Improving the mechanical properties of lightweight foamed concrete using various types of fibres

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Abstract. Lightweight foamed concrete has recently been adopted as a more sustainable construction material due to various features such as reduction in member size, better thermal insulation, and cost savings. This work examines an attempt to improve the brittle nature of foam concrete with the addition of different types of fibres. Five types of fibres were used: steel fibres (hooked-ends), micro steel fibres (straight ends), carbon, glass, and polypropylene fibres. The effect of fibre type on the fresh (density and flowability) and hardened (compressive strength, splitting tensile strength, flexural strength, and static modulus of elasticity) properties of lightweight foamed concrete were thus investigated. The results collected from the experimental work revealed that steel fibres significantly improve the performance of lightweight foamed concrete in terms most properties while other types of fibres (carbon, glass and polypropylene fibres) improved properties at different levels to the steel fibres. Using 0.45 hooked-ends steel fibres gave the most significant improvement in splitting, flexural strength, modulus of elasticity and compressive strength at 162.5%, 83.78%, 72.41%, and 63.63%, respectively.

1. Introduction

The demand for lightweight concrete has increased over the years and it is now used in multiple structural members such as wall panels and roof slabs due to the practical and economic advantages it offers. Using lower density concrete can significantly reduce the self-weight of concrete structure, thus allowing the reduction of column and foundation sizes and the minimisation of other load-bearing elements [13] with a corresponding reduction in terms of cost. In addition, lightweight foamed concrete offers good thermal insulation [14], better fire resistance, and more convenience in handling than standard concrete, as the total mass of materials to be handled is reduced, which again lowers the cost and increases productivity [1]. Foam concrete is a specific type of lightweight concrete with a density ranging from 400 to 1,600 kg/m³, produced by using a foaming agent to generate air voids within the material [15], that make it much more lightweight as compared to regular concrete. It offers many benefits such as reducing the dead weight of structures, offering economies in the design of supporting structures including the foundations and walls of lower floors. To meet the needs of various design choices, a range of foam concretes with different densities can be produced [2]. Foam concrete also requires no coarse aggregate, making it even more lightweight and offering high flowability, thus contributing to the goal of sustainability in terms of conserving natural resources.

However, foamed concrete is a porous material and has poor resistance to cracks and low strength. The usefulness of fibres in terms of reinforcing such concrete in various civil engineering applications is thus indisputable, as this enhances multiple properties including tensile strength, compressive strength,
elastic modulus, crack resistance, crack control, durability, fatigue life, resistance to impact and abrasion, shrinkage, and expansion, [16]. In this work, silica fume was used to improve various concrete properties in both fresh and hardened states, including permeability, durability, and the ability to avoid segregation and bleeding [17]. Superplasticizers, advanced chemical additives used as water reduction agents, were used to increase workability by 10 to 15 percent and to reduce water demand by approximately 30 percent [18]. The addition of different types of fibres was then investigated with regard to the engineering properties of lightweight foamed concrete in term of compressive strength, splitting, flexural strength, and modulus of elasticity, based on a target density of 1,800 kg/m³ [19][20][11]. The foamed concrete samples were cured and tested at 7 days and 28 days for compressive strength, with results as discussed later in this paper.

2. Experimental work

2.1 Materials

Ordinary Portland cement (OPC) of Tasluja type I, in accordance with ASTM C150 [3], was obtained from the United Cement Company and used for all foam concrete mixtures. Tables 1 and 2 show the physical properties and chemical composition of the main compounds of cement. Silica sand was used as the fine aggregate, with a specific gravity of 2.6, Table 3 shows the details of the relevant sieve analysis. Another fine pozzolanic material, silica fume, with a specific gravity of 2.2 and a size of 0.15 μm was also used in this study in a constant proportion of 8% by weight of cement. Table 5 shows the properties of these ingredients. The dry ingredients were mixed with clean water at a temperature of 25 °C, and a foaming agent (protein base) was used to control the density of the resulting lightweight foamed concrete (LWFC) by producing stable air bubbles within the concrete mix; this was supplied by Sika Chemicals Company, and its properties are illustrated in Table 6. The foam was produced by adding 1 litre of the agent to 30 litres of water according to ASTM C796/C796M [4] and using the foam generator device shown in the Figure 1.

