The effects of fibre on the mechanical properties of aerated concrete

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Abstract. Aerated concrete (AC) is lightweight concrete in which air voids are captured in the mortar by means of an aerating agent to meet specific requirements of density and strength. Aerated concrete displays brittle failure in tension, however, and thus an alternative solution to make the concrete more ductile and reduce the problem of cracking is to add steel bars or steel fibre. The aim of this study is thus to investigate the effect of steel fibres on the compressive strength, flexural strength, stress-strain relationship, modulus of elasticity, density, sorptivity, and water absorption of aerated concrete with such fibres as compared to plain aerated concrete. End-hooked steel fibres with lengths of 35 mm and 60 mm with aspect ratios of 64 and 67 respectively were used in this study, with a volume friction (Vf) of 1.5%. The results showed that the effect of the aspect ratio (Lf/df) on flexural strength was most prominent, and that the compressive strength of the fibre reinforced aerated concrete (SFRA)C increased significantly and the density increased slightly, while the water absorption was decreased. The sorptivity of the SFRA with short fibres was similar to that of standard AC, with this being increased slightly with the longer fibres. However, the stress-strain relationship in tension increased most significantly. Overall, 1.5% of steel fibre of 60 mm length provided the highest flexural strength at 28 days.

Keywords: Compressive strength, flexural strength, steel fibre, aerated concrete.

1. Introduction
Concrete often displays brittle failure in tension. One solution to making the concrete more ductile and reducing the problem of cracking is to add steel bars or steel fibre [1], as the introduction of fibres to concrete produces an identical and isotropic material. When the concrete cracks, the randomly oriented fibres arrest crack creation and propagation, which leads to improvements in strength and ductility [2]. Concrete with small fibres is thus very effective, due to its large post-peak stress-strain curve [3]. Many efforts have been made towards developing concrete that offers such enhanced performance and greater safety in building structures, and many different types of precast concrete have been produced, such as fibre-reinforced concrete (FRC), lightweight concrete (LWC), and aerated concrete (AC). FRC has higher ductility or inelastic deformation capacity than normal concrete (NC), but it also weighs more, often requiring an alternative material to be used [4]. Aerated concrete (AC) is lightweight concrete in which air voids are captured in the mortar by means of an added aerating agent to meet specific requirements of density and strength. The cellular structure of AC is created when aluminium reacts with calcium hydroxide or another alkali, which liberates hydrogen gas and forms bubbles [5].
success of the final AC product is based on the speed at which these gas bubbles are formed [6], and, depending on usage, different grain sizes of aluminium (Al) powder are required.

AC has a lower density compared to normal concrete of between 800 kg/m3 and not more than 2000 kg/m3 [7]. However, its brittleness is higher for equivalent mixtures, and it has lower compressive strength. In addition, it has low modulus of elasticity and a fast rate of cracking. The conventional solution to this was reinforcement with steel bars, though a number of studies have been conducted to enhance the effectiveness of LWC as a building material by using steel fibre to create fibre-reinforced lightweight concrete, and such approaches have increased in frequency in recent years [4]. The addition of steel fibres to high-strength LWC significantly improves the properties of the LWC, especially the tensile/compressive strength, but there has been relatively little work carried out on properties of FRC aerated concrete.

Balendran et al. [8] studied the influence of steel fibres on the compressive strength, flexural strength and modulus of elasticity of LWAC and NC. Round and straight steel fibres with a length of 15 mm, diameter of 0.25 mm (aspect ratio of 60) and Vf of 3% were used, and four mixes were prepared: LSP (normal concrete with limestone), LSF (normal concrete with limestone and steel fibre), LWC (lightweight concrete), and LTGF (lightweight concrete with steel fibre). The results showed that the dry density of LSF was 2,470 kg/m3, which decreased to 2,030 kg/m3 for LTGF as the latter matrix had lower density. Similar behaviour was observed for the compressive strength, with LSF having a strength of 115 MPa, which decreased to 91 MPa for LTGF. The flexural strength of concrete is size dependent and LWC is more brittle than LSP of similar mix compositions. The flexural strength of LSF and LTGF decreased when the specimen size increased, and the flexural strength of LSP and LTGF increased when steel fibre was added (LSF). The addition of fibre in LSP resulted in a much smaller increase in flexural strength than in LWC.

