The Effect of Hybrid Fibers on Some Properties of Structural Lightweight Self-Compacting Concrete by using LECA as Partial Replacement of Coarse Aggregate

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ABSTRACT

Self-Compacting Concrete (SCC) is a concrete with high workability. It fills the molds and passes between the narrow openings of reinforcing steel bars without the need for any mechanical pressure or compaction and without the need of a vibrator. Structural Lightweight Self Compacting Concrete (SLWSCC) is an innovative concrete developed in recent years. This concrete type combines the characteristics of lightweight concrete and SCC. This study focused on preparing the appropriate mixture to obtain SLWSCC by using Lightweight Expanded Clay Aggregate (LECA) as a volumetric partial replacement of coarse aggregate by 20, 40, 60, and 80%, reinforced by volumetric ratios of single and hybrid Micro steel Fiber (MF) and Hooked steel Fiber (HF) of 1.5 MF, 0.75 HF+0.75 MF, 1 HF+0.5 MF, and 1.5 HF (%) to evaluate the fresh properties through slump flow, T_{500mm}, V-funnel, L-box, and segregation tests. The results showed that all mixtures fell within the limits of EFNARC/2005. It was found that single and hybrid fiber addition reduces slump flow, L-box, and segregation, while the T_{500mm} and V-funnel values increased. The hard properties of SLWSCC reinforced by fibers, such as compressive strength, flexural strength, splitting tensile strength, oven dry density, and water absorption were studied. The addition of fibers raises compressive, splitting tensile, and flexural strength, with the maximum augmentation of 21.4, 43.4, and 53.8%, respectively, occurring when adding 1 HF + 0.5 MF. The highest value of oven dry density was acquired when adding 1.5 MF and the highest water absorption rate was acquired after the addition of 1.5 HF.

Keywords-SLWSCC; hybrid fibers; micro steel fibers; hooked steel fibers; LECA; compressive strength; flexural strength

I. INTRODUCTION

Self-Compacting Concrete (SCC) is a cast without the need for compaction and operation of a vibrator, as it fills the molds by its own weight. SCC provides improved construction quality, increased speed of construction, lower costs, acquiring high quality concrete on sites, and reducing accidents, noise and vibration, while achieving a higher quality of the external surface of concrete. [1, 2]. Lightweight Agreggate (LWA) or Light Expanded Clay Aggregate (LECA) is manufactured when clay is heated at approximately 1200 °C [3, 4]. It is possible that some structural parts will be exposed to several impacts and stresses. Structural Lightweight Self Compacting Concrete (SLWSCC) combines two important properties of concrete, self-compaction and light weight. The addition of fibers is important in the performance of fiber-reinforced concrete in terms of strength, resistance to corrosion, low weight, and flexibility in design, reducing stress concentrations and improving the overall mechanical properties [4, 5]. Authors in [6] studied the effect of LECA on concrete, and found that it is suitable for construction purposes. The specific weight of LWC was less than that the normal concrete by 16-48% and had higher water absorption. Its strength ranged from 24 to 60 MPa after 28 days. The density of concrete also decreased, ranging from 1290 to 2044 kg/m^3. Steel fibers augment strength in the structure while reducing the width of cracks and stopping their expansion, which leads to an increased life span of the structure [7]. Authors in [8] utilized two types of fibers to ameliorate some of the properties of concrete at an early and late age [8]. The objectives of this study are summarized as:

- The possibility of achieving SLWSCC production using different LECA ratios is explored.
- The effect of employing different proportions of single and hybrid steel fibers (micro steel fibers and hooked steel fibers) on the fresh and hardened properties of SLWSCC is investigated.

II. MATERIAL CHARACTERIZATION

A. Cement

Al-Mass Ordinary Portland cement (OPC) type CEM I-42.5 R was put into service. Its properties conform to the Iraqi Standard Specification No. 5 [9]. Its physical and chemical properties are shown in Tables I and II.

TABLE I. CHEMICAL COMPOSITION OF CEMENT

Oxide	Test results %	Limits of [9]
CaO	62.28	-
SiO_2	21.29	-
Al_2O_3	4.89	-
Fe_2O_3	5.41	-
MgO	2.11	Max 5%
SO_3	2.34	Max 2.8 If C3A > 3.5
Loss on ignition (LOI)	1.73	Max 4%
Insoluble Residue (IR)	0.85	Max 1.5%
Constituent% according to Bogue equations		
C_3S	44.41	-
C_2S	27.62	-
C_3A	3.82	-
C_4AF	16.45	-

TABLE II. PHYSICAL PROPERTIES OF CEMENT

Physical properties	Test results	Limits of [9]
Specific surface area - Blaine method (m^2/kg)	369	≥ 280
Setting time (Vicat's apparatus)		
Initial setting (min)	124	≥ 45
Final setting (hr)	3:30	≤ 10
Soundness using autoclave method (%)	0.65	≤ 0.8
Compressive strength (MPa)		
2 days	24	≥ 20
28 days	46	≥ 42.5

B. Fine Aggregate

Table III depicts the physical and chemical properties of the fine aggregate, while Table IV portrays the sieve analysis, which conforms to the limits of Iraqi Specification No. 45/1983, Zone 2 [10].

