Enhancing the mechanical properties of lightweight concrete using mono and hybrid fibers

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Abstract. This investigation aims to study some properties of lightweight aggregate concrete reinforced by mono or hybrid fibers of different sizes and types. In this research, the considered lightweight aggregate was Light Expanded Clay Aggregate while the adopted fibers included hooked, straight, polypropylene, and glass. Eleven lightweight concrete mixes were considered, these mixes comprised of: one plain concrete mix (without fibers), two reinforced concrete mixtures of mono fiber (hooked or straight fibers), six reinforced concrete mixtures of double hybrid fibers, and two reinforced concrete mixtures of triple hybrid fibers. Hardened concrete properties were investigated in this study. Generally, mono and hybrid fiber specimens showed a significant increase in the splitting tensile strength compared to the plain specimen while they had a slight improvement in compressive strength and modulus of elasticity. The outcomes of the experimental results illustrated that hybrid fibers had the most significant advanced effect on concrete hardened properties. Moreover, the optimization procedure revealed that the best performance in terms of maximum mechanical properties achieved in the mixture reinforced by hybrid fibers [straight + hooked + glass]. The maximum achieved advantage reached (14.18%), (91.97%), and (36.70%) for compressive strength, splitting tensile strength, and modulus of elasticity respectively.

Keywords: Lightweight Concrete, Mono Fiber, Hybrid Fibers, Light Expanded Clay Aggregate, Compressive Strength, Splitting Tensile Strength, Modulus of Elasticity.

1. Introduction
Lightweight concrete can be defined as concrete of substantially lower unit weight than that made from natural gravel. Making concrete lighter is possible, simply through replacing the aggregate with lighter material such as Expanded Clay Aggregate (ECA). Expanded Clay Aggregate is a porous ceramic product characterized by a uniform pore structure of fine and closed cells, densely sintered, and stiff external skin. Lightweight concrete provides constructions of high durability that became more continuously increased in use in different countries nowadays. For structural applications, lightweight aggregate concrete may be adopted, with strengths equal to normal weight concrete. Its reduced mass and enhanced thermal and sound insulation properties, while retaining sufficient strength, are the advantages of lightweight concrete. There are several benefits to reduced weight, the least of which is a reduced demand for power during building. Lightweight aggregate used must be compatible with the ASTM C330 [1] and the compressive strength of LWAC at 28 days ought to be not least than 17 MPa and the density be in the variety of 1120–1920 kg/m³ [2].
In structures construction, adopting Fiber Reinforced Concrete (FRC) had enlarged as it modifies the durability, flexural strength, tensile strength, impact strength as well as a concrete failure mode. The
addition of fibers to concrete had also been known to have little or non-significant influence on the compressive strength and elasticity modulus [3]. Fibers can be categorized as metallic, synthetic, or natural [4], and could be in different geometries. Steel fiber (SF) is the most widely used of all fibers since it improves the mechanical properties of concrete due to its reinforcing advantages, environmental resistance, and economic aspects [5].

Using two or more forms of fibers in an effective grouping can potentially modify concrete's overall properties and lead to performance synergies [6]. Said et al. (2015) [7] inspected the influence of polyethylene fiber on the flexural strength and compressive strength of cubes and slabs of engineered composite cement, the outcomes showed the addition of fiber significantly improved ultimate deflections, failure load, and the ultimate strength of slabs.

Tassew et al. (2014) [8] Presented results that improved the effect of glass fiber by phosphate cement binder on the mechanical properties of modified ceramic concrete. The conclusion presented the effect of fiber content was directly proportional to the compression, flexure, and toughness, while the workability decreased as the fiber content increased.

Chen and Liu (2005) [6] inspected the contribution of hybrid fibers to the workability, mechanical properties (compressive strength, splitting tensile strength, shrinkage, and toughness index) of manufactured expanded clay lightweight concrete. Fiber-reinforced lightweight concrete specimens were separated into six groups; Three groups were strengthened with mono fiber (steel, carbon, or polypropylene fibers) of volume fraction (1%), the other three groups were reinforced with two types of fibers (hybrid fibers) with volume fraction (0.5%) for each type of fibers (0.5% steel, 0.5% carbon and 0.5% polypropylene). All combinations of altered fiber types resulted in an improvement in the strength and durability index. The combination of carbon-steel fibers provides the best performance, 27.6 percent increase in compressive strength, a 38.3 percent increase in splitting.

