Shrinkage and impact strength of fibre-reinforced artificial lightweight aggregate concrete

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Abstract. A sustainable High-Performance Lightweight Aggregate Concrete (HPLWAC) that uses artificial aggregate as part of its coarse ingredients (LWA) as well as being reinforced with single, double, and triple hybrid fibres in many forms, and aspect ratios (l/d) was developed. HPLWAC with a compressive strength of 47MPa and an oven-dry density equal to 1828 kg/m³ at 28 days, was made using various fibres: steel fibres with hooked ends (S1), plastic fibre (P), micro steel fibre (S), and polypropylene fibre (PP). In addition, four mixes of each type of HPLWAC were considered: reference concrete mix, single fibre reinforced concrete mix, double-hybrid concrete mix, and triple-hybrid concrete mix. Concrete specimens reinforced with the triple hybrid fibre (MAH5) withstood the maximum number of the blows to ultimate failure and first crack. The increments of rate of increase in impact resistance to ultimate failure were 1275, 977, 950, and 862 % at 7, 28, 60, and 90 days compared with the reference concrete. The drying shrinkage related to the concrete sample reinforced with single plastic fibres was reduced in comparison to the reference concrete. The percentage reductions in drying shrinkage of the single fibre (MAP) concrete specimen were 30.54 %, 20.23 %, 16.12 %, 14.38 %, 14.26 %, and 12.14 % at 7, 14, 28, 60, 90, and 180 days respectively. The hybrid fibre-reinforced samples (MAH4 and MAH5) indicated a reduction in drying shrinkage in comparison to the samples reinforced with single plastic fibre (MAP). The percentage decreases in the drying shrinkage for (MAH5) were 58.3 %, 40.6 %, 32.7 %, 26.4 %, 25.2 %, and 19.5 % at 7, 14, 28, 60, 90, and 180 days, respectively in comparison with the reference specimen (MAR). SEM indicated that all the specimens of HPLWAC had thick and dense cement pastes with elevated C-S-H content and reduced porosity indicating that high-strength was obtained for such specimens.

Keywords: Impact strength, Drying shrinkage, Artificial aggregate, Lightweight concrete, Hybrid fibre.

1. Introduction

The lightweight aggregate utilised in concrete decreases the weight of its related structural members, in turn decreasing the load transferred to the foundations. In addition, less effort is required for transporting such members [1]. Lightweight structural concrete (SLWC) provide certain other benefits such as an elevated ratio of strength to weight; high capacity to withstand tensile strain; low thermal expansion coefficient; and sound insulation improvements in comparison with the reference strength concrete [2]. Due to the inherent benefits related to SLWC, various lightweight concrete (LWC) structures, from low-rise bungalows multi-story constructions, bridges, and marine and off-shore
frameworks have been developed worldwide [3,4]. LWC is nevertheless used less than normal weight concrete (NWC) due to its low tensile to compressive strength ratio; low fracture resistance and higher shrinkage and flexural toughness. These properties do not only indicate the constraints on structural applications of LWC, they impact the long-term durability and structural performance [5]. The incorporation of discontinuous fibres in LWC can help compensate for these issues by improving tensile strength through composite behaviours. Fibres offer an approach to decreasing unsteady crack propagation; efficiently bridging small cracks while supporting compressive toughness and resistance to shrinkage cracking [6]. Typically, there are limited functions offered by the inclusion of a single type of fibre. Combining at least two fibre types (various fibre geometries and types) is thus more common in NWC, as the efficiency of such hybrid systems surpasses the performance of a single fibre type due to synergies between fibres.

Sustainable construction approaches have been developed due to mounting concern regarding the planet’s future, as the construction industry is a major consumer of resources as well as producing a great deal of waste [7]. Thus, alternative material, including construction or demolition waste and the by-products of other industries, are increasingly being examined with an eye to their use as environmentally sustainable natural aggregate substitutes in concrete [8]. The use of natural coarse lightweight aggregate (LWA) leads to the consumption of natural resources; thus, it is essential to use other types of LWA in concrete, and to replace the massive consumption of natural LWA requires producing and applying multiple forms of lightweight artificial aggregate. Thus, using waste materials as LWA has been considered as the principal aim of various studies; in particular, artificial LWA is developed using various procedures and raw materials [9].

A detailed study on the static and dynamic properties of high strength shale lightweight concrete including various volume fractions of enlarged-end steel fibre (0.5%, 1%, 1.5%, and, 2%) with lengths of 32 mm and aspect ratios of 50 was implemented by Wang and Wang [10]. The compressive strength and density of the reference light-weight aggregate concrete were 60.4 MPa and 1,963 kg/m³, respectively at 28 days. Their results indicated that the compressive strength of high strength LWAC reinforced with steel fibre offered little improvement, while the splitting tensile strength and flexural strength were significantly enhanced compared with the reference LWAC. The impact resistance and flexural toughness were significantly increased with the increase in fibre content, and high strength lightweight concrete reinforced with 1% and 1.5% volume fractions of steel fibre showed beneficial enhancement in strength and fracture toughness.

