The combined effect of lightweight coarse aggregate and steel fibers on the mechanical properties of concrete

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ABSTRACT
The most evident properties of LWAC by which it is differentiated from normal weight concrete are its lower density and better insulating potential. The aim of this study is to examine the combined effect of lightweight coarse aggregate and steel fibers on concrete’s mechanical properties. In this study, three different types of coarse aggregate (normal weight, crushed clay brick and Attapulgite) with different percentages of steel fiber (0%, 0.5%, and 1%) were used. The results show that replacing normal weight concrete with lightweight concrete leads to a decrease in unit weight, compressive strength, splitting-tensile strength and modulus of elasticity, while water absorption increases. With the increase of steel fiber ratios in the mixtures, the mechanical properties of lightweight concrete improve significantly compared with the control sample with no fiber. When 1% steel fiber is used, the splitting-tensile strength increases by about 115.6% and 55.7% and compressive strength decreases by about 7.4% and 22.2% for crushed clay brick and Attapulgite, respectively, compared with normal weight concrete.

Keywords: lightweight concrete, crushed clay brick, Attapulgite, steel fiber, mechanical properties.

I. Introduction
The significant properties of low density and higher insulation, in particular for structural applications, make lightweight concrete (LWC) an important part of construction today, as these properties reduce the self-weight of structural elements. This results in a reduction in the sectional dimensions of these members, and a reduction in the total sizes and number of foundations required, such as footings, rafts and piles, that lead to cost reduction and sustainable benefits by saving the natural sources of the materials beside the environmental benefits, since some of lightweight aggregates (LWA) produced from industrial wastes or by-product[1].

In ancient times, around 3000 BCE, lightweight aggregate concrete (LWAC) was used and aggregates of volcanic rocks were used in the concrete. Since that time, the demand for LWAC has increased and manufacturing technologies have been developed for production lines in factories. In the manufacture of lightweight aggregates, natural minerals such as clays, slates
and shales, and industrial by-products such as fly ash, bed ash, and blast furnace slag are currently used[2].

In several fields of construction, including multi-story towers, high-rise buildings, bridges, petroleum platforms, marine structures and architectural projects, structural lightweight aggregate concrete (LWAC) is attractive for designers owing to its greater strength and more durable behavior than other types of LWC, which sometimes have higher costs and complicated production stages[3]. Problems such as its low tensile/compressive strength ratio, low fracture strength, high brittleness, low flexural strength and greater shrinkage, limit its use. The addition of steel fiber to LWC has a major effect on improving its properties, especially its tensile/compressive strength ratio, earthquake resistance, crack resistance and fracture resistance[4]. Finally, adding steel fiber to LWACs means that properties which are desirable in a structural member, such as sound and thermal insulation, strength and lightness, can be obtained at the same time. Therefore, by reducing dead loads, more economical solutions can be possible[5].

Shafigh et al.[6] The effect of SF on the mechanical properties of LWC was examined. They revealed that the increase in compressive strength of LWC with SF was higher at older ages than at early ages resulting in improved cohesion and bond between the fibers and the matrix at older ages. In another study, Hassan p. et al.[7] tested the mechanical properties of LWC with SF at 0.25-1 %. The results indicate that 1% SF incorporation improved the tensile strength of LWC by bridging the cracks to 77 % and consequently reducing the growth rate of tensile cracks. Rahmat et al.[8] Study the mechanical characteristics of lightweight concrete containing steel or polypropylene fibres for 3, 7, 28 and 60 days. The optimum content of steel fibers to achieve the maximum compressive and splitting tensile strengths of lightweight concrete was % and 3 %, respectively, according to the results. Nejati, F. et al. [9] Investigate the effect of fibres on the mechanical properties of lightweight concrete under totally dry and wet conditions in terms of tensile strength, compressive strength and elastic modulus. The results indicate that the presence of fibers to the concrete mixture would minimize the slump drop. The use of fibres also plays a major role in the strength of the specimens' tension. In addition, the biggest increase in the tensile strength of steel fibre samples was 83.3 % relative to the non-fibrous specimen when measured at 90 days of age. The steel fiber also increased the water absorption of the samples. At 28 days of age, the highest improvement in the elastic module was 18.9 % compared to the non-fibrous sample.

So, it seems that the LWC mechanical properties can be enhanced by using fibres also, previous research has shown the possibility of using Attapulgite and crushed bricks as a structural material based on the resulting mechanical properties and structural behaviours [10-12] but no one studied the behaviour of these materials with steel fibre, and this is the aim of this study.