Okuyucu et al. [9] studied the influence of hooked-end steel fibres with an aspect ratio of 54.5 and volume fraction of 1.5% on the compressive strength, modulus of elasticity, and flexural strength of semi-lightweight concrete (SLC), semi-lightweight concrete with 35% UPP (Unexpanded perlite powder) replacement (SLC-P), steel-fibre-reinforced semi-lightweight concrete (SFRSLC), and steel fibre-reinforced lightweight concrete with 35% UPP replacement (SFRSLC-P). The results showed that the compressive strength of FRSLC increased slightly when steel fibre was added, but decreased for SFRSLC-P when UPP was used as a replacement. However, the modulus of elasticity of the SFRSLC mixtures without UPP was similar to those of the SLC. The modulus of elasticity of the SFRSLC-P was reduced as a result of UPP substitution not only for fibre-reinforced mixes but also for fibre free mixtures. The maximum load for flexural strength of SFRSLC was 43.1 kN with 0.9 mm deflection, which decreased to 29.5 kN and 0.5 mm for SFRSLC-P when UUP was replaced. There was a slight increase in compressive strength of LWAC when steel fibre was added; however, a significant improvement in flexural strength was obtained.

Mo et al. [10] further studied the effects of hooked-end steel fibres of 35 mm in length and an aspect ratio of 65 in volume fractions of 0, 0.5, and 1% with regard to the compressive and flexural strength of cement-based and geopolymer oil palm shell lightweight aggregate concretes. The compressive and flexural strength increased with increases in fibre content, with the highest values occurring with 1% replacement.

These works suggest that both short and long steel fibres with hooked ends cause an increase in the flexural strength of LWAC. According to the literature review, it can also be concluded that most researchers have focused on the use of steel fibres in normal and lightweight aggregate concrete. The aim of the current research is thus to study the influence of steel fibres on the physical and mechanical properties of aerated concrete (AC) as compared to AC without fibres. Hooked-end steel fibres with lengths of 35 mm and 60 mm and aspect ratios of 64 and 67, respectively, were used in a volume fraction (Vf) of 1.5%. The compressive strength, flexural strength, stress-strain relationship, modulus of elasticity, density, sorptivity and water absorption of steel fibre-reinforced concrete (SFRAC) were then compared with those of unreinforced AC.
2. Experiments

2.1. Materials

2.1.1 Cement: Portland cement with standard strength at 3 and 7 days greater than 15 and 23 MPa, respectively, with a fineness of 2,300 cm²/gm as defined in Iraqi specification No.5/1984 [11].

2.1.2 Sand: Natural Sand (0 to 4.75mm) from the Al-Najaf Sea Region was used as fine aggregate per Iraqi specification No.45/1984-2 [12].

2.1.3 Aluminium powder (Al): 0.5% aluminium powder with a particle size of 125 µm and purity of 99.7% was used per a previous study conducted by Nedwell et al. [13].

2.1.4 Superplasticizer (SP): Daracem 215 Superplasticizer was used.

2.1.5 Steel fibre: In this study, 3Dramix (65/35 BG) fibre with an aspect ratio of 64 was used as the short fibre and 5Dramix (65/60 BG) with aspect ratio of 67 was used as the long fibre. The 3Dramix has an original anchorage and standard tensile strength, while the 5Dramix offers a combination of perfectly shaped hook, high ductility wire, and extreme tensile strength, offering ultimate anchorage, a high L/D ratio, and glued fibre. The density of steel fibre is 7,850 kg/m³.

2.2 Mix proportion

All mixes’ cement, sand, water, Al, and SP were kept constant. The mix proportion of steel fibre reinforced aerated concrete was set according to the previous study by Nedwell et al. [13], as shown in Tables 1; the properties of fibre are shown in Table 2.

Table 1. Mix properties of aerated concrete mixtures (kg/m³).

| Material       | AC   | 35 SFRAC | 60 SFRAC |
|----------------|------|----------|----------|
| Cement         | 350  | 350      | 350      |
| Sand           | 700  | 700      | 700      |
| Water          | 175  | 175      | 175      |
| Aluminium      | 1.75 | 1.75     | 1.75     |
| Superplasticiser (SP) L/m³ | 3.5  | 3.5      | 3.5      |
| Fibres (V_f%)  | -    | 5.25 (1.5)| 5.25 (1.5)|

