0	80	75	70	65	60	55
Gravel *Kg*	0	209	262	314	366	419	471
LECA *Kg.*	320	131	123	115	107	98	90
S.F. *Kg.*	0	39	39	39	39	39	39
S.P. *Kg.*	0	9	9	9	9	9	9

w/c*: water cement ratio,* ***S.F****: silica fume,* ***S.P****: Superplasticizer*

3.3 <u>Specimens preparation</u>

3.3.1 Standard Molds

The standard steel molds, Cubes of (150×150×150) mm, cylinders of (300×150) mm, and prisms of (150×150×500) mm, for casting the specimens was prepared and oiled for casting the specimens, as shown in Fig. (3-6).

Fig. (3-6) standard steel molds

3.3.2 Mixing Procedures

LWAC mixing was conducted in a rotary tilting drum type mixer with a capacity of $0.35m^3$. The mixing procedure was according to BS 1881-125:2013[12].

3.3.3 Casting and curing

Before the mixing process, all standard steel molds were prepared, cleaned, and their inner surfaces were lubricated one day before casting. After preparation of molds and completed the mixing process, the cylinders and cubes were filled with mix in three layers, while the prism molds were filled in two layers; each layer was compacted by the vibrating rod. The top surface of the concrete specimens was leveled and smoothly finished after casting was completed using a hand trowel, as shown in Fig. (3-7). Twenty-four hours after casting, cylinders, prisms, and cubes were removed from the molds and kept in the water tank at the temperature of the laboratory for 28 days. After curing, the specimen was ready for testing.

Fig (3-7) Casting, levelling, labelling of the standard steel molds.

3.4 <u>Lightweight Aggregate Concrete Tests</u>

3.4.1 Workability test

A Slump test according to ASTM C143M [14]was carried out to evaluate the workability consistency of the LWAC mixture and measure the property of fresh LWAC.

3.4.2 <u>Test Setup</u>

After the samples were cured and prepared to be tested at age 28 days, they were cleaned and placed in a suitable position in test machine. A hydraulic machine TORSEE with a capacity of 200 Ton (2000 kN) has been used for applying and measuring the load, shown in Fig. (3-8).

Fig. (3-8) Universal hydraulic machine TORSEE

3.4.3 LWAC Hardened Tests

To evaluate the mechanical properties for each mix, six cubes and three cylinders were cast to obtain the average compressive strength (f_{cu}) at 7 and 28 days according to BS. EN 12390-1:2021[15] and ASTM C39M[16], three cylinders to evaluate split tensile strength (f_t) according to ASTM C 496[17], three prisms to gain the average of modulus of rupture (f_r) according to ASTM C78[18], three cylinders to obtain the average elastic modulus according to ASTM C469[19] , and three cylinders to obtain equilibrium density according to ASTM C567[2]. Fig. (3-9) shows the molding and testing techniques.

Fig. (3-9) LWAC Hardened Tests

4. <u>Results and Discussions</u>

This article presents the experimental results for the influence of LECA/gravel replacement ratio and LWAC density in trail mix, and mechanical properties of SFLWAC like workability, density, compressive strength, flexural strength, splitting tensile strength, and static modulus of elasticity, with or without steel fiber.

4.1 <u>Slump Test of SFLWAC</u>

The LWAC workability without steel fiber was 159 mm, while this workability was reduced by 2.5, 4.4, 7, and 8.9% for mixes that contained hooked end SF volume content of (0.5, 0.75, 1, and 1.5) %, respectively. Similarly, the workability of LAWC was reduced by 10.1 and 7.6% for mixes that contained 1% straight and corrugated SFs, respectively. Accordingly, the workability of the fresh concrete is highly affected by the addition of SFs due to increased friction between mixed constituents resulting from using steel fibers. Fig. (4-1) illustrate slump tests for mixes. The incorporation of steel fibers into LWAC has a negative effect on workability due to the anchoring effect of fibers distributed uniformly in LWAC, moreover they increase the total surface area of LWAC [5].