TABLE III. CHEMICAL AND PHYSICAL PROPERTIES OF FINE AGGREGATES

Property	Test result	I.Q.S.45: 1984 limits
Specific gravity	2.58	-
Absorption (%)	0.71	-
Dry rodded density (kg/m^3)	1634	-
Sulfate content (SO_3)	0.21	0.50% (max)

C. Coarse Aggregate

In this research, the maximum size of 10 mm crushed gravel with density of 1679 kg/m^3, 0.6% absorption, and 0.06% SO_3 was deployed. Its physical properties conform to the Iraqi Standard Specification IQS No. 45/1983[10] as observed in Table V.

TABLE IV. FINE AGGREGATE SIEVE ANALYSIS

Sieve no.	Passing %	Limits of [10]
10 mm	100	100
4.75 mm	93.1	90-100
2.36 mm	77.8	75-100
1.18 mm	66.5	55-90
600 μm	54.3	35-59
300 μm	26.2	8-30
150 μm	3.2	100

TABLE V. GRADING OF NATURAL COARSE AGGREGATE

Sieve size (mm)	Cumulative passing (%)	Iraqi Specification [10]
20	100	100
14	100	100
10	96	85-100
4.75	20.6	0 - 25
2.36	2.7	0-5

D. Silica Fume (SF)

In this research, micro silica fume (MF) by the ISOMAT Iraq Branch was used, and several proportions were applied. The chemical and physical properties of micro silica fume are listed in Tables VI and VII. The material complies with the requirements of (ASTM C 1240/ 2020) [11].

TABLE VI. CHEMICAL ANALYSIS OF SILICA FUME

Oxide	Oxide content %	Specifications [11]
SiO_2	92.5	≥ 85.0
Al_2O_3	0.36	-
Fe_2O_3	1.30	-
CaO	1.8	-
SO_3	0.63	-
MgO	2.3	-
Na_2O	0.09	-
K_2O	0.08	-
LOI	2.8	≤ 6.0
Moisture content	0.35	≤ 3.0

TABLE VII. HYSICAL PROPERTIES OF SILICA FUME

Physical properties	Test results	Specifications [11]
Percent retained on 45 µm (No. 325) sieve (%)	8	≤ 10
Accelerated pozzolanic strength activity index at 7days (%)	123.5	≥ 105
Specific surface (m^2/g)	17	≥ 15

E. Lightweight Expanded Clay Aggregate (LECA)

LECA with a nominal size of 9.5 mm, bulk density of 320 kg/m^3, 0.05% SO_3, and 20% water absorption were applied. LECA grading is illustrated in Table VIII according to ASTM C330-17 [12]. Due to its high absorption it was submerged in water for 24 h before being added to the mixture.

F. Water

Tap water conforming to the requirements of Iraqi Standard No. 1703/2018 [13] was used at a temperature of approximately 25 ^oC.

TABLE VIII. LECA GRADING

Sieve size (mm)	Passing %	ASTM C330-17 Nominal size 9.5_{mm} - 2.36_{mm}
12.5	100	100
9.5	96	80 - 100
4.75	17	5 - 40
2.36	2.5	0-20

G. Steel fibers

Straight steel fibers with hooked ends (HF) and golden-colored micro steel fibers were deployed as presented in Figure 1. Table IX demonstrates the dimensions and mechanical properties of both steel fiber types.

H. Concrete Mixtures

A total of 9 mixtures were constructed. In five of the mixes the coarse aggregate was replaced with LECA in different proportions, as noticed in Figure 2.

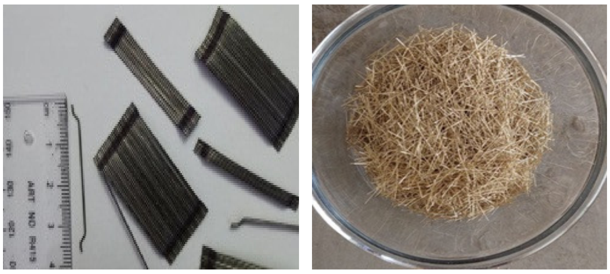

Fig. 1. The two types of steel fibers used.