![Figure 1. Foam generator device](image)

A chemical additive (superplasticizer Sika ViscoCrete® -5930, conforming to ASTM C494M–04) was also used during the work to enhance the material’s workability; its effective contribution was made by reducing the ratio of W/C. Various types of fibres were used in this study; steel fibres (hooked ended and straight), carbon fibres, polypropylene fibres and glass fibres. Figure 2 shows these materials, and table 4 illustrates their properties.
Figure 2. Types of fibres: 1) Polypropylene, 2) Carbon, 3) Hook-ended steel, 4) Straight steel, 5) Glass

Table 1. Physical properties of cement

| Physical Properties                              | Test Result | Limits of IOS 5:1984 |
|-------------------------------------------------|-------------|----------------------|
| Fineness using Blain air                        | 405         | >230                 |
| Permeability apparatus (m²/kg)                  |             |                      |
| Soundness using autoclave method                | Not available | <0.5%                |
| Setting time using Vecat’s instrument Initial (min) | 135         | >45 min <10hr .      |
| Final (hrs.)                                    | 3.25        |                      |
| Compressive strength for cement paste cube (70.7mm) at 3 days (MPa) | 24.4        | >15                  |
| 7 days (MPa)                                    | 32.3        | >23                  |

Table 2. Chemical composition and main compounds of cement

| Compound Composition | Chemical Composition | Percentage by Weight | Limit of Specification Iraqi No5/1984 |
|----------------------|----------------------|----------------------|--------------------------------------|
| Lime                 | Cao                  | 61.19                | -                                    |
| Silica               | SiO2                 | 21.44                | -                                    |
| Alumina              | Al2O3                | 4.51                 | -                                    |
| Iron oxide           | Fe2O3                | 3.68                 | -                                    |
| Magnesia             | MgO                  | 2.31                 | 5.0 (max)                           |
| Sulphate             | SO3                  | 2.7                  | 2.8 (max)                           |
| Loss on ignition     | L.O.I.               | 2.39                 | 4.0 (max)                           |
| Insoluble residue    | I.R.                 | 1.18                 | 1.5 (max)                           |
| Lime saturation factor | L.S.F.              | 0.87                 | (0.66-1.02)%                        |
| Main compounds (bogue’s equation)              |                      |                      | Limits of Iraqi Specification No.5/1984 [15]. |
| Tricalcium Silicate | C3S                  | 42.83                | -                                    |
| Dicalcium Silicate  | C2S                  | 29.4                 | -                                    |
| Tricalcium           | C3A                  | 5.73                 | -                                    |
| Aluminate            |                      |                      | -                                    |
| Tetracalcium aluminoferrite              | C4AF              | 11.19                | -                                    |
Table 3. Sieve analysis of silica sand

| Sieve No. | % Passing |
|-----------|-----------|
| 4.75      | 100       |
| 2.36      | 100       |
| 1.18      | 100       |
| 600       | 100       |
| 300       | 64        |
| 150       | 8         |

Table 4. Properties of fibres

| Type of fibre     | Hooked-end steel | Straight steel | Polypropylene | E-glass | Carbon |
|-------------------|------------------|----------------|---------------|---------|--------|
| Average fibre length (mm) | 60 | 15-16 | 12 | 12 | 8 |
| Average fibre width (mm)     | 0.75 | 0.2±0.02 | 18 micron | 13±10% micron | 7±2 micron |
| Aspect ratio (L/D)             | 80 | 40-80 | 666.67 | - | 1140 |
| Specific gravity Kg/m³          | 7800 | 7800 | 910 | 2540-2600 | 1700 |
| Tensile strength (MPa)          | >1100 | >2850 | 300-440 | 3450-3790, at 22°C | 3500 |