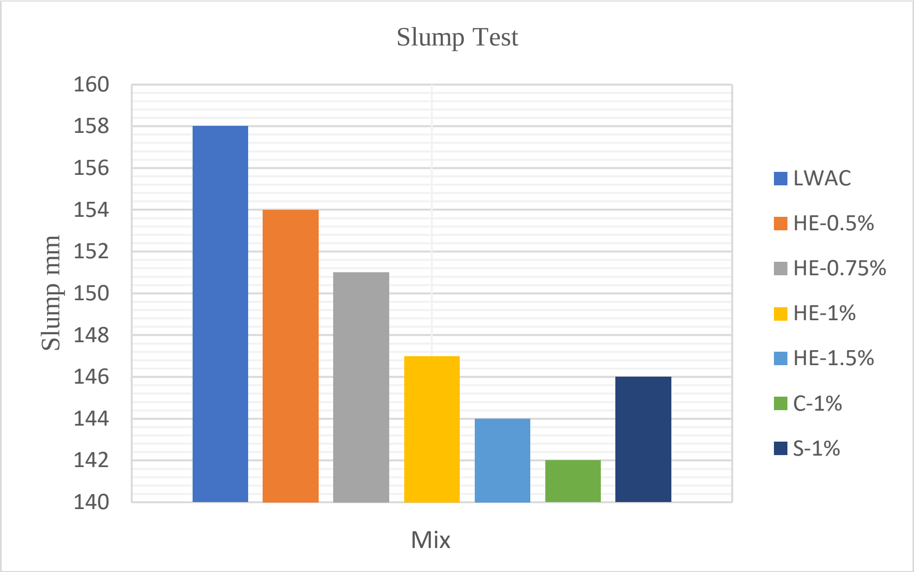


Fig. (4-1)

4.2 Equilibrium and Unit Weight Densities

The fresh density of SFLWC mixes was measured in accordance with ASTM C138M[20], while The equilibrium density of LWAC in this research was determined according to ASTM C567M[2] procedures. The selected mix LW5 has unit weight density of 1905 kg/m^3 and equilibrium density of 1943 kg/m^3, which satisfied the requirements of ACI 318-19[1] which states that the equilibrium density ranged between 1440 to 2160 kg/m^3. Fig. (4-2) show the effect of LECA/Gravel ratio on unit weight, equilibrium densities, respectively.