TABLE IX. PROPERTIES OF STEEL FIBERS

Property	Hooked fibers	Micro steel fiber
Length (mm)	35	12
Diameter (mm)	0.55	0.2
Aspect ratio (L/D)	64	60
Tensile Strength (MPa)	2200	≥ 2850
Density (kg/m^3)	7800	7850

Fig. 2. Casting concrete molds.

The LWSCC mixes were constructed to obtain structural LWC that met the requirements of [14, 15], as displayed in Table X, with 2.75 Kg/m^3 superplastisizer and 5% silica fume as a partial replacement of cement for all mixes. The SLWSSC was attained with a volumetric partial replacement of coarse aggregate with LECA ratio of 80% and compressive strength of 22.4 MPa and density of 1822 kg/m^3 at 28 days of curing were acquired as spotted in Table XI.

III. RESULTS AND DISCUSSION

A. Fresh Properties of SLWSCC

In this research, five tests were conducted with fresh concrete, as mentioned, through which the workability was determined without fibers and with the addition of fibers in different proportions as disclosed in Tables XI and XII. The workability was directly proportional with the percentage of LECA, due to its rounded appearance, low specific gravity. This result is compatible with the findings in [16, 17]. It was noticed that the workability gradually decreases with the addition of fibers, but it was found that the greatest decrease in workability occured for the fiber ratio of 1.5HF, where the former was (12.3) % due to interference and friction between the fiber (hooked steel fiber) and the rest of the components of the mixture, as revealed in Table XII.

TABLE X. MIX PROPORTIONS

Mix	Cement (kg/m^3)	SF (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	LECA (kg/m^3)	Water (kg/m^3)	MF V_f %	HFV_f %
M0	520	26	937	780	0	164	-	-
M20	520	26	937	624	29.7	164	-	-
M40	520	26	937	468	59.4	164	-	-
M60	520	26	937	312	89.2	164	-	-
M80	520	26	937	156	118.9	164	-	-
M80/1.5MF	520	26	937	156	118.9	164	1.5	0
M80/ 0.75HF+0.75MF	520	26	937	156	118.9	164	0.75	0.75
M80/1HF+0.5MF	520	26	937	156	118.9	164	0.5	1
M80/1.5HF	520	26	937	156	118.9	164	0	1.5

TABLE XI. FRESH AN HARDENED PROPERTIES OF VOLUMETRIC REPLACEMENT OF COARSE AGGREGATE WITH LECA (%)

x	Slump Flow (SF)(mm)	T_{500mm} (s)	V – funnel (s)	L - Box	Segregation Index, %	Comp. strength (MPa)	Density (kg/m^3)
						28 day	
M0	661	4.7	10.56	0.85	12.7	41.1	2402
M20	674	3.9	9.60	0.88	13.5	36.5	2255
M40	688	3.1	8.90	0.89	14.2	30.6	2140
M60	699	2.6	8.0	0.91	15.4	25.3	1979
M80	710	2.2	7.4	0.93	16.7	22.4	1822

TABLE XII. FRESH PROPERTIES OF FIBER SLWSCC

Mix	Slump flow (mm)	T_{500mm} (s)	V- funnel (s)	L-box	SI, %
M80	710	2.2	7.4	0.93	16.7
M80/1.5MF	670	2.6	9.5	0.90	12.8
M80/ 0.75HF+0.75MF	659	3.2	10.0	0.88	10.9
M80/1HF+0.5MF	641	3.7	10.2	0.85	9.4
M80/1.5HF	623	3.9	13.1	0.82	8.5

It was found that the addition of 1.5 HF reduced slump flow from 710 to 623 mm. Slump flow time (T_{500mm}) ranged from 2.2 to 3.9 s (Table XII and Figure 3). The V- funnel results ranged from 7.4 to 13.1 s (Table XII and Figure 4).

Fig. 3. T_{500mm} test.

Fig. 4. V-Funnel time test.

The L-box values varied from 0.82 to 0.93, as shown in Table XII, while the SI results ranged from 8.5 to 16.7%. All results were consistent with the SCC accepted standards of EFNARC / 2005 [15]. The EFNARC limits for the slump flow test range between 550 and 650 mm for slump class SF1, and between 650 and 750 mm for slump class SF2. Concerning T_{500mm}, the test limit is more than 2 s, for the V-funnel test it is between 9 and 25 s, for the L-Box test, it must be more than 0.8, and for SI, it must be less than 20% for class SR1 and less than 15% for class SR2.