In this paper, steel (hooked and straight), polypropylene, and glass fibers were mixed in proportion to the hybrid fiber reinforced concrete made, and a series of mechanical tests were carried out to research the effect of fiber types on compressive, splitting, and elasticity modulus for lightweight concrete.

2. Experimental Program

2.1. Materials

In this work, ordinary Portland cement was used, it’s a product of United Cement Company (MAS) Al-Sulaymaniya / Iraq that’s satisfied the requirements of the Iraqi Specification No.5/1984 [9] and ASTM C150-2007 [10] Chemical composition and physical analysis of the used cement were illustrated in Tables (1 and 2) respectively. Regarding the fine aggregate, natural sand compatible with the requirements of the Iraqi Specification No.45/1993 [11] was considered. The gradation analysis of the fine aggregate was listed in Table 3, it can be classified as zone (2) and the physical properties of it was shown in Table 4. Figure 1 shows Light Expanded Clay Aggregate (LECA) that was used as coarse aggregate in the present study to produce lightweight concrete. The grain size of the coarse aggregate was ranged between (4-10) mm. Moreover; silica fume was regarded as a partial cement replacement, both the chemical composition and physical properties of silica that conformed to the ASTM C-1240-03 Limitations were listed in Table 5 [12]. Conplast SP-423 was the type of superplasticizer used. Four types of fiber were adopted in this study: hooked steel fiber, straight steel fiber, polypropylene fiber, and glass fiber as shown in Figure 2, all the details of the considered fibers were illustrated in Table 6.
Table 1. Chemical composition of cement.

| Compound Composition | Chemical Composition | % Weight | Iraqi Specification No. 45 / 1993 |
|----------------------|----------------------|----------|----------------------------------|
| 1 Silica SiO₂         |                      | 19.18    | Not limited                      |
| 2 Lime CaO           |                      | 61.98    | Not limited                      |
| 3 Iron Oxide Fe₂O₃   |                      | 4.22     | Not limited                      |
| 4 Alumina Al₂O₃      |                      | 5.42     | Not limited                      |
| 5 Lime saturation factor L.S.F | | 0.96    | 0.66-1.02 |
| 6 Magnesia MgO       |                      | 0.24     | Max. 5                           |
| 7 Sulfate SO₃        | C₃A<5%               | 2.18     | Not applicable                   |
| 8 Insoluble residue  | I.R                  | 0.85     | Max. 1.5                         |
| 9 Loss on ignition   | L.O.I                | 3.14     | Max. 4                           |
| 10 Tricalcium silicate C₃S |                  | 58.51    | Not limited                      |
| 11 Dicalcium silicate C₂S |                  | 10.59    | Not limited                      |
| 12 Tricalcium aluminates C₃A |              | 6.97     | Not limited                      |
| 13 Tetra calcium alumina ferrite C₄AF |                | 12.82    | Not limited                      |

Table 2. Cement's physical properties.

| Physical Properties                        | Test Result | Iraqi Specification No. 5 / 1993 |
|--------------------------------------------|-------------|----------------------------------|
| Setting time                               |             |                                  |
| The initial setting of time : (mint)       | 107         | Min. 45                          |
| The final setting of time : (hour)         | 4.67        | Max. 10                          |
| Compressive Strength, MPa                  |             |                                  |
| 3 days                                     | 15.47       | Min. 15                          |
| 7 days                                     | 22.71       | Min. 23                          |

Table 3. Fine aggregate analysis.

