Effects of steel fibres and silica fume on the behaviours of square ferrocement slabs under flexural loading

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Abstract. Ferrocement is a type of thin reinforced concrete made of a cement-sand matrix with closely spaced relatively small diameter wire meshes, with or without steel bars of small diameter which are known as skeletal steel. This work concerns the behaviours of square ferrocement slabs with dimensions of 500 x 500 x 30 mm when subjected to flexural load. This study included testing thirteen ferrocement slabs, and the main variables considered in the experimental work were the number of wire mesh layers, percentage of silica fume and presence of steel fibre. The effects of these variables on the behaviours and load carrying capacities of tested slabs under central loads were investigated. From the experimental results, increasing the percentage of silica fume from 0% to 6% caused ultimate flexural loads to increase up to 4.5% replacement. The load carrying capacity also increases with presence of steel fibre reinforcement, and the ductility is high where steel fibres are included. The results also suggest that an increase in wire mesh layers from six to ten layers leads to an increase in load capacity by 76%. Finally, the results show that the addition of steel fibres can reduce the crack width and increase the number of cracks compared to samples without fibres.

Keywords: Ferrocement; Fibre; Silica Fume; Slab, behaviour

1. Introduction
Ferrocement is a refinement of reinforced concrete (RC), with the main difference between ferrocement and RC being scale. Ferrocement uses smaller sized reinforcing wires or meshes and mortar without coarse aggregates [1]. The main advantages of ferrocement are that it can be constructed in any shape; that its raw materials are easily available, especially in developing countries; and that high levels of skill are not required in its construction. Ferrocement also has superior strength properties compared to conventional reinforced concrete [1-5].

With developments in construction techniques, ferrocement has recently been used in many different applications within the structural engineering field, such as strengthening applications [6, 7] and constructing thin elements in buildings [8, 9]. More research is thus needed on this material to improve its chemical and physical properties and the behaviour of various ferrocement elements, especially slab elements.

In recent years, silica fume (SF) and fibres such as steel, polypropylene, carbon, and glass have become commonly used in concrete; in particular, the use of SF and steel fibre in concrete has been increasing rapidly. SF has many desirable properties as an additive material or as a partial replacement for cement. The addition of silica fume or steel fibre to mortar predominantly leads to enhancement of the mechanical properties of mortar: the most important result of adding silica fume to concrete is low permeability and higher strength, while the most important result of adding steel fibre to concrete/mortar is an enhancement to the tension capacity [10].
Several papers have been written within the last two decades on the behaviours of ferrocement slabs. Al-Rifaie and Trikha carried out experimental work on ferrocement slabs in which three different arrangements of hexagonal mesh reinforcements were studied [11]. A total of twelve simply supported square slabs were tested under uniform loads with varying numbers of mesh layers. Hago et al. similarly presented a study of the ultimate load and service behaviours of ferrocement roof slab panels [12]. Six simply supported slabs with two symmetrical point loads were tested. The effects of the number of wire mesh layers and the structural shape of the panels on the ultimate flexural strength, first crack load, crack spacing, and load-deformation behaviours were then studied. Shri and Thenmozhi performed a series of flexural tests to study the flexural behaviours of ferrocement slabs [13]. Flexural tests were carried out on ferrocement polypropylene fibre reinforced slabs. They studied the fibre content and thickness of slabs as well as the number of wire mesh layers. An increase in the number of cracks with a reduction in width of cracks was found in the case of adding ferrocement polypropylene fibres. Shannag and Bin Ziyad presented an experimental work to examine the flexural behaviour of ferrocement plates reinforced with discontinuous fibres [14]. The number of steel mesh layers, spacing of transverse wires, and types of wire were investigated. All plates were tested under a central point load. Mahmood and Majeed studied the flexural behaviour of flat and folded ferrocement panels [15]. From their experimental work, they observed that the number of wire mesh layers not have a significant effect on the cracking load for the folded panels. Sah and Kumar studied the general behaviours of fibre reinforced ferrocement hollow slabs [16]. The ductility, stiffness, degradation, ultimate load carrying capacity, and energy absorption of the ferrocement slabs were determined.

The aim of the current study is to estimate the influence of using SF and steel fibres on the behaviours of ferrocement slabs and on compressive and flexural strengths of mortar.

