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# Structural Behavior of Composite Reinforced Ferrocement Plates

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## Abstract

The results of an experimental investigation to examine the structural behavior of composite reinforced ferrocement concrete plates are presented in this paper. The precast permanent ferrocement forms are proposed as a viable alternative to the steel panels in some of its uses. The experimental program comprised casting and testing of eighteen reinforced ferrocement plates having the dimensions of 550mm width, 1100mm length and different thicknesses (60, 80,100) mm. Each control plate was reinforced with four steel bars of 6mm diameter at the bottom of the plate and six steel bars of 6mm diameter at the transverse direction. Two types of steel mesh were used to reinforce the ferrocement plates. These types are: (12 X 12 mm) welded wire mesh, and (33 X 16.5mm) expanded wire mesh. Single layer, double layers and three layers of each type of the steel mesh were employed. All specimens were tested under 3-lines flexural loadings. The flexural performances of the all tested plates in terms of strength, stiffness, cracking behavior and energy absorption were investigated. The results showed that high serviceability and ultimate loads, crack resistance control, and good energy absorption properties could be achieved by using the developed ferrocement plates.

*Keywords**:** Ferrocement strength; Cracking, Deformation Characteristics; Energy Absorption, ductility.*

## 1. Introduction

The rapids development of reinforced concrete support the development of ferrocement until the second half of the 20th century. However, today there is increased recognition of ferrocement in many applications, where its properties, ease of construction and cost effectiveness provide a convincing extension to reinforced concrete technology.

Ferrocement has been used for at least 150 years as a boat building material due to its strength and its ability to resist corrosion. Early, Ferrocement technology had limited applications like garden benches, boats, and water tanks; however, due to the many researches that were conducted on ferrocement recently, the applications of ferrocement have become versatile such as load bearing applications, different roofing systems, repair works, water structures like tanks, and precast ferrocement elements.

Ferrocement, which is a structural material comprising cement mortar matrix reinforced with closely spaced wire steel mesh, is now recognized as a construction material with superior qualities of crack control, impact resistance, and toughness, largely due to the close spacing and uniform dispersion of reinforcement within the material. One of the main advantages of ferrocement is that it can be constructed with a wide spectrum of qualities, properties, and cost, according to customer's demand and budget. Ferrocement is not a new technology in itself, it has been used since 1847 when Joseph-Louis Lambot developed a boat made out of ferrocement. Over the years the applications of ferrocement have become more widespread including new applications especially in the construction industry (National Academy of Sciences, 1973). While most ferrocement housing applications have been directed toward low-cost housing solutions; excellent quality, durable, well finished, and serviceable housing products can be readily produced with ferrocement. These products encompass various structural elements such as walls, beams, slabs and roofing systems. Moreover, ferrocement has also been used as a repair material for concrete elements. Many investigators have reported the physical and mechanical properties of this material and numerous test data are available to define its performance criteria for construction and repair of structural elements (Fahmy et.Al.1994,1999). Al-Rifaie and Hassan (1994) presented the results of an experimental and theoretical study of the behavior of channel shaped ferrocement one-way bending elements. The results showed that this type of elements can undergo large deflections before failure and is suitable for construction of horizontally spanning unit for one-way bending. Mays and Barnes (1995) presented the results of an experimental investigation of the feasibility of using ferrocement as a low permeability cover layer to reinforced concrete members located in environments, where there is a high risk of reinforcement corrosion. They found that the resistance to chloride penetration in accelerated ageing tests was enhanced by using Styrene Butadiene Rubber (SBR) or acrylic bond coat between the ferrocement forms and the concrete. They also reported that the use of permanent ferrocement formwork gave an increase in strength of 15% over the conventional reinforced concrete. Fahmy et.Al. (2004 and 2005) presented the use of the ferrocement technology in developing ferrocement sandwich and cored panels for floor and wall construction.

The study of ferrocement plates is a part of developing the ferrocement panels for floors and walls alike. The importance of these panels is evident in the case of disasters as earthquakes, for example, low cost earthquake resistant ferrocement small house was used in the earthquake of October 2005 in City of Pakistani Kashmir. These houses can be use as a temporary or permanent, according to the case. Finally it was found that the composite ferrocement with bricks used as permanent slabs can be loaded as in multi storey buildings. The use of ferrocement depends not only on housing but also extends up to the bridges; a suspension highway bridge by using ferrocement was constructed in China in 1992. The stiffening girders are ferrocement box beams. The deck system is made of orthogonal anis tropical ferrocement plates with longitudinal ribs. Ferrocement was used as a cover on the external surface of the internal coating and insulating layers of the suspending cables. The system has been granted patents. Another Chinese bridge used ferrocement as floating caissons in the construction of bridge piers in 1970.