| Sieve Size (mm) | Test Results | Limit of Iraqi Specification No. 45 / 1993 |
|-----------------|--------------|--------------------------------------------|
|                 | % Passing by mass | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
| 10.0            | 100          | 100    | 100    | 100    | 100    |
| 4.75            | 90.1         | 90-100 | 90-100 | 90-100 | 95-100 |
| 2.36            | 78.7         | 60-95  | 75-100 | 85-100 | 95-100 |
| 1.18            | 68.9         | 69-90  | 55-90  | 75-100 | 90-100 |
| 0.60            | 51.6         | 30-70  | 35-59  | 60-79  | 80-100 |
| 0.30            | 19.3         | 5-34   | 8-30   | 12-40  | 15-50  |
| 0.15            | 3.3          | 5-20   | 0-10   | 0-10   | 0-15   |
| 75×10⁻³         | 2.07         | 5 Max. |        |        |        |
Table 4. Fine aggregate's physical properties.

| No. | Physical Properties       | Test Results | Iraqi Specification No. 45 / 1993 |
|-----|---------------------------|--------------|-----------------------------------|
| 1   | Sulfate contained %       | 0.19         | 0.5 (max)                         |
| 2   | Specific gravity          | 2.67         | -----                             |
| 3   | Absorption %              | 0.65         | -----                             |

Figure 1. Light Expanded Clay Aggregate (LECA).

Table 5. ASTM C-1240 Chemical composition of silica fume.

| No. | Compound composition | Chemical composition | % Weight | ASTM C-1240 Limitations |
|-----|----------------------|----------------------|----------|-------------------------|
| 1   | Silica               | SiO₂                 | 91.09    | ≥85                     |
| 2   | Magnesia             | MgO                  | 2.11     | ---                     |
| 3   | Alumina              | Al₂O₃                | 0.19     | ---                     |
| 4   | Sulfate              | SO₃                  | 0.91     | ---                     |
| 5   | Iron Oxide           | Fe₂O₃                | 1.07     | ---                     |
| 6   | Lime                 | CaO                  | 0.85     | ---                     |
| 7   | Loss on ignition     | L.O.I                | 3.77     | ≤ 6.0                   |
Figure 2. Types of the used fibers.

Table 6. Properties of the used fibers.

| Type of fiber   | Diameter (mm) | Length (mm) | Aspect ratio | Tensile strength (MPa) | Density (kg/m$^3$) |
|----------------|---------------|-------------|--------------|------------------------|-------------------|
| Hooked         | 0.50          | 30          | 60           | 1700                   | 7800              |
| Straight       | 0.25          | 14          | 56           | 2500                   | 7800              |
| Polypropylene  | 0.84          | 30          | 36           | 430                    | 990               |
| Glass          | 0.60          | 30          | 50           | 1200                   | 2540              |

2.2. Concrete Mixing
Concrete was mixed using a mechanical pan mixer which is of approximately 0.25 m$^3$ capacity, mix proportions of the designed lightweight concrete mix are shown in Table 7. Initially, to ensure a homogeneous distribution of the silica in the mix, dry mixing for both silica fume and cement was considered for around two minutes. This was followed by adding and mixing the sand and the aggregate for three minutes, then the mixture was added after the mix of superplasticizer (SP) and water, and the mix compositions were blended for a further four minutes. Finally, in three minutes, the quantity of fibers was homogeneously distributed in the mixture and the mixing progression continued for an additional two minutes. Afterward, fresh lightweight concrete was cast.

Table 7. Mix proportions of used LWC mix.

| Material          | Proportion (kg/m$^3$) |
|-------------------|-----------------------|
| Cement            | 542.5                 |
| Water             | 237                   |
| Coarse Agg. (LECA)| 202.34                |
| Fine Agg. (sand)  | 1005                  |
| silica fume       | 50                    |
| superplasticizer  | 7                     |
2.3. Tested Specimens

In this investigation, several fibers (hocked steel fiber, straight steel fiber, glass fiber, and polypropylene fiber) were adopted to reinforce lightweight concrete specimens with different combinations and with a constant volume fraction of 1.5%. Thirty-three cubes and sixty-six cylinders (eleven sets each comprised three cubes and six cylinders) were cast and tested. Table 8 showed the designation of the tested specimens. To evaluate the compressive strength, cubes of (150x150x150) mm were cast according to B.S.1881: part 116 [13] . Concerning the splitting tensile strength and modulus of elasticity, (150x300) mm cylinder molds were cast to be compatible with the ASTM C496/C496M-17 [14] for splitting tensile strength test requirements and ASTM C469/C469M-14 [15] for modulus of elasticity. The tested specimens were divided into three groups, the first group indicated the effect of adding fiber(mono or hybrid) compared with the specimens that didn’t contain fibers while the second and third groups characterized the effect of hybrid fibers with volume fraction(1.5%) compared with two mono-type forms of steel fibers (hooked and straight) with same volume fraction ratio(1.5%).