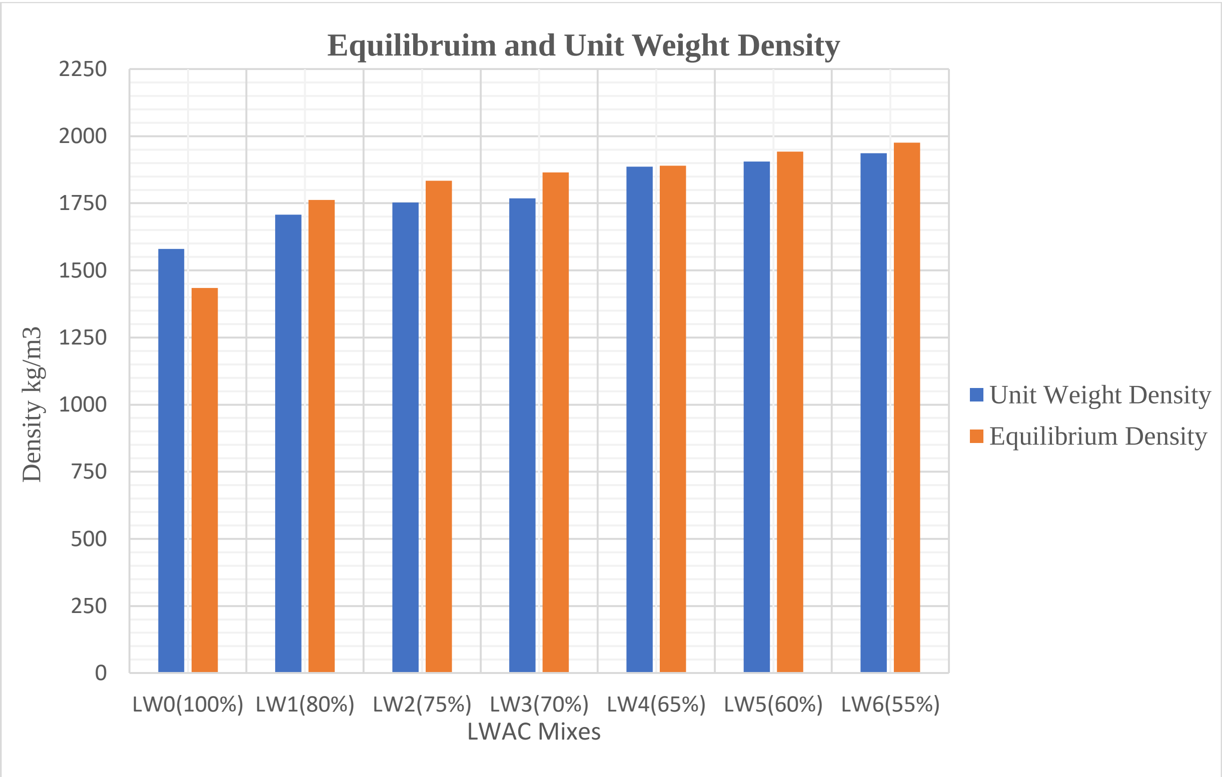


Fig. (4-2) Unit weight and Equilibrium densities of LWAC mixes

4.3 Compressive Strength

4.3.1 Compressive Strength of Trail Mixes

Fig. (4-3) show the effect of parameter namely LECA/gravel replacement ratio on the compressive strength of LWAC at age 28 day. The compressive strength ranged between 16.4 to 30.77 MPa. It is worth mentioning that the weakest component in the LWAC structure is aggregate and not the intermediate transition zone as in the normal weight concrete NWC. In other words, the properties of aggregate play a significant role in determining the strength of LWAC. So, the compressive strength reduction due to the replacement of gravel with LECA may related to the low strength and density of LECA.

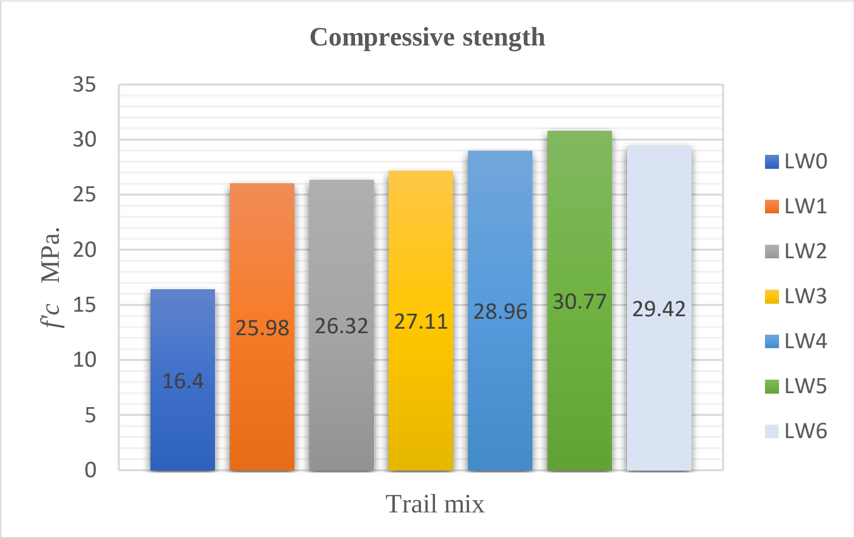


Fig. (4-3) Compressive strength of trail mixes

4.3.2 Compressive Strength of SFLWAC

The average laboratory compressive strength of LWAC without steel fiber was 30.71 MPa. LWAC with 1.5% volume fraction of hooked end steel fibers showed a significant enhancement in compressive strength, superior to volume fractions of (0.5, 0.75, and 1) % of the same steel fiber type, they enhanced by (0.9, 3.5, 6.0, and 11.8)% compared with LWAC without steel fibers. On the other hand, LWAC with 1.0% volume fraction of corrugated, and straight SFs, showed an increase in compressive strength of (4.7, and 4.2) %, respectively, compared with LWAC without SFs. This may be attributed to the homogeneous dispersion of the steel fibers in addition to their bridging effect [22]. Fig. (4-4) shows a comparison of compressive strength of SFLWAC mixes.