Table 5. Properties of silica fume

| Technical Properties       | Limit of ASTM 1240 | Limit of ASTM C618 |
|-----------------------------|--------------------|--------------------|
| Bulk density                | 660 Kg/m³          | -----              |
| Loss of ignition            | 3.4%               | Max 6%             | Max 6%             |
| Moisture content            | 0.6%               | Max 3%             | Max 3%             |
| Total silica content        | 94.7%              | Min 85%            | Min 70%            |
| SiO₂                        |                    |                    |                    |
| Chloride ion                | 0.055%             | -----              | -----              |
| Relative strength           | 116%               | Min 105%           | -----              |
| Available alkali            | 0.01%              | -----              | 0.05%              |
| Surface area                | 27.3246            | Min 15m²/g         |                    |
| Colour                      | Grey powder        | -----              | -----              |
Table 6 Properties of foaming agent

| Technical Properties of foaming agent |      |
|--------------------------------------|------|
| Form/colour                          | Yellow transparent liquid |
| Density                              | 1.0075 – 1.0175 kg/L, at 20°C |
| Freezing point                       | -5°C |
| Total chloride ion                   | Max. 0.1%, Chloride-free |
| pH value                             | 9-11 |
| Chemical base                        | Air entraining synthetic liquid |

2.2 Mix proportions

The objective of this study was to assess improvements in the mechanical properties of LWFC based on the addition of different types of fibres.

On this basis, a constant ratio of 1:1.1 cement to fine aggregate was maintained, with a constant 8% by weight of dry ingredients of silica fume was mixed with 35% water in the mixer, with the gradual addition of pre-prepared foam to achieve the required density of 1,800Kg/m³ ± 50. For each case, the relevant fibres were added in the proportions outlined in table 7 and distributed throughout the mixture by hand.

Table 7. Mix proportions

| Mix**   | w/c | C/S | SF* | SP.* | Steel hooked | Steel straight | Carbon | Glass | PP* |
|---------|-----|-----|-----|------|--------------|---------------|--------|-------|-----|
| Mbase   | 0.35| 1:1.1|     |      |              |               |        |       |     |
| MSS     | 0.35| 1:1.1| 8%  | 0.8% |              |               |        |       |     |
| MSFH    | 0.35| 1:1.1| 8%  | 0.8% |              |               |        |       | 0.45|
| MSFS    | 0.35| 1:1.1| 8%  | 0.8% |              |               |        |       | 0.5 |
| MCF     | 0.35| 1:1.1| 8%  | 0.8% |              |               | 0.2    |       |     |
| MGF     | 0.35| 1:1.1| 8%  | 0.8% |              |               |        | 0.6  |     |
| MPP     | 0.35| 1:1.1| 8%  | 0.8% |              |               |        |       | 0.4 |

*SF silica fume, SP. Superplasticizer, PP polypropylene fibres.

**(Mbase)=mix without any addition, (MSS)=Mbase+ SF and SP., (MSFH)=MSS+ steel hooked fibres
(MSFS)=MSS+ steel straight, (MCF)=MSS+ carbon fibres, (MGF)=MSS+ glass fibres, (MPP)=MSS+ polypropylene fibres.

Figure 3. Procedure for LWC creation (L-R): basic mix; homogeneous mix; adding foam; adding fibres
3. Experimental tests

All specimens were tested after 7 and 28 days of curing into 25 °C clean water to ensure development of sufficient strength. Tests were performed on the foamed concrete in both its fresh state (fresh density and flow test) and hard state (splitting tensile strength, flexural strength, compressive strength, modulus of elasticity) as follows:

3.1 Fresh density

A 1-litre container was filled with fresh foamed concrete and weighed; the following equation was then used to compute the fresh density of foamed concrete:

\[
D_{\text{fresh}} = \frac{M}{V}
\]

where

- \( M \) = Mass of fresh concrete (Kg)
- \( V \) = Volume of the container (m\(^3\))
- \( D_{\text{fresh}} \) = Density of fresh concrete (Kg/m\(^3\))

![Figure 4: Measurement of fresh density](image)

3.2 Flow test

The purpose of the test was to assess the workability of the foam concrete. The test was performed according to ASTM C1437 [22] as shown in the equation below:

\[
\text{Flow (\%) = } \frac{d_1 - d_0}{d_0}
\]

where \( d_1 \) is the average of four readings, in mm, and \( d_0 \) is the original internal base diameter in mm.