2. Research significant
The significance of this paper can be summarised as follows:

1. Investigation of the effect of single and hybrid fibres on the impact strength, and dry shrinkage of HPLWAC containing artificial LWA produced from locally available materials.
2. Study of the usefulness of micro-structure photographs of single and hybrid fibres within such HPLWAC.

3. Experimental program
3.1 Materials
High-performance LWAC prepared according to previous research [11];
1. Normal-weight natural sand with a maximal size of 4.75mm was utilised in this study, obtained from the Al-Ukaider region, of gradation zone 2 and meeting Iraqi Specification requirements No.45/1984 in terms of grading, physical features, and sulphate content.
2. Ordinary Portland cement (type I) from the Bazian Company in Iraq was used. This cement satisfies Iraqi Specifications No.5/1984. A chemical admixture with adjusted Poly-carboxylic ether (Sika-Viscocrete5930) was utilised. This third-generation superplasticizer fulfils the requirements of ASTM C494M/04 [14] type F.

3. Lightweight artificial aggregate was produced from bentonite clay along with liquid waste featuring sodium silicate from a local glass plant, as indicated in [12]. The LWA made with grading conforming to the specifications of ASTM C330 [13]. Table 1 shows the features of the developed LWA.

4. Sika Company silica fume was utilised in this study, satisfying the physical and chemical demands of ASTM C-1240 [15].

Four fibre types were used:
A- Macro hooked steel fibres (S\textsubscript{1}) of 30mm length and 0.5mm diameter (aspect ratio l/d = 60), density of 7,800kg/m\textsuperscript{3}, and ultimate tensile strength for fibres of 1,180MPa.
B- Straight steel fibres (S) with lengths of 13mm and diameters of 0.2mm (aspect ratio l/d=60), density of 7,800kg/m\textsuperscript{3}, and ultimate tensile strength for fibres equal to 1,180MPa.
C- Crimped plastic fibre (P) with lengths of 50mm, diameters of 0.8mm, and aspect ratio l/d = 63, with minimum tensile strength between 250MPa and 350MPa.
D- Micro polypropylene fibre (PP) with lengths of 12 mm, diameters of 18micron (aspect ratio l/d = 677), and minimum tensile strength equal to 350MPa.

Table 1. Features of LWA * [12].

| Properties                        | Specification | Test Results |
|-----------------------------------|---------------|--------------|
| Specific gravity                  | ASTM C127     | 1.53         |
| Absorption %                      | ASTM C127     | 12.9         |
| Dry loose unit weight, kg/m\textsuperscript{3} | ASTM C330-5  | 538.22**     |
| Dry rodded unit weight, kg/m\textsuperscript{3} | ASTM 29/C29M | 543.21       |
| Aggregate crushing value %        | BS 812-part 110-1990 | 51.6 |
| Sulfate content (as SO\textsubscript{3}), % | BS 3797-part 2-1981 | 0.97***     |

* Physical tests were carried out in “National Center for Construction Laboratories and Researches” (NCCLR).
** In the limit of ASTM C 330 ≤ 880 kg/m\textsuperscript{3}.
*** In the limit of B.S. 3797 part 2 ≤ 1.0%

3.2 Concrete mixes

Reference Light-weight Aggregate Concrete mix and several Lightweight Aggregate Concrete mixes reinforced with single and hybrid fibre were developed. Table 2 demonstrates the specifics of the concrete mixtures examined in this study.

Table 2. Specifics of LWAC mixes

| Mix symbol | Fiber volume fraction (%) | Mix proportion |
|------------|--------------------------|----------------|
|            | S1  | P  | S  | PP |                    |
| MAR        | 0   | 0  | 0  | 0  | 1:1.18:0.73 by weight (Cement: Sand :LWA), Cement content 550 kg/m\textsuperscript{3} |
| MAP        | 0   | 0.75 | 0 | 0 | w/c =0.25, HRWRA= 3L/ 100kg of cement, silica fume 10% asa replacement, by weight of cement |
| MAH4       | 0   | 0.50  | 0  | 0 |                   |
| MAH5       | 0.25 | 0  | 0.25  | 0 |                   |
3.3 Experimental tests

3.3.1 Compressive strength

According to [11], the results for compressive strength and density were as listed in Table 3.