Table 2. Properties of fibres

| mixture code  | Geometry | Aspect ratio | V_f (%) | d (mm) | l (mm) | Tensile strength N/mm² |
|---------------|----------|--------------|---------|--------|--------|------------------------|
| 35 SFRAC      | Hooked   | 64           | 1.5     | 0.55   | 35     | 1345                   |
| 60 SFRAC      | ends     | 67           | 1.5     | 0.90   | 60     | 2300                   |

a V_f: volume fraction
b d: fibre diameter
c l: fibre length
2.3. Testing procedure
Standard 100 mm cube specimens were used for the compressive strength (fc) testing per BS 12390-3 [14], while 100×100×500 mm beams with 3-point bending were used for flexural strength (fst) testing per BS EN 12390-5 [15]. Cylinders with 100 mm diameter and 200 mm height were used for testing the modulus of elasticity (E) per BS EN- 12390-13 [16], and this was calculated based on stress corresponding to 40% of the ultimate strength and the longitudinal strain produced by this stress [17]. The dry density was measured per BS EN 12390-7 [18], and cylinders with 75 mm diameter and 70±5 mm height were used for the water absorption and sorptivity tests per BS 1881-122 [19] and BS 772-11 [20], respectively.

3. Test Results and Discussion

3.1. Compressive strength
The effect of steel fibre on the compressive strength of AC varies, as shown in Table 3. The increase in compression with the addition of steel fibres ranges from negligible to slightly less than 1% [21]. The 28-day compressive strength of the mixes thus falls between 26 MPa and 36 MPa. The addition of steel fibres also enhances the compressive strength of AC by 14% for 35 SFRAC and 37% for 60 SFRAC. Gao et al. [22] suggested that the incorporation of steel fibre into the matrix led to an increase in the ultimate compressive strength by arresting the growth of cracks; this could be due to the bonds between the mortar and the steel fibre. In addition, SFRAC with higher aspect ratio fibres showed greater compressive strength, possibly because higher transverse confinement effects could be obtained by the enhanced pull-out behaviour of steel fibres.

Opposite behaviour was obtained by Bhargava et al.[23], who noted that the increase in peak stress percentage decreases with increases in the aspect ratio, as short steel fibre with length 25mm and Vf 1.5% becomes active earlier than long fibre with length 50 mm and the same Vf in terms of controlling the propagation of initial micro-cracks. Short fibres are also higher in number and therefore, much closer together; thus, short fibres enhance the strength of composite more than longer fibres.

| Steel fibre | Aspect ratio | Dry density kg/m³ | Compressive strength MPa | Modulus of elasticity GPa | Flexural strength MPa |
|-------------|--------------|--------------------|--------------------------|--------------------------|----------------------|
|             | -            | 1804               | 26                       | 14                       | 4.2                  |
| 35 SFRAC    | 64           | 1901               | 30                       | 14.1                     | 4.4                  |
| 60 SFRAC    | 67           | 1901               | 36                       | 16.0                     | 6.9                  |

3.2. Flexural strength
The flexural strength of the AC and SFRAC specimens are shown in Table 3, and this increases with the addition of fibres. The mechanism of increase may be attributed to the strong fibre-mortar bond, which increases slightly with the short steel fibre to 4.7%, and significantly to 64% with long steel fibres. The random distribution of the steel fibres affects the flexural strength of the concrete and fibre size plays an important role in the mechanical behaviour of the composite. To bridge a large number of micro-cracks under load and to avoid large strain localisation, a large number of short fibres is preferable, because the uniform distribution of such short fibres increases the strength and ductility of the composite [24].

Flexural strength plays an essential role in beam failure, and random distribution of steel fibres controls cracking. The load after failure was increased to cause more cracks, and fibres addition was found to increase the ultimate flexural tensile strength of material. Long fibres are needed to bridge discrete macro-cracks at higher loads and the volume fraction of long fibres can be much smaller than the volume fraction of short fibres, however [25].
In this current study, the results show that the greatest flexural strength, 6.9 MPa, was obtained for the long steel fibre samples at l/d ratio = 67. Steel fibres with higher aspect ratios have higher peak tensile strength because of their higher bridging force. In addition, long fibres are more effective in delaying crack propagation and offer more resistance to being pulled out due to better bonding characteristics. Mo et al. [10] clarified that longer fibres tend to orient along the length of the specimen due to the boundary effects in random generation. Therefore, the number of fibres across the crack plane relative to the direction of applied load increases for longer fibres.

3.3. Stress-strain in tension

The stress-strain relationships in tension for AC and SFRAC are shown in figure 1. For each specimen, a maximum, minimum, and average reading was recorded. Comparing these results, the maximum figures showed the differences between the gradings most clearly, and thus these maximum values are reported in figure 1.

The tensile stress and strain show differences according to the steel fibre aspect ratio. The mechanisms of reinforcing AC with short and long fibres were analysed, and the stress-strain curves in tension plotted as shown in Figure 1.