2. Experimental Work

2.1 Materials

The ordinary Portland cement and fine aggregate used throughout this investigation conform to ASTM standards [17, 18]. A ratio by weight of one part cement and two parts sand was mixed in addition to percentages of silica fume and steel fibre as mentioned in Table 1. The water-cement ratio was used was 0.425. Ordinary tap water was used for casting and curing throughout this study.

Locally available steel wire mesh of 12.5 mm square openings with average wire diameter of 0.7 mm was used in this investigation. Several specimens of the wire were taken from the wire mesh and tested according to ACI 549. 1R-97 [5] under direct tension with a 5 kN capacity Bench-Top testing machine model BT-1000. The average yield strength, $f_y$, was 390 MPa, the ultimate strength, $f_{ut}$, was 600 MPa and the modulus of elasticity, $E_s$, was 97,500 MPa. The wires were tested at the civil engineering department of the University of Basrah.

The silica fume used in this study contained about 91.4% silicon dioxide (SiO$_2$) and the specific surface area was 18,000 m$^2$/kg. Silica fume was used as a weight percentage of cement content as specified.

Superplasticizer_SP90, DCP Company (SP), was used in this investigation. Chemically, it is of the naphthalene formaldehyde sulphonate type.

A hooked steel fibre of 16 mm in length and about 0.4 mm in diameter was also used in this study.
Table 1. Details of specimens tested containing silica fume and steel fibre

| No | Group | Dimensions mm | Specimen designation* | Diameter of Wire mesh mm | No. of wire mesh layers | Silica Fume (SF) % | Steel Fibre % | SP% |
|----|-------|---------------|------------------------|-------------------------|------------------------|-------------------|---------------|-----|
| 1  |       | 500 x 500 x 30 | S6_0                   | 0.7                     | 6                      | 0                 | 0             | 0   |
| 2  |       |               | S8_0                   | 0.7                     | 8                      | 0                 | 0             | 0   |
| 3  |       |               | S10_0                  | 0.7                     | 10                     | 0                 | 0             | 0   |
| 4  | A     |               | S6_1.5                 | 0.7                     | 6                      | 1.5               | 0             | 1.4 |
| 5  |       |               | S6_3                   | 0.7                     | 6                      | 3                 | 0             | 2.8 |
| 6  |       |               | S6_4.5                 | 0.7                     | 6                      | 4.5               | 0             | 4.1 |
| 7  |       |               | S6_6                   | 0.7                     | 6                      | 6                 | 0             | 6.0 |
| 8  |       | 500 x 500 x 30 | SF6_0                  | 0.7                     | 6                      | 0                 | 1             | 0   |
| 9  |       |               | SF8_0                  | 0.7                     | 8                      | 0                 | 1             | 0   |
| 10 | A1    |               | SF6_1.5                | 0.7                     | 6                      | 1.5               | 1             | 1.4 |
| 11 |       |               | SF6_3                  | 0.7                     | 6                      | 3                 | 1             | 2.8 |
| 12 |       |               | SF6_4.5                | 0.7                     | 6                      | 4.5               | 1             | 4.1 |
| 13 |       |               | SF6_6                  | 0.7                     | 6                      | 6                 | 1             | 6.0 |

* S6_0: (S: Slab, 6: number of layers; 0: Silica percentage).
* SF6_1.5: (S: Slab; F: steel fibre, 6: number of layers; 1.5: Silica percentage).