2. Experimental Work
The experimental program consisted of testing 100x200 mm cylinder specimens and 100 mm cube specimens for each concrete mix, were tested to find the mechanical properties of concrete. Steel molds were used for casting cube and cylinder samples, the internal surfaces of molds have been cleaned and oiled to avoid adhesion with concrete after hardening. In accordance with ASTM C642-13, B.S. 1881: part 116:1989, ASTM C496-11 and ASTM C469-14, the oven dry density, compressive strength, splitting tensile strength and elasticity modulus were carried out, respectively.
2.1 Materials
- Cement: Resistant Portland cement. The laboratory testing of the physical and chemical properties was carried out in accordance with Iraqi specification No. 5 (1984).
- Fine Aggregate: In this study, natural sand was used, with a maximum size of 4.75 mm. The grading test results conform to Iraqi specification No. 45 (1984).
- Coarse Aggregate: Three types of coarse aggregates have been used in this study:
  1. Lightweight Coarse Aggregate (Attapulgite): Two names for this mineral are Attapulgite and Palygorskite. Bradley coined the name Attapulgite in 1940 for the Attapulgus mineral from Georgia, U.S.A. [13]. Attapulgite is a fibrous silicate which has a relatively large surface area and acidic properties that make the clay most useful as an adsorbent and catalyst. Attapulgite forms on the Earth’s surface in low-temperature clay environments therefore it is categorized as clay [14]. In 1970 Carrol introduced the chemical form of Attapulgite as:

$$\text{Si}_8\text{Mg}_5\text{O}_{20}\text{(OH)}_2\text{(OH}_2)_4\cdot 4\text{H}_2\text{O}$$

Attapulgite clay is found as a bluish green and gray clay lumps in the Al-Najaf (Tar Al-Najaf) and Karbala regions (see Plate 1). The Attapulgite used in the present study was obtained from the Tar Al-Najaf region.

![Plate 1. Attapulgite rocks in Tar Al-Najaf region](image)

Using a hammer, the rocks were crushed manually into smaller sizes, to give a finished product with a maximum size of about 10 mm, as shown in Plate 2. Sieve analysis of the Attapulgite aggregate was implemented according to ASTM C330-05 [15], and the results are shown in Figure 1.

![Plate 2. Crushing Attapulgite rocks using a hammer](image)
Figure 1. Adopted grading of Attapulgite

The prepared raw material was arranged in loose layers about 100–125 mm thick on a special bed of carbon silicate materials in a gas-fired furnace [16]. The furnace, made of fiber glass and ceramic fiber plates, has internal dimensions of 64 ×64×100 cm and includes special plates made of carbon silicate to withstand temperatures up to 1400 °C and weights up to 100 kg with dimensions of 45×45 cm, as shown in Plate 3. The temperature in the furnace was manually controlled and measured using a thermal cable from K up to 1100 °C and a digital screen, as shown in Plate 4.

Plate 3. Furnace and carbon silicate plates

Plate 4. Thermal cable type K and digital screen

The Attapulgite sample was heated to temperatures ranging from 1000-1100 °C, the temperature gradually increased at a rate of 5°C /minute to 1000-1100 °C and left for 30 minutes. The cooling phase was then begun by opening the door of the furnace very slightly, enabling heat exchange with the laboratory temperature until the next day. [16]. Plate 5 shows Attapulgite burning at 1000-1100 °C.
2. Lightweight Coarse Aggregate (crushed clay brick): Crushed clay brick obtained from demolished buildings was used as a LWCA to produce lightweight concrete. The brick samples were first crushed into smaller sizes using a hammer to achieve a final product of nearly 10 mm maximum aggregate size. Plate 6 shows the crushing of clay bricks. Sieve analysis of the crushed clay brick aggregate was carried out according to ASTM C330-05[15], as shown in Figure 2.

3. Normal Weight Coarse Aggregate: Normal weight coarse aggregate (NWCA) with a maximum size of 10 mm (Figure 3 shows the sieve analysis of NWCA) was used in this study to manufacture normal weight concrete.
Steel Fibers: Straight steel wire fibers made by Ganzhou Daye Metallic Fibers Co. Ltd., China were used in this research. The fibers are shown in Plate 7 and Table 1 lists the properties of the steel fiber.

Plate 7: Steel fiber

Table 1. Steel fiber properties

| Property                  | Data      |
|---------------------------|-----------|
| Diameter (D) (mm)         | 0.2       |
| Average length (L) (mm)   | 13        |
| Aspect ratio (L/D)        | 65        |
| Tensile strength (N/mm²)  | 2850      |
| Density (kg/m³)           | 7860      |
| Color                     | Gold      |

Chemical Admixture: In this analysis, a superplasticizer of high-performance concrete (or high-range water reduction agent (HRWRA)) was used, known as SikaViscocrete-5930. It was Imported from Egypt's Sika Company, Sika ViscoCrete -5930 is a third-generation concrete and mortar superplasticizer, an aqueous solution of modified polycarboxylates. It meets the specifications of ASTM-C- 494-99 types G and F superplasticizers.