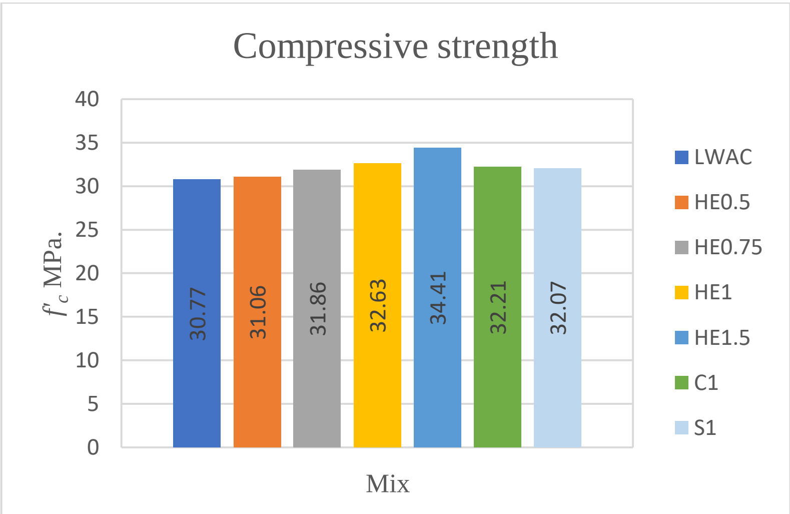


Fig. (4-4) Compressive strength of SFLWAC

4.4 <u>Split tensile strength</u>

LWAC without steel fiber was obtained an average tested splitting tensile strength of 2.97 MPa. When compared with LWAC without SFs, LWAC that contains a hooked end SF with a volume fraction of 1.5% exhibits the highest splitting tensile strength by 19.2%, while the same steel fiber type with variable volume fractions of (0.5, 0.75, and 1) % had enhanced splitting tensile strength by (7.7, 9.4, 14.5) %, respectively. From Fig. (4-5), it was deduced that LWAC, which includes hooked end, corrugated, and straight SFs with a constant volume fraction of 1%, showed an increase in splitting tensile strength by (14.5, 14.1, and 11.5) %, respectively, compared with LWAC without SFs.

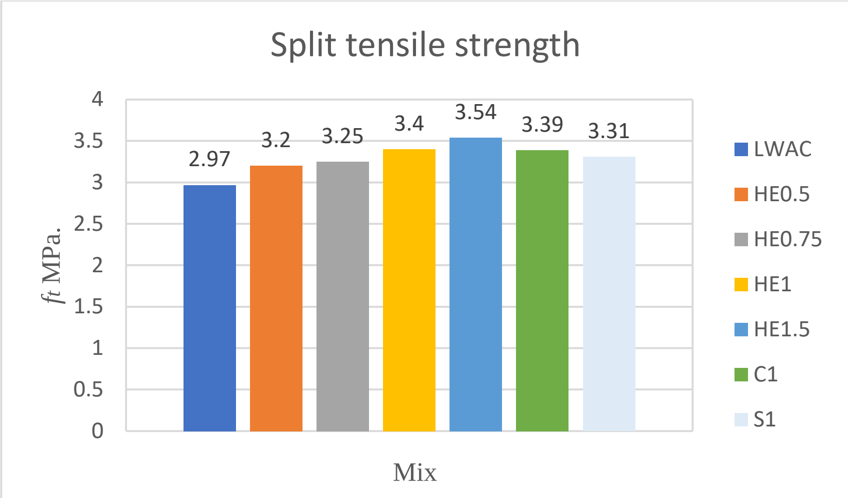


Fig. (4-5) Split tensile strength of SFLWAC mixes

4.5 Flexure strength

The flexural strength results are presented in Fig (4-6). It is shown that LWAC that comprised hooked end steel fiber with a volume fraction of 1.5 percent achieved the highest splitting tensile strength by (145.6) % comparison to LWAC without steel fibers, whereas the volume fractions of (0.5, 0.75, and 1) percent of the same steel fiber type had improved modulus of rapture by (15.1, 39.4, and 66.7) %, respectively, compared with LWAC without SFs. while LWAC with a constant volume fraction of 1.0% of hooked end, corrugated, and straight SFs) increased flexural strength by 66.7, 36.5, and 18.3%, respectively, Compared to LWAC without steel fibers