B. Hardening Properties of LWSCC

1) Compressive Strength

The results of compressive strength test according to BS EN 12390-3: 2019 [18] were 22.4 – 26.7 MPa at 28 days as per requirements of ACI 213R-03 [14], as revealed in Table XIII and Figure 5. The highest percentage increase in compressive strength for samples containing fibers (1HF + 0.5MF) was about 21.4% compared to the reference mix without fibers, due to the homogeneous distribution of fibers throughout the SLWSCC mixture. The high elastic modulus of MF can be an additional reason for the increased compressive strength [19], since the fibers have the ability to delay the formation of micro-cracks and then stop their propagation to some extent [20].

TABLE XIII. COMPRESSIVE STRENGTH TEST OF SLWSCC

Mixes	Compressive strength, MPa		
	7 day	28 day	56 day
M80	17.6	22.4	26.0
M80/1.5MF	19.8	25.4	28.9
M80/ 0.75HF+0.75MF	20.4	26.1	29.6
M80/1HF+0.5MF	21.2	27.2	30.9
M80/1.5HF	20.7	26.7	30.3

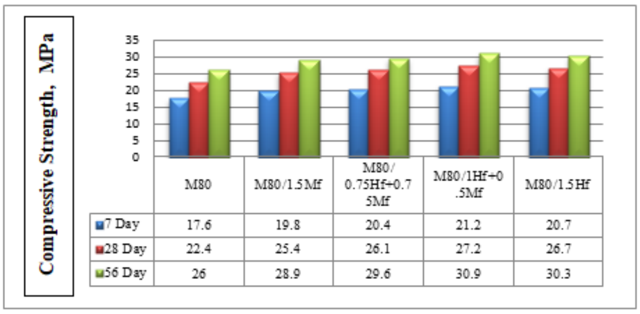

Fig. 5. Compressive strength results.

C. Splitting Tensile Strength

The results of the splitting strength according to ASTM C496/C496M-17 [21] at 7, 28, and 56 days are manifested in Table XIV and Figure 6. The results indicated that the splitting tensile strength increases continuously with age. It was also noted that the cleavage strength of the SLWSCC mixtures containing 1HF+0.5MF was the best ratio of hybrid fibers, as it increased by 43.4% compared to the mixture without fibers. This occurred due to the action mechanism of the fibers in preventing the spread of cracks and improving the bonding between the fibers in the matrix [22]. The cleavage strength of SLWSCC mixtures containing single and hybrid fibers rose significantly in comparison with the mixture without fibers.

TABLE XIV. SPLITTING TENSILE STRENGTH TEST OF SLWSCC

Mixes	Splitting tensile strength, Mpa		
	7 days	28 day	56 days
M80	1.98	2.6	2.79
M80/1.5MF	2.64	3.48	3.90
M80/ 0.75HF+0.75MF	2.73	3.59	3.96
M80/1HF+0.5MF	2.88	3.73	4.3
M80/1.5HF	2.81	3.65	4.1

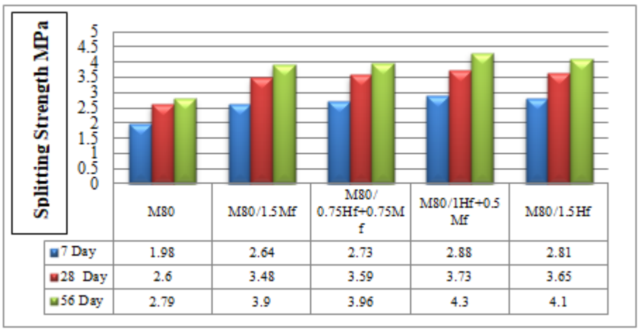

Fig. 6. Splitting tensile strength.

D. Flexural Strength

The results of this test according to ASTM C293/C 293M–16 [23], are portrayed in Table XV and depicted in Figure 7. The fibers were used in different proportions. The result exhibited an increase in the concrete's resistance to cracking at a percentage of hybrid fibers (1HF+0.5MF) because short fibers can bridge small cracks, which usually form in the early stages of flexural strength, with high efficiency. When the cracks are larger, the long fibers act as a bridging mechanism, and as a result, the enhancement of ductility depends mainly on the long fibers.