Table 8. Designation of the test specimens.

| Cubes and cylinders designation | Fiber’s type               |
|---------------------------------|-----------------------------|
| NF                              | No fiber                    |
| H1.5                            | Hocked steel fiber          |
| S1.5                            | Straight steel fiber        |
| HG1&0.5                         | Hocked & Glass fiber        |
| HP1&0.5                         | Hocked & Polypropylene fiber|
| HS1&0.5                         | Hocked & Straight steel fiber|
| HS0.5&1                         | Hocked & Straight steel fiber|
| SG1&0.5                         | Straight & Glass fiber      |
| SP1&0.5                         | Straight & Polypropylene fiber|
| SHP 0.5&0.5&0.5                  | Straight, Hocked & Polypropylene fiber|
| SHG 0.5&0.5&0.5                  | Straight, Hocked & Glass fiber|

3. Test Results and Discussion

3.1. Compressive Strength

The outcomes of the compressive strength have been presented in Table 9 and the mode failure is shown in Figure 3. Test results of group one indicated that the influence of both mono and hybrid fibers increased the compressive strength slightly as compared with the reference specimen of plain concrete (NF), the maximum achieved percentage of increase was the specimen SHG 0.5&0.5&0.5 by(14.18)%. From the test results of specimens that contained mono fiber (H1.5 and S1.5), hooked steel fiber produced the highest increase percentage of about (6.93%) compared to (NF) specimen while for the six double hybrid reinforced fibers specimens (HG1&0.5, HP1&0.5, HS1&0.5, HS0.5&1, SG1&0.5, and SP1&0.5) the mix of hooked of volume fraction (1%) and straight with volume fraction (0.5%) [HS1&0.5] exhibited the highest enhancement by (11.6%) compared to (NF) specimen. Furthermore; specimens of triple hybrid fibers (SHP0.5&0.5&0.5 and SHG0.5&0.5&0.5) presented the optimum improvement in the compressive strength by (12.96 and 14.18) % respectively. This can be disrupted by the fact that various restriction conditions will be created by hybrid fibers of various sizes and styles. Furthermore, this condition may be attributed to the increase in the strength of the mechanical bond since both fibers can slow the creation of micro-cracks and to some extent prevent their propagation afterward [16].
Figure 3. Mode of compressive failure.

Table 9. Mechanical properties of LWC For group one.

| Cubes and cylinders designation | Compressive strength (MPa) | % Variation | Splitting tensile strength (MPa) | % Variation | Modulus of Elasticity (MPa) | % Variation |
|--------------------------------|---------------------------|-------------|---------------------------------|-------------|-----------------------------|-------------|
|                              | $f_c'$                     |             | $f_t$                           |             | $E_c$                       |             |
| Ref.(NF)                      | 29.4                       |             | 2.24                            |             | 17465.87                    |             |
| H 1.5                         | 31.44                      | 6.93        | 3.7                             | 65.18       | 20645.22                    | 18.20       |
| S 1.5                         | 30.79                      | 4.73        | 3.5                             | 56.25       | 20143.46                    | 15.33       |
| HG 1&0.5                      | 30.69                      | 4.39        | 3.4                             | 51.79       | 20390.52                    | 16.74       |
| HP 1&0.5                      | 29.69                      | 0.99        | 3.2                             | 42.85       | 20289.47                    | 16.17       |
| HS 1&0.5                      | 32.81                      | 11.6        | 3.75                            | 67.41       | 21986.39                    | 25.88       |
| HS 0.5&1                      | 31.79                      | 8.13        | 3.56                            | 58.93       | 21421.10                    | 22.65       |
| SG 1&0.5                      | 30.42                      | 3.47        | 3.3                             | 47.32       | 21237.5                     | 21.59       |
| SP 1&0.5                      | 29.52                      | 0.41        | 3                               | 33.93       | 21571.428                   | 23.51       |
| SHP                           | 33.21                      | 12.96       | 4.1                             | 83.04       | 22645.8                     | 29.65       |
| 0.5&0.5&0.5                   | 33.57                      | 14.18       | 4.3                             | 91.97       | 23876.33                    | 36.70       |