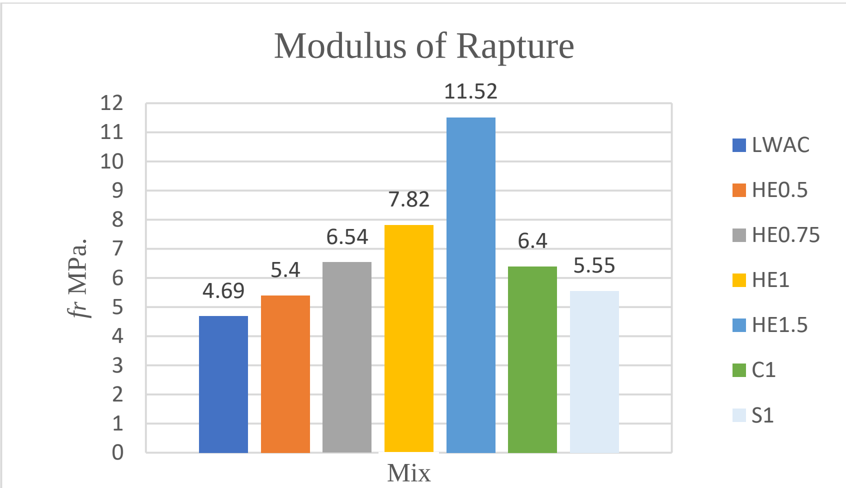


Fig. (4-6) Flexure strength of SFLWAC mixes

4.6 Modulus of Elasticity

The static modules of elasticity results of SFLWAC mixes are shown in Fig. (4-7). It can be seen that adding 1.5% of hooked end steel fibers led to a maximum increase in the modulus of elasticity and that improved by 134.8% compared with LWAC without fiber. whereas adding (0.5, 0.75, and 1%) of hooked end steel fiber increased modulus of elasticity by 12.9%, 24.4%, and 52% respectively, compared to LWAC without fibers. Also, it can be observed that adding 1% of corrugated, and straight steel fiber enhanced the modulus of elasticity by 34.2, and 20%, respectively, comparison to LWAC without steel fiber. This is presumably due to the use of steel fibers at 1%volume content providing higher compressive strength and consequently a better modulus of elasticity.

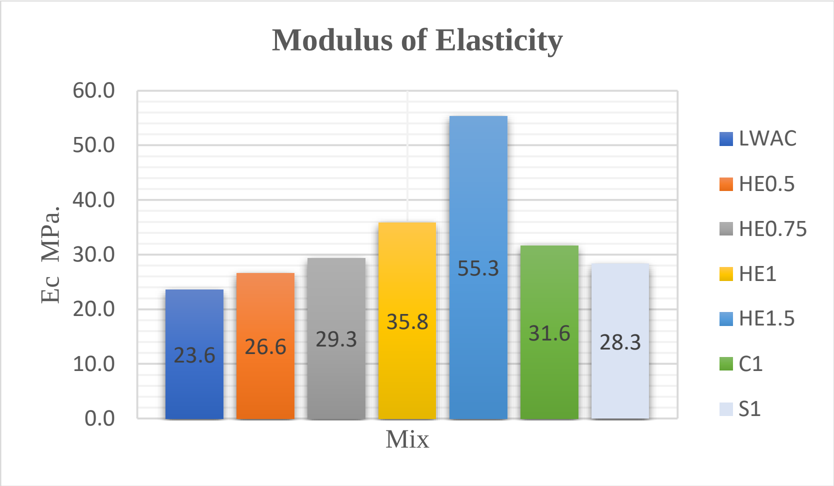


Fig. (4-7) Modulus of Elasticity of SFLWAC mixes

5. Conclusion

According to the results of this experimental study, the following conclusions can be drawn:

1- The results showed that the equilibrium density decreased with increasing LECA/gravel due to the low bulk density of LECA compared to the gravel.
2- The results showed that decreasing the volume of LECA in LWAC increases the compressive strength; as a result, the LECA/gravel replacement ratio decreases the compressive strength due to the decrease in aggregate cavities.
3- The splitting tensile strength of SFLWAC approximately ranged from 7.7% to 19.2% of LWAC without steel fiber.
4- The modulus of rupture of SFLWAC approximately ranged from 15.1% to 145.6% compared to LWAC without steel fiber.
5- Experimental results indicate that the presence of steel fiber in LWAC mixes led to an increasing modulus of elasticity of SFLWAC; it ranged between 23.6 and 55.3 GPa.

6. References

[1] A. 318-19, Building Code Requirements for Reinforced Concrete and Commentary on Building Code Requirements for Structural Concrete, Report of ACI Committee 318, 2019.

[2] ASTM C567/C567M-19, Standard Test Method for Determining Density of Structural Lightweight Concrete," ASTM International, West Conshohocken, PA, 2019.

[3] J. Gao, W. Sun, and K. Morino, Mechanical properties of steel fiber-reinforced high-strength, lightweight concrete, Cement and Concrete Composites, vol. 19, no. 4, pp. 307–313, 1997.

[4] Alaa Rashad, Lightweight expanded clay aggregate as a building material-An overview," Constrtuction Building Materials, 2018.

[5] A. Z. Hamoodi, M. S. Zewair, and M. F. Ojaimi, Shear Behavior of Fiber-Reinforced Concrete Beams, International Journal of GEOMATE, Vol. 21, Issue 86, 2021, pp. 167–179.

[6] Iraqi Standard Specification, IQS No. 5/2019, Portland cement, Central Organization for Standardization and Quality, Baghdad, 2019.

[7] Iraqi Standard Specification, IQS No. 45/1984, Aggregate from natural sources for concrete and construction, Central Organization for Standardization and Quality, Baghdad, 1984.

[8] ASTM A820/A820M-16, Standard specification for steel fibers for fiber-reinforced concrete, ASTM International, 2016.

[9] ASTM C494/C494M-19, Standard Specification for Chemical Admixtures for Concrete, ASTM International, 2019.

[10] ASTM C1240/C1240M-20, Standard Specification for Silica Fume Used in Cementitious Mixtures, ASTM International, 2020.

[11] ACI 211.2-98 (Reapproved 2004), Standard Recommended Practice for Selecting Proportions for Structural Lightweight Concrete," *ACI J.1998*

[12] British Standard BS:(1881-125-2013), Testing concrete Part 125: Methods for mixing and sampling fresh concrete in the laboratory,2013

[13] ACI 544.4R-18, Guide for Design with Fiber-Reinforced Concrete: Reported by ACI Committee 544. 2018.

[14] ASTM C143/C143M-20, Standard Test Method for Slump of Hydraulic-Cement Concrete Standard. ASTM International,

2020.

[15] British Standard BS-EN-12390-1-2021, Testing hardened concrete, 2013

[16] ASTM C39/C39M-20, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, 2020.

[17] ASTM C496/C496M-17, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, 2017.

[18] ASTM C78/C78M-21, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), ASTM International, 2021

[19] ASTM C469/C469M-14e1, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM International, 2014.

[20] ASTM C138/C138M-17a, Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete, ASTM International, 2017.

[21] Hussein R. Lazim, Structural Behavior of Reinforced Deep Beams Using Lightweight Concrete, M.Sc. thesis, University of Basra, Iraq, 2016

[22] Tao Wu; Yijia Sun; Xi Liu; and Hui Wei, Flexural Behavior of Steel Fiber–Reinforced Lightweight Aggregate Concrete Beams Reinforced with Glass Fiber–Reinforced Polymer Bars, Journal of Composites for Construction, Volume 23 Issue 2 - April 2019