2.2 Experimental Procedure

The experimental study was intended to assess the effect of SF incorporation along with superplasticizer and steel fibre on the behaviours of ferrocement slabs as well as on mortar properties. Silica fume was used at a constant of the water–binder ratios, and super-plasticizer was incorporated to maintain the w/c ratio at a constant level. Steel fibre was used in some specimens, as noted in Table 1.
The slump was of S3 class (slump between 100 and 150 mm) [19]. A horizontal type mixer was used for the mixing procedure, and casting was carried out on a vibrating table. The control specimens were put together with slab moulds on the vibrating table. The casting process was started by applying the mortar in thin layers to reduce or to eliminate the disturbance of the spacing mesh layers. The wire mesh layers were distributed uniformly throughout the slab section. The control specimens were cast in two layers at the same time as the slab specimens. The specimens were demoulded and stored in a water tank until testing (28 days), and removed from the tank and kept at the natural temperature of the laboratory on the day of testing. Several 50 mm cubes were used to determine the compressive strength of the mortar, while 50 × 250 mm prisms under central point loads were used to estimate the flexural tensile strength. The average values of the strength of three specimens are presented in the results. All slabs were tested using a Testing Machine of 150 kN capacity at the civil engineering department of the University of Thi Qar. The testing of all slabs was carried out at 28 days. All slabs were cleaned, and painted with white paint before testing, in order to clarify the propagation of cracks. Central point loading was applied through a steel frame, and the loading pad was interconnected with a thin rubber sheet to achieve uniform contact. The initial reading of the deflection dial gauge was recorded at the beginning of the test. In all tests, the load was applied in small increments and increased gradually up to failure. Figure 1 shows the slab test set up.

3. Results and Discussion
For all ferrocement slabs, the compressive and flexural strength of mortar mixes and maximum load and deflection of the slab were determined at 28 days.

3.1 Compressive and Flexural Strength of mortar
Three control (50 mm) cube specimens were tested according to ASTM C109 [20] to obtain the compressive strength of the mortar (f_{cu}) with silica fume and steel fibre. Tests were carried out using a compression testing machine at 2000 kN. The tests were conducted after 28 days from casting. Flexural strength of mortar (f_{t}) tests were performed on three 50 x 50 x 250 mm prism specimens. The prisms were tested according to BS 1881 part 118 [21]. Third point loading was applied using a Matest testing machine of 150 kN capacity. The compressive and flexural strength of mortar for the test specimens are listed in Table 2.

Figures 2 and 3 and Table 2 show the variations of flexure strength and compressive strength with SF replacement percentages and varying SP content with and without steel fibre. The content of SP used
for each mix was designed to ensure that the slump stayed within the S3 class (slump between 100 and 150 mm) [19]. The compressive strength values were plotted for each silica fume replacement percentage, as seen in Figure 2. The results indicated that, in general, the compressive strength of mortar with silica fume increased up to the 4.5% replacement percentage of silica fume with 4.1% superplasticizer dosage; beyond this percentage the strength started to decrease. The strength of mortar/concrete with silica fume may be enhanced through three mechanisms: the first one attributes the improvement in strength to a reduction in the content of Ca(OH)₂(CH) when using SF, the second one attributes the strength enhancement to aggregate and cement interfacial zone refinement, and the last one commends pore size refinement and matrix densification [22-25]. The decrease in the strength of silica fume mortar can be attributed to the fact that the use of a high percentage of SF in mortar may lead to a surplus of the small-sized fractions, and that movement of some Portland cement grains will occur, resulting in a decreasing of the strength of the mortar due to unpacking of the system [26].

When 1% steel fibre is added to mortar mix, a slightly increase in compressive strength is obtained, as seen from Figure 2. The variations of flexural strength with SF replacement percentage, SP, and steel fibre content are summarized in Table 2 and Figure 3. In general, SF incorporation slightly increases the flexural strength of mortar. It important to mention that, as the percentage of SP varies with the SF content, variations in the compressive and flexural strength may be due to variations in the SF content and also due to changes in SP content. The flexural strength obeys almost the same trend as the compressive strength at 28 days. The results of this study indicated that the flexural strength of mortar with silica fume increased up to the 4.5% replacement percentage of silica fume with appropriate superplasticizer dosage; beyond this percentage the strength started to decrease. Also, it can be noted from Figure 3 that 1% of fibre inclusion leads to an increase in the flexural strength of mortar.