Regarding the second group, where specimens of mono hooked steel fiber (H1.5) was depended to be the reference specimen, using glass and polypropylene fibers as a partial replacement of hooked fiber (HG1&0.5 and HP1&0.5) led to a decrease in the compressive strength of LWC by (2.39 and 5.57) % respectively as compared with the reference specimen (H1.5) as shown in Table 10. It was also concluded that polypropylene fiber was more influenced by the reduction of the compressive strength than those caused by the glass fiber, this is related to the low strength properties of polypropylene fiber. As the same of group one the two triple hybrid fibers of (SHP0.5&0.5&0.5 and SHG0.5&0.5&0.5) exhibited the highest improvement in the compressive strength by (5.63 and 6.78) % respectively. In the third group, (S1.5) was considered as the reference specimen. The results were provided in Table 11. The results were similar to those of the second group, glass and polypropylene fibers (SG1&0.5 and SP1&0.5) again decreased the compressive strength of LWC by (1.2 and 4.12) %
respectively and the two triple hybrid fibers (SHP0.5&0.5&0.5 and SHG0.5&0.5&0.5) showed the highest improvement upon the compressive strength by (7.86 and 9.03) % respectively.

Table 10. Mechanical properties of LWC For group two.

| Cubes and cylinders designation | Compressive strength (MPa) | Splitting tensile strength (MPa) | Modulus of Elasticity (MPa) |
|--------------------------------|-----------------------------|----------------------------------|----------------------------|
| H 1.5                          | 31.44                       | 3.7                              | 20645.22                   |
| HG 1&0.5                       | 30.69                       | 3.4                              | 20390.52                   |
| HP 1&0.5                       | 29.69                       | 3.2                              | 20289.47                   |
| HS 1&0.5                       | 32.81                       | 3.75                             | 21986.39                   |
| HS 0.5&1                       | 31.79                       | 3.56                             | 21421.10                   |
| HSP 0.5&0.5&0.5                | 33.21                       | 4.1                              | 22645.8                    |
| HS 0.5&1                       | 33.57                       | 6.78                             | 23876.33                   |

The comparison between the three groups, the two triple hybrid fibers of (SHP 0.5&0.5&0.5, SHG 0.5&0.5&0.5) show the highest improvement in compressive strength for all types of plain specimens. This is because, the three types of fibers with different lengths, diameters, and surface contact led to support of more than one weakness in the concrete; Where straight steel fibers delayed the appearance of the initial crack and the hooked steel fiber made the mix more connected with each other and prevented the expansion and widespread while Polypropylene fiber because of its high ductility and high surface contact, the mix was more connected. Therefore, this combination gave the highest improvement than the other.