2.2 Concrete Mix

As explained previously, concrete with an oven-dry density of less than 2000 kg/m³ and a compressive strength of cylinder more than 17 MPa for 28 days was the structural lightweight aggregate concrete. These mixes were manufactured in accordance with the guidelines of the 211.2-98 ACI Committee.[17].

One reference mix proportion of Attapulgite coarse aggregate was used in this study. The selected mix had the proportions of 1:2.1:1.2 by weight of cement, with 365 kg/m³ cement content, 769 kg/m³ dry fine aggregate content, and 408 kg/m³ dry Attapulgite coarse aggregate content. The w/c ratio was 0.4 while the superplasticizer content was was changed to achieve
the same workability for comparison purposes between different mixes. Table 2 shows the details of the mixes used in this study.

### Table 2. Details of mixes

| Mix          | N  | B1 | B2 | B3 | A1 | A2 | A3 |
|--------------|----|----|----|----|----|----|----|
| Cement kg/m³ | 365| 365| 365| 365| 365| 365| 365|
| Fine aggregate kg/m³ | 769| 769| 769| 769| 769| 769| 769|
| Coarse aggregate kg/m³ | 720| 408| 408| 408| 408| 408| 408|
| W/C          | 0.4| 0.4| 0.4| 0.4| 0.4| 0.4| 0.4|
| Steel fiber% (SF) | 0  | 0  | 0.5| 1  | 0  | 0.5| 1  |
| Superplasticizer% | 0.25| 0.38| 0.38| 0.48| 0.38| 0.38| 0.48|
| Slump, mm | 50 | 50 | 30 | 30 | 50 | 30 | 30 |

N: normal weight concrete  
B: Crushed clay brick aggregate concrete  
A: Attapulgite  
W/C: Water-cement ratio.

### 2.3 Mixing procedure

Mixing was carried out using a 0.1 m³ rotary mixer. Before placing the materials in the mixer, the interior surface of the pan was cleaned and moistened. The components were mixed according with ASTM C 192/C 192M-05[18]. The coarse aggregate with some mixing water and chemical admixture were placed in the mixer. Before adding them to the mixer, the chemical admixture was mixed with some of the mixing water. After mixing for a few seconds, the fine aggregate was added to the mixer with some mixing water. Finally, the cement was added to the mixer with the remaining mixing water. After all the concrete components have been added, the mixture was mixed for another three minutes, rested for three minutes and then mixed for two minutes. All type of aggregate was soaked in water for 24 hours to avoid the absorption of concrete mixing water by aggregates. To achieve the saturated surface dry (SSD) condition of the aggregate particles, the aggregate was exposed to air, and the surface of the aggregate particles was then dried using a blower and cloth, as recommended by ACI 211.2-98[17].

### 3. Results

- **Oven Dry Density**

  The oven dry density of Attapulgite LWC and crushed clay brick LWC were consistent with the requirements of the unified European standard (CEN ENV 1992-1-4, 1994) [19] and RILEM[20] which limit the maximum density to 2000 kg/m³. The oven dry densities of concrete are shown in Figure 4.
In Figure 4, it is clear that Attapulgite has a lower density than normal and crushed clay brick by about 23.6% and 9.9%, respectively. On the other hand, crushed clay bricks reduce density by about 15.3% compared with normal aggregate. Furthermore, the addition of different percentages of steel fiber increases the density slightly, as shown in Figure 5.

- Cube and Cylinder Compressive Strength

Table 3 shows the results of compressive strength and Plate 8 shows the failure patterns.

### Table 3. Cube and cylinder compressive strengths

| Symbol                      | N   | B1   | B2   | B3   | A1   | A2   | A3   |
|-----------------------------|-----|------|------|------|------|------|------|
| Cube compressive strength, MPa | 40.5 | 27   | 34.47| 37.5 | 25   | 29.43| 31.5 |
| Cylinder compressive strength, MPa | 32.4 | 24.13| 31.05| 33.7 | 21.5 | 25.64| 27.52|
Plate 8. Failure patterns for cube / cylinder compressive strength test

As the table shows, the use of crushed clay brick and Attapulgite as lightweight aggregates in concrete reduces cube compressive strength by about 33.3% and 38.3% respectively compared with NWAC. On the other hand the addition of steel fiber in the matrix is supposed to improve the compressive strength through the resultant arrest growth of cracks on the basis of a steel fiber and cement paste bond. Addition of 0.5% steel fiber increases cube compressive strength by about 27.7% and 17.7%, while the use of 1.0% steel fiber increases cube compressive strength by about 38.9% and 26% for crushed clay bricks and Attapulgite respectively, compared with the use 0% steel fiber, See Figure 6.