| No. | Specimens designation | $f_{cu}$ (MPa) | $f_{r}$ (MPa) | Ultimate Load ($P_u$) (kN) | Ultimate Deflection ($\Delta_{ul}$) (mm) |
|-----|-----------------------|----------------|--------------|--------------------------|----------------------------------|
| 1   | S6_0                  | 47.7           | 6.9          | 8.8                      | 3.9                              |
| 2   | S8_0                  | 44.8           | 7.0          | 11                       | 8.5                              |
| 3   | S10_0                 | 47.9           | 7.0          | 15.5                     | 9.6                              |
| 4   | S6_1.5                | 56.2           | 7.5          | 9.3                      | 4                                |
| 5   | S6_3.0                | 50.0           | 7.0          | 9.4                      | 3.5                              |
| 6   | S6_4.5                | 54.1           | 6.9          | 10.2                     | 6.9                              |
| 7   | S6_6.0                | 49.3           | 6.75         | 9.2                      | 6                                |
| 8   | SF6_0                 | 48.4           | 7.3          | 10                       | 4.4                              |
| 9   | SF8_0                 | 46.4           | 7.4          | 13.0                     | 9.0                              |
| 10  | SF6_1.5               | 54.0           | 7.8          | 12                       | 5.5                              |
| 11  | SF6_3                 | 53.7           | 7.4          | 11.3                     | 6.5                              |
| 12  | SF6_4.5               | 55.4           | 8.0          | 12.2                     | 7.6                              |
| 13  | SF6_6                 | 51.0           | 7.0          | 10.2                     | 8.0                              |
3.2 Behaviour of Ferrocement Slabs
One of the main objectives of this study was to examine the structural behaviour of ferrocement slabs subjected to point load. Based on the results for ferrocement slabs, the behaviours of thirteen slabs were investigated and discussed. Table 2 and Figures 4 to 13 show the effect of changes in SF percentage and presence of steel fibre to load carrying capacity, and load-deflection curves. In the current research program, the ferrocement slabs were categorized into two different groups, A and A1 as illustrated in Table 1.

3.2.1 Load-Deflection Relationships
The load-mid-span deflection relationships obtained from two groups of slab specimens (A and A1) are shown in Figures 4 and 5. These figures show that the load-deflection curve was approximately same for all tested specimens, with linear behaviour at the initial stage followed by nonlinear behaviour till failure. The relationships can be divided into three stages. In the first stage, the slabs behave elastically, remaining free from cracks; the deflections are linearly proportional to the applied
load. A deviation of this relationship from linearity is shown at the end of the first stage. After this stage, cracks start to occur in the tensile region of specimens and propagate with increasing crack width, indicating the second stage of the load-mid-span deflection. During this stage, a gradual yielding of the steel wire mesh layers occurs, as multiple wire mesh layers are placed at different levels of depth and these mesh layers yield at different loading levels. The last stage (failure stage), which is also referred to as the plastic stage, is initiated by inelastic straining of the tension reinforcement, and is characterised by a rapid increase in deflection until failure occurs.

3.2.2 Effect of number of wire mesh
Table 2, and Figures 6 and 7 show the effect of number of mesh layers (volume fraction of wire mesh reinforcement) on the behaviours of ferrocement slabs. It is clear that as the number of wire mesh layers increases, the load carrying capacity of the ferrocement slab increases; this increase is attributable to the specific surface of the mesh reinforcement. It is also clear from Figures 6 and 7 that the ductility of the slab increases with an increase in the amount of reinforcement. The ratios of increase in load carrying capacity with increases in the number of wire mesh layers from six to eight and to ten layers are 25% and 76%, respectively. The ferrocement slab SF8_0 with eight layers of wire mesh and steel fibre content provides a gain in strength of 30% when compared with SF6_0, which contains six layers of wire mesh and contains the same amount of steel fibre.

3.2.3 Effect of Silica Fume (SF) on behaviours of ferrocement slabs
The percentage of SF was changed from 0 to 1.5, 3, 4.5, and 6% to determine the effect of SF content on the behaviours of ferrocement slabs. From Table 2 and Figures 4 and 5, the load carrying capacity increases with a corresponding increase in the compressive strength of mortar. For slabs without steel fibre, the increases of silica fume content from 0 to 1.5%, 3%, 4.5%, and 6% increased the load carrying capacities by 6%, 7%, 16%, and 5%, respectively, in comparison to that of a ferrocement slab without silica fume. Adding SF to the mortar mix thus shows an improvement in the behaviour performance by increasing strength.

Due to the high amount of silica fume in slabs S6_6 and SF6_6, significant decreases in the maximum loads were observed. The ultimate loads of S6_6 and SF6_6 with 6% silica fume were the lowest, at about 11% and 19% reductions when compared to S6_4.5 and SF6_4.5 with 4.5% silica fume, respectively.