Table 3. Compressive strength for HPLWAC [12].

| Mix symbol | Compressive strength (MPa) | Oven dry density 28 days |
|------------|-----------------------------|--------------------------|
|            | 7days | 28days | 60days | 90days |               |
| MAR        | 40.0  | 47.0   | 51.8   | 53.5   | 1828          |
| MAP        | 37.7  | 43.2   | 46.0   | 47.2   | 1821          |
| MAH₀       | 39.0  | 45.6   | 48.4   | 49.2   | 1823          |
| MAH₅       | 41.8  | 48.5   | 53.9   | 54.8   | 1835          |

3.3.2: Impact Resistance

A drop weight test has been carried out, followed by the test method proposed by the ACI 544 committee [16] for fibre-reinforced concrete, which involves assessing the number of blows required to develop the first visible cracks on the specimen’s top surface to indicate first-crack strength. Several blows were then applied to each sample until it cracked enough to touch the positioning lugs, representing the failure strength. Three specimens were tested for each concrete mix. The impact of energy was computed as

$$EI = N \times m \times g \times h$$

where $EI$ represents the impact energy (measured in N.m);
$M$ represents the drop hammer mass (measured in kg);
$N$ represents the number of blows;
$h$ represents the drop hammer height (measured in m); and
$g$ represents the acceleration of gravity (measured in m/s²).

3.3.3 Dry shrinkage

Tests of drying shrinkage were undertaken on 100x100x400 mm concrete specimens, as per ASTM C-157 [18]. Points of stainless steel were applied in parallel pairs on the concrete surface faces at 150mm spacing. The specimen length variation was measured with the use of a digital extensometer, conforming to ASTM C490 [19], with an accuracy equal to 0.002mm as checked at the beginning and the end of each observation using a plain steel bar of 305mm length. Specimens were taken from moulds after 24 h, and the drying shrinkage measured at after periods to 14, 28, 60, 90, and 180 days. The resultant mean value of the measured prisms was implemented for each mix. The drying shrinkage was computed as

$$L_x = (L_x - L_i) / G \times 100$$

where
$L_x$ represents the reading of the digital extensometer of a sample at $x$ age (measured in mm);
$L$ represents the specimen’s drying shrinkage at $x$ age %,
$G$ represents the length of the nominal gauge (150); (measured in mm);
$L_i$ represents the initial reading of the digital extensometer of a specimen; (measured in mm).
3.3.4 Scanning Electronic Microscopy (SEM)

A portion of the surface of the fracture of the concrete samples was prepared so that several microstructure images could be obtained. Specimens were dried in an oven at 60ºC for 7 days, then impressed in an epoxy resin with little viscosity and cured at 40ºC for 24 h. Those specimens were then coated with a light and thin conductive material film to prevent electric charge forming as the electron beam scans were taken. These tests were then carried out at the Applied Science Department at the University of Technology.

4. Results and discussion

4.1 Impact Resistance

The number of blows needed to create the first cracks and then failure, and the impact resistance for each specimen is listed in table 4. The results indicate that enhancement of the concrete specimen (MPa) enhances the impact resistance to both ultimate failure and first crack. The maximum numbers of blows at ultimate failure and first crack as listed for the concrete specimen reinforced with triple fibre (MAH5) showed an increase in rate of impact resistance at ultimate failure of 1,275, 977, 950, and 862 % at 7 days, 28 days, 60 days, and 90 days, respectively, in comparison with the reference specimen. Figure 1 presents the failure mode of the fibre-reinforced specimens of HPLWAC. In general, the reference concrete specimens cracked and displayed brittle case failure with an extended ultimate strain range. The cracks begin at the middle of the bottom surface face of the disk sample and then increase upward and across the support with an increase in the number of blows. However, while fibre-reinforced concrete samples also crack at ultimate strain, they can transfer the load more efficiently during the growth of the crack through the concrete, showing that fibres can bridge cracks developing in concrete and prevent specimens from splitting apart [20].