TABLE XV. FLEXURAL STRENGTH TEST OF SLWSCC

Mix	Flexural strength, Mpa		
	7 days	28 days	56 days
M80	2.9	3.85	4.13
M80/1.5MF	4.01	5.39	5.9
M80/ 0.75HF+0.75MF	4.21	5.66	6.1
M80/1HF+0.5MF	4.39	5.92	6.43
M80/1.5HF	4.32	5.83	6.37

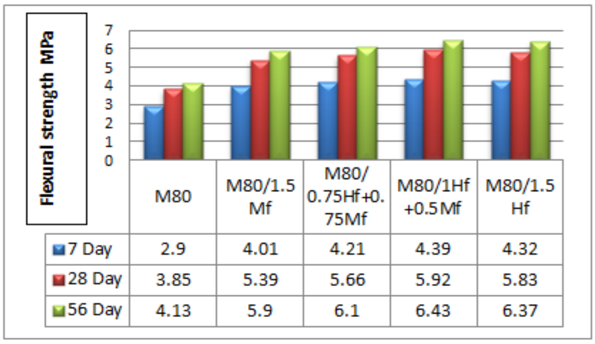

Fig. 7. Flexural strength.

E. Oven Dry Density of LWSCC

The results of density according to ASTM C567-05a [24] for SLWSCC samples at 28 days are illustrated in Table XVI and are displayed in Figure 8. It has been shown that density was directly proportioned to the fiber addition percentage, but as the percentage of hook fibers increases, the density decreased due to the reduction in workability and the formation of voids within the mixture, thus density decreased.

F. Water Absorption

This test was conducted according to ASTM C642-13 [25] by utilizing cylinder specimens of 100 × 200 mm. The results of this test are provided in Table XVII and Figure 9. It was noticed that water absorption slightly increased with the addition of fibers, whether single or hybrid.

TABLE XVI. OVEN DRY DENSITY RESULTS OF SLWSCC

Mixes	Oven dry density (kg/m^3)
M80	1822
M80/1.5MF	1890
M80/ 0.75HF+0.75MF	1884
M80/1HF+0.5MF	1880
M80/1.5HF	1875

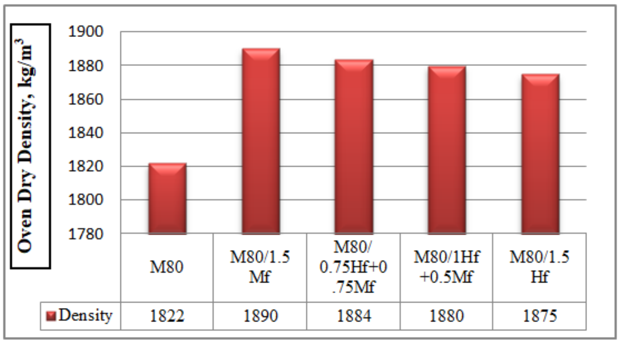

Fig. 8. Oven dry density of SLWSCC.

TABLE XVII. WATER ABSORPTION RESULTS OF SLWSCC

Mix	Water Absorption (%)
M80	4.12
M80/1.5MF	4.46
M80/ 0.75HF+0.75MF	4.49
M80/1HF+0.5MF	4.52
M80/1.5HF	4.58

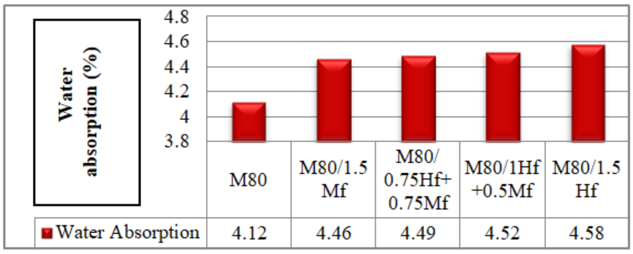

Fig. 9. Water absorption.

IV. CONCLUSION

The following conclusions were reached from the experimental results:

- When using LECA as an alternative material in different proportions to coarse aggregate for SCC mixtures, structural lightweight concrete was obtained with LECA volumetric replacement by 80%.
- All results of fresh concrete tests fall within the acceptance criteria of EFNARC, 2005. It was found that adding fibers reduces the slump flow, L-box, and segregation index for

single and hybrid fibers reaching a max reduction for mix M80/1.5HF by 12.3, 11.8, and 49%, respectively. As for the T_{500mm} and V-funnel tests, the results were higher compared to the reference mixture reaching a max maximum increase for mix M80/1.5HF by 77.2 and 77%, respectively.

- Fibers of different proportions and types were utilized, single type MF, HF, and hybrid fiber type 0.75HF + 0.75MF and 1HF + 0.5MF. The best result was an increase in the concrete's resistance to cracking from 1HF+0.5MF hybrid fibers.
- Water absorption increased when either single or hybrid fibers were added.
- It was also observed that as the fibers increased, the density rose, but as the percentage of hook fibers increased, the density of concrete decreased.

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