Figure 6: Increase in cube compressive strength with steel fiber %

As shown in Plate 8, the pattern of the cracks at failure differed according to steel fiber content. The number of cracks also increased as the steel fiber content increased. This indicates that the steel fiber has blocked particulate movement and decreased crushing. Figure 7 shows the average ratios of cube and cylinder compressive strength (fcu,fc') for normal weight concrete and lightweight concrete.
The results indicate that the splitting tensile strength of crushed clay brick and Attapulgite are about 19.03% and 23.88% lower than NWAC, respectively, and the fracture path through NWAC particles is the same as that of Attapulgite lightweight aggregate particles(0%SF) and crushed clay brick aggregate particles(0%SF). When steel fiber increased, the tensile strength improved due to the presence of steel fiber which increased the bond between particles. Figure 8 shows the development of splitting tensile strength with increase in steel fiber content and Plate 9 shows the failure patterns.

Steel fibers significantly limit the propagation of micro-cracks that are often present in concrete (see Plate 9). Tension cannot be passed without fibers through the crack in concrete, i.e., when the capacity of tensile of the plain concrete is reached, the micro-crack can easily
expand, resulting in brittle failure. The behavior of the steel fibers is to reduce the concentration of stress by:

1. Fibers bridge the crack near the micro-cracks and thus transmit some of the load through the crack.

2. Fibers that, due to its higher modulus of elasticity compared to that of the surrounding concrete resist more loads near the crack tip.

- Water Absorption

The water absorption results of NWC and LWC are shown in Figure 9, according to the ASTM C642-13[21] formula.

![Figure 9. Water absorption](image)

The results show that the water absorption of Attapulgite aggregate concrete is approximately 122.49% and 390.15% greater than that of crushed clay brick aggregate concrete and NWAC, contributing to a greater extent to the development of the strength of Attapulgite aggregate concrete than that of crushed clay brick aggregate concrete and NWAC. On the other hand, the addition of steel fiber reduces water absorption in both Attapulgite aggregate concrete and crushed clay brick aggregate concrete, as Figure 10 shows.

![Figure 10. Reduction in water absorption with increased steel fiber content](image)

- Static modulus of elasticity

The ACI 318-19[22]predicted static elasticity moduli for LWC and NWC are shown in Figure 11.
In Figure 11, it is clear that Attapulgite has a lower modulus of elasticity, and as a result, it has lower compressive strength and density, than normal and crushed clay brick by about 45.65% and 19.23%, respectively. The elasticity modulus is a function of compressive strength and density, and the elasticity modulus also increases with an increase in compressive strength. Actually, the compressive strength increases as the SF % ratio increases. This is evident from the previous results, where the modulus of elasticity of crushed bricks with 1% fibers was about 13.26%. Lower than normal.

4. Conclusions

1. Lightweight aggregate concrete densities are 1589-1868 kg/m³, complying with the requirements of the unified European standard (CEN ENV 1992-1-4, 1994), RILEM, which limit the maximum density to 2000 kg and ACI 213-14, which limits the maximum density to 1120–1920 kg/m³. In addition, the cylinder compressive strength of lightweight aggregate concrete is 21.5-33.7, complying with the ACI 213-14 that limited to 17.2 MPa.

2. The use of crushed clay brick and Attapulgite as a lightweight coarse aggregate reduces density by about 15.28% and 23.64% respectively, compared with normal weight concrete.

3. Cube compressive strength reduces to 33.33% and 38.27%, and splitting tensile strength reduces to 19.03% and 23.88% when normal weight is replaced by crushed clay brick and Attapulgite, respectively.

4. The average ratios of cube and cylinder compressive strength for normal weight concrete, crushed clay brick and Attapulgite are 0.8, 0.89 and 0.86, respectively.

5. Crushed clay brick and Attapulgite have 120.31% and 390.15% respectively greater water absorption than normal weight concrete.

6. Compressive strength and density increases with the increase of steel fiber content, which leads to an increase in the modulus of elasticity.

7. The use of steel fibers were enhances the bond between aggregates and cement paste, leading to a 41.9- 115.6% increase in splitting tensile strength and 5.9%-55.7% for crushed clay brick and Attapulgite with 0.5% and 1% SF respectively, compared with normal weight concrete.
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