3.2. Splitting Tensile Strength

Generally, the results shown in Table 9 indicated that adding fibers significantly improved the splitting strength compared to the plain specimens (NF) for both mono and hybrid fiber concrete specimens. From the two concrete mixes containing mono fiber (H1.5 and S1.5], the highest attained percentage of increase in the splitting tensile strength was (65.18%) for the specimens (H1.5) relative to the reference specimens (NF) while the maximum gained value (67.41%) regarding the six considered double hybrid fibers reinforced specimens was presented by one of (hooked + straight) fibers with...
volume fraction (1 and 0.5) % respectively. This was compatible with the case of compressive strength. It was also found that specimens (SHP0.5&0.5&0.5 and SHG0.5&0.5&0.5) showed the highest splitting tensile strength relative to the other mixes (no fiber, mono or hybrid fibers). For the second and the third groups, Table (10 and 11), the results were almost similar to each other as there was a decrease in the splitting tensile strength when glass and polypropylene fibers were added by (0.5%) as a partial replacement of the steel fiber (hooked or straight). A case of similarity with the results of the compressive strength test was detected regarding the influence of the polypropylene fiber upon the tensile strength compared to the glass fiber effect, the highest reduction In the second and third group was achieved by the specimen (SP1&0.5) to be (14.28%). On the other hand, there was a significant modification obtained in the case of using triple hybrid fibers, the highest percentage of rising in splitting was (22.86%) for the specimen (SHG0.5&0.5&0.5). This is due to the interaction effect of hybrid fibers, tiny fibers can bind the formation of crack more professionally due to their small diameter, and their account in a unite weight of concrete is substantially greater than that of long dense fibers, for the same fraction of fiber volume. Long hooked-end fibers are enormously involved in crack bridging as the micro-cracks form and enter into larger macro cracks. In this way, ductility and tensile strength will primarily be enhanced [17].

Splitting failure characteristics of LWC was completely changed with the presence of fibers. Non-fibers concrete specimens were suddenly failed in a brittle mode and they were separated into two parts as shown in (Figure 4), while failed specimens of mono or hybrid fibers consisted of two parts that due to fibers bridging effect.

![Figure 4](image)

**Figure 4.** Type of splitting failure; (a-b) Modes failure of Specimens with no fiber, (c-d) Modes failure of specimens with (1.5%) fiber.

### 3.3. Modulus of Elasticity

To establish a stress-strain curve that’s required to estimate the modulus of elasticity, one strain gauge of (30) mm length was setting on the mid-height of the cylinder and connect to a data logger as shown in Figure 5. The increasing percentage in the modulus of elasticity for all the tested specimens compared with the reference one (NF) were shown in Table 9. It was noticed that mono straight fiber developed the less advanced (15.33) %, while the greatest modification was achieved in the case of using triple fibers (29.65 and 36.70) % of specimens (SHP0.5&0.5&0.5 and SHG0.5&0.5&0.5) respectively. This was well-matched with the outcomes of both compressive and tensile strength tests. Concerning the second group, reduction in the modulus of elasticity was achieved when glass and polypropylene fibers were used as a partial replacement of hooked fiber (HG1&0.5 and HP1&0.5) as
listed in Table 10. This can be interpreted by the direct relationship between the modulus of elasticity and the compressive strength. The state differed when straight steel fiber was used as a partial replacement of hooked fiber (HS1&0.5 and HS0.5&1), a case of modification obtained to be (6.50 and 3.76) % respectively. The same was applicable for specimens of triple fiber condition which again characterized the optimum modification to be (9.70 and 15.65) % for specimens (SHP0.5&0.5&0.5 and SHG0.5&0.5&0.5) respectively. The recorded data of the third group reflected the same outcomes as the second one as shown in Table 11.

Among all the mixes the triple hybrid fibers of (SHG0.5&0.5&0.5) showed the highest improvement in modulus of elasticity by (36.70, 15.65, and 18.53) % for group one, two, and three respectively.

4. Conclusions
Based on the results of this study, the following conclusions can be drawn:

- The addition of (1.5 % volume fraction) mono steel fiber to LWC increases its mechanical properties (compressive strength, splitting tensile strength, and modulus of elasticity) while the hybrid fibers increased it more.
- Generally, the outcomes showed that fiber inclusion substantially enhanced the splitting tensile strength of reinforced concrete specimens for both mono and hybrid fibers, while the compressive strength and elasticity modulus increased slightly compared to the reference specimens (NF, H1.5 or S1.5).
- The adopted triple hybrid fibers combinations showed the highest improvement upon the compressive strength and in both splitting tensile strength and modulus of elasticity.
- When glass and polypropylene fibers were added by (0.5%) volume fraction as a partial replacement of steel fiber (hooked or straight), a decrease in the compressive strength, splitting tensile strength and modulus of elasticity of the LWC was produced as compared with the reference specimen (H1.5 or S1.5).
- Polypropylene fiber had more negative effects on the hardening concrete properties than those caused by the glass fiber.

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