![Figure 5: Measurement of flowability](image)
3.3 Splitting tensile strength
The splitting tensile test was undertaken as per ASTM C496 using a cylinder with dimensions 150 x 300 mm.

![Splitting tensile test](image)

Figure 6. Splitting tensile test

3.4 Flexural strength
This test was performed according to ASTM C79 [5] on prism specimens of 100 x 100 x 500 mm, as shown in Figure 7.

![Flexural test](image)

Figure 7. Flexural test

3.5 Compressive strength
Compression tests were performed on cubic 100 mm samples at the ages of 7 and 28 days. The value of each foam concrete mixture was assessed as an average of three samples, in accordance with ASTM C39 [6] and BS 1881-116 [7].

![Compressive strength test](image)

Figure 8. Compressive strength test
3.6 Modulus of elasticity
An object’s modulus of elasticity is the slope of its stress–strain curve in area of elastic deformation. Testing was carried out according to ASTM C469/C469M [8] on 150 x 300 mm cylinder specimens, as shown in Figure 9.

![Figure 9. Modulus of elasticity test](image)

4. Result and discussion

4.1 Density
The most effective tolerance for dry density is ±50 kg/m³, though this could reach up to ±100 kg/m³ for higher density foamed concrete mixes (1,600 kg/m³) [9]. The results of the research work in this case were therefore within the permissible range according to BS EN 12350 [10], part 6: 2000. The purpose of determining the fresh density was to identify the actual volume for the design mix and to allow casting control.

4.2 Flow test
The flow test results showed a clear decline in the susceptibility to flow in the foamed concrete in the presence of the fibres in general, regardless of the type used. By comparing the results of the base mix including silica fume (MSS) with those of mixes including various fibres, the rates of decline, as shown in figure 10, were identified as 18.51%, 16.3%, 12.6%, 20%, and 13.3% for mixture with hooked end steel fibres, straight steel fibres, carbon fibres, glass fibres, and polypropylene fibres, respectively. The highest percentage of decline was seen for glass fibres of 12 mm length, included as 0.6 by volume of mix, followed by steel fibres of both types (hooked and straight), then polypropylene (PP) fibres; the fibre with the least effect on flowability was carbon fibre. These results can be attributed to the increase in the volume fraction and the length of the fibres in the mix, which leads to the mixture being more stiff, rigid and constrained, forcing the mix to stop flowing.
4.3 Splitting tensile strength
The splitting tensile strength results showed better tensile strength for foamed concrete reinforced with fibres as compared with the base concrete mix due to an increased ability to absorb energy that gives greater flexibility to the concrete. Comparing the results between the different types of fibres, steel fibres, especially the hooked-end type, improved the splitting strength of the concrete significantly, most likely due to the shape of these fibres, as the hooked at the end of the fibre causes the concrete components to adhere to them, increasing the difficulty in breaking the concrete as it is no longer possible to separate the components easily [23]. The other type of steel (straight) fibres also improve the resistance of concrete to splitting, but they are less efficient than the first type due to the smoothness of their ends which allow slipping among the concrete components. The other types of fibres also gave good results in the splitting tensile strength test, reducing micro-cracks and limiting crack distribution during testing [23].

![Figure 10. Results of flow tests](image)

![Figure 11. Results for splitting tensile strength tests](image)

4.4 Flexural strength
The results presented in Figure 12 regarding flexural strength show that the interactive effect of both short and long fibres on flexural strength are substantial, especially for steel fibres with hooked ends. These had the greatest impact on improving flexural strength, with about 83.78% improvement over the base concrete mix, due to their long length and ability to act as a connecting bridge to avoid the spread of micro cracks and to reduce crippling brittle failure, thus enhancing the strength and durability of the concrete [11]. The straight steel fibres had less effect, at about 75.67% improvement compared with the base mix, due to their shorter length, which allowed slippage before yielding. The other short
fibres, carbon, glass, and PP, also showed lower effects in terms of improving flexural strength at about 32.43%, 48.65%, and 54.05% improvements on the base mix, respectively. As shown in the in flexural test, fibre failure may occur due to fibre slippage under tensile loads after binder matrix failure [21]. The effect of the shorter fibres was thus restricted to holding micro cracks, and regulating the expansion of cracks, resulting in increased composite tensile strength.