| Mix symbol | No. of blows up to 7 days | 28 days | 60 days | 90 days |
|------------|--------------------------|---------|---------|---------|
| First crack | Ultimate failure | Impact energy at failure (N.m) | % Increase in impact energy failure | First crack | Ultimate failure | Impact energy at failure (N.m) | % Increase in impact energy failure |
| MAR        | 10 | 52 | 1058.4 | --- | 15 | 73 | 1486 | --- | 28 | 80 | 1628.3 | --- | 33 | 93 | 1892.9 | --- |
| MAP        | 437 | 560 | 11398 | 977 | 527 | 652 | 13271 | 793 | 576 | 700 | 14248 | 775 | 617 | 749 | 15245.2 | 705 |
| MAH4       | 456 | 587 | 11948 | 1029 | 545 | 674 | 13719 | 823 | 610 | 734 | 14940 | 818 | 638 | 787 | 16018.6 | 746 |
| MAH5       | 575 | 715 | 14553 | 1275 | 628 | 786 | 15998 | 977 | 683 | 840 | 17097 | 950 | 727 | 895 | 18216.8 | 862 |
4.2 Dry shrinkage
The drying shrinkage results for various HPLWACs containing artificial LWA at up to 180 days aging are listed in table 5 and graphed in figure 2. The results show that concrete specimen drying shrinkage for single plastic fibre MAP was reduced in comparison to the reference concrete (MAR). The percentage reductions in drying shrinkage of single (MAP) concrete specimens were 30.54 %, 20.23 %, 16.12 %, 14.38 %, 14.26 %, and 12.14 % at 7, 14, 28, 60, 90, and 180 days, respectively, as a result of cracks being arrested by fibre. Each hybrid fibre sample, MAH4, and MAH5, showed low drying shrinkage compared to MAP. The smallest drying shrinkage was noted for the concrete specimen reinforced with triple hybrid fibre (MAH5). The percentages of drying shrinkage decrease for MAH5 were 58.3 %, 40.6 %, 32.7 %, 26.4 %, 252 %, and 19.5 % at 7, 14, 28, 60, 90, and 180 days, respectively, in comparison with the reference specimen (MAR). This is a result of the synergy of combined macro and micro steel fibres in arresting crack widening [11]. Each concrete specimen with artificial LWA showed some decrease in drying shrinkage. The reduction percentages for reference concrete specimens (MAR) were 9.12 %, 12.2 %, 10.1 %, 9.22 %, 7.19 %, and 4.2 % at 7, 14, 28, 60, 90, and 180 days, respectively.

| Mix. symbol | Drying shrinkage strain × 10⁻⁶ |
|-------------|-------------------------------|
|             | 7 days | 14 days | 28 days | 60 days | 90 days | 180 days |
| MAR         | 168    | 266     | 382     | 465     | 560     | 624      |
| MAP         | 117    | 212     | 320     | 396     | 478     | 547      |
| MAH4        | 92     | 190     | 298     | 375     | 438     | 526      |
| MAH5        | 70     | 158     | 257     | 342     | 419     | 502      |

Table 5. Drying shrinkage of HPLWAC specimens.
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**Figure 2.** Drying shrinkage of HPLWAC specimens containing LWA

4.3 **HPLWAC Micro-structure**

Scanning Electronic Micrograph (SEM) of a variety of HPLWAC specimens prepared for this research were done with the intent of studying the microstructure of the concrete specimens. Four representative images were taken for each specimen, and a selection of images was selected for further examination. Figures 3-a and 3-b show the micro-structures of cement paste for a sample of HPLWAC with artificial Lightweight Aggregate, without fibres. The cement paste is dense, with low porosity, which confirms interest in the use of the silica fume in concrete mixture for filling pores due to its chemical reactions with CaO that create additional gel (C-S-H). SEM images of the specimen of HPLWAC with artificial Lightweight Aggregate reinforced with fibres of MAP are shown in figure 4. The micro-structures of the cement paste can be seen as having high density, with small pores.

**Figure 3.** SEM Images of Fracture Surface a 28 Days Age for reference HPLWAC Specimen

The triple fibre-reinforced samples [(0.25 % (S1+ PP +S)] which contained artificial LWA (MAH5) showed sufficient bonds with the cement paste to produce mechanical anchorage and interlocking as a result of the particles of cement paste at the surface of PP fibre, as depicted in figure 5. PP fibre fractures and later debonding can happen at the interface, and long fibres can protrude from the
composite, producing significant frictional losses of energy, contributing to the superior hardness of the composite.

**Figure 4.** SEM Images of fracture surface at 28 days age for single plastic fibre HPLWAC Mix
5. Conclusion

From experimental results presented, the conclusions below were drawn:

1. The inclusion of fibres in HPLWAC significantly improves the impact strength at first crack and ultimate failure for each single and hybrid fibre specimen relative to reference specimens. The highest number of blows at first crack and ultimate failure were seen in concrete specimens reinforced with triple hybrid fibre (MAH5).
2. Drying shrinkage of concrete specimens reinforced with single plastic fibre was decreased compared with the reference concrete. Hybrid fibre-reinforced specimens (MAH4 and MAH5) showed low drying shrinkage compared to specimens reinforced with single plastic fibre (MAP).
3. SEM showed that each HPLWAC specimen had a dense, compacted cement paste with a high C-S-H content and low porosity, which promotes high strength in those specimens, as determined by primary examination.

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7. Reference

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