![Stress-strain from lab tests for AC and SFRAC specimens in tension.](image)

Aerated concrete fails suddenly once the strain corresponding to its ultimate strength is exceeded; it reaches its ultimate tensile strength when a crack starts. However, for SFRAC specimens, fibres crossing the crack interfaces can continue to transfer more load across the crack surfaces. In addition, the random distribution of fibres helps to increase the resistance of AC to such cracks, decreasing the crack width and space.

The AC thus has a low tensile strength that increases when the steel fibre is added. The short fibre had one end hooked, which caused an increase in bonding with the matrix, and the tensile strength of AC was 1.39 N/mm² when the short fibre was used. However, the long steel fibre had higher tensile strength (see Table 3) based on two hooked ends, which caused the bond with the AC to be stronger and made it more difficult for the fibre to be pulled out. The tensile strength of AC with long fibre was thus increased to 1.68 N/mm². Lower strain was found for AC, which increased from 0.0000187 to 0.001671 when the short steel fibre was added. Long fibre has a higher length of development, which caused an increase in the strain of SFRAC to 0.002560.

3.4. Modulus of elasticity
The Modulus of elasticity (E) of SFRAC was compared to that of the AC at 28 days, as shown in Table 3. The addition of steel fibre enhanced the fibre-matrix bond and therefore increased the strength. The modulus of elasticity of AC with short steel fibre was 14.1 GPa, slightly higher than that of the AC without steel fibre. This increased to 16 GPa when long steel fibre was added, as long steel fibre displays more ductile-post peak compressive behaviour. The percentage increase is low in the elastic deformation stage because the main role of steel fibre begins after the concrete suffers plastic deformation.

3.5. Density
Density is one of the essential criteria for AC classification. The dry densities of the tested SFRACs were higher than those of ACs without fibres, increasing from 1,804 kg/m$^3$ to 1,901 kg/m$^3$ when steel fibres were added, as shown in Table 3. All the specimens produced a dry density less than 2,000 kg/m$^3$ and therefore could be classified as structural lightweight concrete, however [26].

3.6. Sorptivity
SFRAC with short fibres has similar sorptivity to AC, as shown in Table 4. However, this increased slightly to 13.9 mm/min with long fibres. The role of the steel fibre was to fill the void spaces with air bubbles, which led to a reduction in the permeability of concrete by locking the air spaces and so, when these air bubbles became filled, the permeability of concrete was greatly reduced. Other researchers [6], however, discovered that SFRC has a lower sorptivity than NC, and that this decreases with increasing Vf. This discrepancy may be because those samples were dried in an oven for 4 days at 50 °C and then allowed to cool for 3 days, while in the current research, the specimens were dried in an air oven at a temperature of 70°C±5 °C to a constant mass and allowed to cool for 24± 0.5h.

Table 4. The sorptivity and water absorption of AC and SFRAC

| AC with a steel fibre | Sorptivity mm/min | Water absorption % |
|----------------------|------------------|--------------------|
| AC                   | 13.0             | 10.1               |
| 35 SFRAC             | 13.0             | 9.7                |
| 60 SFRAC             | 13.9             | 8.1                |

3.7. Water absorption
Water absorption tests were performed on 75 mm cylinder cored specimens after they had been placed in water for 7 days. The results showed that the water absorption of AC was higher than that of SFRAC, as shown in Figure 2. However, Zinkaah [20] noted that the water absorption of lightweight concrete with steel fibre was higher than without fibre and it increased from 1.31% to 9.24% when the steel fibre’s Vf increased from 0 to 1% due to the interlocking of steel fibres, which causes spaces that represent suitable locations for water diffusion.

4. Conclusion
Based on the results obtained from experimental investigation into failure of aerated concrete with steel fibre, the following conclusions are presented:

- The density and elastic modulus are not significantly affected by adding steel fibre to the mix. However, relatively strong effects on flexural strength and stress-strain in tension were confirmed.
- The sorptivity of AC and SFRAC with short fibres were similar, but this increased slightly for SFRAC with long fibres.
- The water absorption of AC was higher than that of SFRAC, though the lowest value was seen with long steel fibres.
Steel fibres with high aspect ratios lead to higher compressive, tensile, and flexural strength.