4.5 Compressive strength
The compressive strength of LWFC is generally weaker as compared to conventional concrete due to its lightweight nature. Different additives are thus often used to enhance the final strength, such as superplasticizer, which helps reduce the w/c ratio, and silica fume, which contains pozzolanic components. Laboratory experiments have also shown that it is possible to increase the strength of lightweight concrete by using various fibres, with the best improvements offered by steel fibres of both hooked and straight types. These work as reinforcement in mixes, enhancing the bond mechanisms of the matrix in LWFC [11]. Fibreglass, PP, and carbon fibres have less effect on the $f'_c$ of foamed concrete due to low stiffness and ductility. In addition, it was observed that an increase in the curing period led to an enhanced compressive strength of LWFC, which is clear on comparing the test results at 7 days and 28 days of curing, as shown in Figure 13; this is due to the completion of the cement reactions, which increase the consistency and bonding of the concrete components with each other over time.
4.6 Modulus of elasticity

Reviewing the modulus of elasticity results shown in Figure 14, which represent the ability of foamed concrete to withstand deformation as a result of the stress applied to it in addition to indicating the stiffness of this concrete [12], high proportions of about 72.41% over that for the mix without fibres were observed on using steel fibres with hooked ends; this reflects the ability of the concrete to deviate more elastically with such additions as compared to with other types of fibres due to the tight bonding between the matrix and the steel fibres. The steel fibres play an important role in the transmission of stress, reducing the strain and thus increasing the stiffness of the mix. However, even the fibres with the least impact, carbon fibres, offer a 49.56% increase in the elasticity of concrete. All fibres thus contributed to enhancing the modulus of elasticity of the foam concrete, with rates of improvement for straight steel fibres, glass fibres, and polypropylene fibres being 68.97%, 64.14%, and 55.17%, respectively, due to their ability to absorb more of the applied load. These all offer foaming concrete greater elasticity.

![Figure 14. Results for modulus of elasticity tests](image)

5. Conclusion

Based on the laboratory tests, the following conclusions can be drawn for this study:

All types of fibres showed positive results with regard to improving the mechanical properties of foamed concrete when compared to the values for foamed concrete without fibres;

The best type of fibre for improving foamed concrete was steel fibres with hooked ends, followed by steel fibres with straight ends;

The least effective fibre in terms of improving the mechanical properties of foamed concrete was carbon fibre due to its effects on the internal porosity and compactness of the concrete;

Using a lower w/c ratio improves compressive strength and does not affect workability due to the presence of foam bubbles and superplasticizers in the mixture, which help to significantly improve workability;

The flowability of the foam concrete decreases significantly on the addition of fibres, as these cause the components of the mixture to stick to them, making the mixture more stiff, rigid, and constrained;

The $f'_c$ of foamed concrete was improved with an increase in the curing period, as evidenced from the results of the tests at 7- and 28-days curing;
The tensile strength of foamed concrete is greatly increased by the presence of fibres due to this increasing its ability to absorb the energy represented by the axial force and the reduction in the size of cracks generated by closely linking the components of the concrete to each other;

The modulus of elasticity improves greatly, reducing the strain and development stiffness of the specimens, in the presence of fibres.

6. Recommendation

Research work on lightweight-foamed concrete remains limited, yet promises great scope for future studies. The following studies related to the properties of lightweight foamed concrete should thus be considered for investigation:

1. A wider study related to the effect on foamed concrete of adding fibres in different proportions;

2. A study on improving the properties of foamed concrete by using more than one type of fibre in the same mixture (hybrid fibres); and

3. A study of the mechanical properties of foamed concrete reinforced with single or hybrid fibres with densities ranging between 1,200kg/m$^3$ and 1,600kg/m$^3$.

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