3.2.4 Effect of Steel Fibre on behaviours of ferrocement slabs
From Table 2 and Figures 8 to 13, the ultimate load increased with the addition of 1% steel fibre reinforcement for all slabs, with and without silica fume. All slabs were failed in flexure in a tensile mode; the cracks were formed in the tensile stress zone, before yielding of wire mesh layers occurred. In general, cracks started to appear as the load was increased and then wider cracks will be developed at the centre region of the slab. Increasing the applied load led to a complete failure. More ductility was observed in slabs with steel fibres, where the cracks formed uniformly and with smaller width on the bottom surface of the testing slabs. This may be due to bridging effect of steel fibres. That steel fibres improve the ductility of ferrocement slabs can be concluded from the results of this study. Flexural strength was also increased with steel fibres; this may be because steel fibres help to bridge cracks across specimens and, at the final stage a pulled-out or broken steel fibre may occur due to a transfer of tensile stress through cracks. The tensile zone of steel fibre slabs still sustains a load at the initial stage of propagation of cracks, and increases of tensile strength in ferrocement indirectly lead to increases in the flexural strength of ferrocement slabs. Figures 8 to 13 show the effect of fibres on the strength of ferrocement slabs: the load carrying capacities of steel fibre ferrocement slabs SF6_0 and SF8_0 increased by 14% and 18%, respectively, with 1% steel fibre in comparison with ferrocement slabs S6_0 and S8_0, without steel fibres. Those figures were for specimens without silica fume; for steel fibre ferrocement slabs with silica fume, the load carrying capacity increased by a maximum
percentage of 29% for the SF6_1.5 slab in comparison with ferrocement slab S6_1.5, as given in Table 2.

Figure 4. Load–deflection curves of SF-ferrocement slabs without steel fibre

Figure 5. Load–deflection curves of SF-ferrocement slabs with steel fibre

Figure 6. Effect of no. of wire meshes on load–deflection curves of ferrocement slabs
Figure 7. Effect of no. of wire meshes on load–deflection curves of ferrocement slabs with fibre

Figure 8. Effect of fibre on load–deflection curves of ferrocement slabs without SF

Figure 9. Effect of fibre on load–deflection curves of ferrocement slabs without SF (8-layers)
Figure 10. Effect of fibre on load–deflection curve of ferrocement slab with 1.5% SF

Figure 11. Effect of fibre on load–deflection curve of ferrocement slab with 3% SF

Figure 12. Effect of fibre on load–deflection curve of ferrocement slab with 4.5% SF
3.3 Failure Modes of Tested Slabs
For all tested slabs, the failure mode was flexural failure; a yielding of the steel wires occurred, and no crushing of mortar was observed on the compression face of the cross sections. All cracks were initiated at the bottom face of the slabs. Figure 14 shows the crack patterns and failure modes of some tested slabs. It may be concluded that the volume fraction (steel fibre reinforcement) plays a principle role in determining the crack patterns. The presence of the steel fibre results in preferable behaviours, characterised by a large number of cracks with small crack width. All steel fibre slabs showed gradual and ductile behaviour in comparison with ferrocement slabs without steel fibre.

Figure 13. Effect of fibre on load–deflection curve of ferrocement slab with 6% SF
Figure 14. The crack patterns and failure modes of some tested ferrocement slabs – bottom face
4. Conclusions
The test results of this study show that silica fume and superplasticizer combinations can enhance the strength of the mortar in ferrocement up to the addition of 4.5% silica fume. Increasing the number of wire mesh layers tends to increase the ultimate loads of ferrocement slabs tested under flexural loading. Increasing the number of wire mesh layers (for the same wire diameter and opening) from six to ten layers significantly increases the carrying capacity and ductility of ferrocement slabs. An increase in the number of cracks with a reduction in crack width showed in slabs that contained higher numbers of wire meshes. The experimental results also show that the percentage of SF and presence of steel fibre increases the load carrying capacity of ferrocement slabs as compared to those without fibre. An addition of 1% steel fibre leads to an increase in the load carrying capacity by 18% for slabs without silica fume and 29% in slabs with silica fume. Finally, steel fibre increases the ductility of slabs as compared to those without steel fibres, increasing the number of cracks while reducing crack width.

5. References
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