5. References

[1] Vidhya, K., T. Palanisamy, and R. Selvan, An experimental study on behaviour of steel fibre reinforced concrete beams. International Journal of Advanced Research Methodology in Engineering & Technology, 2017. 1(2): p. 178-183.
[2] Wafa, F.F., Properties and Applications of Fiber Reinforced Concrete. JKAU: Eng. Sci, 1990. 2: p. 49-63.
[3] Winkler, A., C. Edvardsen, and T. Kasper, Examples of bridge, tunnel lining and foundation design with steel-fibre-reinforced concrete. International Concrete Abstracts Portal, 2017. 310: p. 451-460.
[4] Domagala, L., Modification of Properties of Structural Lightweight Concrete with Steel Fibres. Journal of Civil Engineering and Management, 2011. 17(1): p. 36-44.
[5] Mobasher, B., Mechanics of fiber and textile reinforced cement composites. . Vol. 1st. 2012, USA: CRC press.
[6] Holt, E. and P. Raivio, Use of gasification residues in aerated autoclaved concrete. Cement and Concrete Research, 2005. 35(4): p. 796-802.
[7] BS EN 206-1, BS EN 206-1:2000 - Concrete. Specification, performance, production and conformity. Beton. Festlegung, Eigenschaften, Herstellung und Konformitaet. 2001.
[8] Balendran, R.V., et al., Influence of steel fibres on strength and ductility of normal and lightweight high strength concrete. Building and Environment, 2002. 37(12): p. 1361-1367.
[9] Okuyucu, D., et al., Some characteristics of fibbereinforced semi-lightweight concrete containing unexpanded perlite both as aggregate and as a supplementary cementing material. Magazine of Concrete Research, 2011. 63: p. 369-375.
[10] Mo, K.H., et al., Shear behaviour and mechanical properties of steel fibre-reinforced cement-based and geopolymer oil palm shell lightweight aggregate concrete. Construction and Building Materials, 2017. 148: p. 369-375.
[11] IOS, Iraqi Organization of Standards, 5: Portland Cement. 2001, National Centre for Construction Laboratories and Researches.
[12] IOS, Iraqi Organization of Standards, 45: Aggregates from Natural Sources for Concrete and Construction. . 2001, National Centre for Construction Laboratories and Researches.
[13] Nedwell P., Shabbar R., and Wua Z.. Mechanical properties of lightweight aerated concrete with different aluminium powder content. in International Conference on Advances in Sustainable Constructon Materials & Civil Engineering Systems (ASCMCES). 2017. Sharjah, United Arab Emirates.
[14] BS EN 12390-3, Testing hardened concrete. Compressive strength of test specimens. 2009.
[15] BS EN 12390-5, Testing hardened concrete. Flexural strength of test specimens. 2009.
[16] BS EN 12390-13, Testing hardened concrete, Part 13: Determination of secant modulus of elasticity in compression. 2013.
[17] Gao, J., W. Sun, and K. Morino, Mechanical properties of steel fiber-reinforced, high-strength, lightweight concrete. Cement and Concrete Composites, 1997. 19(4): p. 307-313.
[18] BS EN 12390-7, Testing hardened concrete Part 7: Density of hardened concrete. 2009.
[19] BSI 1881-122, Testing concrete. Method for determination of water absorption 2011.
[20] BS EN 772-11, Methods of test for masonry units. Determination of water absorption of aggregate concrete, autoclaved aerated concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water absorption of clay masonry units, 2011.
[21] Fanella, D.A. and A.E. Naaman, Stress-strain properties of fiber reinforced mortar in compression. Journal of the American Concrete Institute, 1985. 82(4): p. 475-483.
[22] Gao, J.M., W. Sun, and K. Morino, Mechanical properties of steel fiber-reinforced, high-strength, lightweight concrete. Cement & Concrete Composites, 1997. 19(4): p. 307-313.
[23] Bhargava, P., U. Sharma, and S. Kaushik, Compressive Stress-Strain Behavior of Small Scale Steel Fibre Reinforced High Strength Concrete Cylinders. Journal of Advanced Concrete Technology, 2006. 4(1): p. 109-121.

[24] Shweta, P. and R. Kavilkar, Study of Flexural Strength in Steel Fibre Reinforced Concrete. International Journal of Recent Development in Engineering and Technology, 2014. 2(5): p. 13-16.

[25] Mehta, K. and P. Monteiro, Concrete: microstructure, properties and materials Vol. 4. 2013, New York McGraw Hill Professional.

[26] Niknamfar, A. and S. Eesapoor, Generating a Structural Lightweight Concrete, in Proc. 3rd Int. Conf. of Science and Engineering in the Technology. 2017: Copenhagen, Denmark.