The results of an experimental investigation to examine the structural behavior of composite reinforced ferrocement concrete plates are presented in this paper. The precast permanent ferrocement forms are proposed as a viable alternative to the steel panels in some of its uses.

The experimental program comprised casting and testing of eighteen reinforced ferrocement plates having the dimensions of 550mm width, 1100mm length and different thicknesses (60, 80,100) mm. Each control plate was reinforced with four steel bars of 6mm diameter at the bottom of the plate and six steel bars of 6mm diameter at the transverse direction. Two types of steel mesh were used to reinforce the ferrocement plates. These types are: (12 X12mm) welded wire mesh, and (33 X16.5mm) expanded wire mesh. Single layer, double layers and three layers of each type of the steel mesh were employed. All specimens were tested under 3-lines flexural loadings.

## 2 Materials and Method

The experimental study conducted on the properties of the materials and tests conducted on the ferrocement are explained below

### *2.1 Ferrocement Materials*

The ferrocement plates produced in the laboratory. And it is made using the following materials :

### *Cement*

The cement used was the ordinary Portland cement, which was provided from the Suez factory. Its chemical and physical characteristics satisfy the Egyptian Standard Specification E.S.S. 373/1991. Table 1 show the mechanical, physical and chemical properties of the cement used.

TABLE 1 : MECHANICAL, PHYSICAL AND CHEMICAL PROPERTIES OF THE CEMENT

| Property | Value | Limits |
|---|---|---|
| Specific gravity | 3.15 | -- |
| Setting time | | |
| Initial min. | 60 | Not less than 45 min |
| Final hrs. | 5.3 | Not more than 10 hrs |
| Fineness | 2870 cm2/gm | Not less than 2500cm2/gm |
| Soundness (Expansion) | Zero | Not more than 10 mm |
| Crushing strength (Kg/cm2) | | |
| 3 days | 195 Kg/cm2 | Not less than 183.42 |
| 7 days | 295 Kg/cm2 | Not less than 275.13 |
| 28 days | 385 Kg/cm2 | 366.84 Kg/cm2 |

### *Silica fume*

To increase the strength of the mortar as possible, condensed silica fume was used as a partial replacement of the cement. It was delivered in a powder form with a light-gray color. It gives black slurry when it is mixed with mortar. The chemical composition of silica fume is given in Table 2.

### *Fine aggregate*

The fine aggregate used was clean desert sand having physical and mechanical properties as shown in table 3

### *Super plasticizer*

A super plasticizer complies with ASTM (C494-type F) .with a specific weight of 1.17 at 25 °c and brown in color, was used to provide the necessary workability needed for the concrete mix.

### *Water*

Clean drinking fresh water free from impurities is used for mixing and curing of the test specimens.

TABLE 2 : CHEMICAL COMPOSITION OF SILICA FUME.

| Chemical | Weight % |
|---|---|
| Si O2 | 92-94 |
| Carbon | 3-5 |
| Fe2 O3 | 0.1-0.5 |
| Ca O | 0.1-0.15 |
| AL2 O3 | 0.2-0.3 |
| Mg O | 0.1-0.2 |
| Mn O | 0.008 |
| K2 O | 0.1 |
| Na2 O | 0.1 |

TABLE 3: PHYSICAL AND MECHANICAL PROPERTIES OF FINE AGGREGATE.

| Property | Test results for sand |
|---|---|
| Specific gravity (S.S.D) | 2.6 |
| Volume weight | 1.7 |
| Voids ratio | 30% |
| Fineness modulus | 2.91 |
| Clay, silt, and fine dust | 2% (by weight) |
| Percent of chloride | 0.03 (by weight) |

### *Reinforcing meshes*

Two types of reinforcement were used in reinforcing concrete plates, expanded metal mesh of diamond size 16.5 mm and 33 mm, while square welded steel mesh of size 12.5 mm and wire diameter equal 0.55 mm. The average results of the elastic modulus, yield strength, ultimate strength of expanded steel mesh and welded steel mesh used plus the specifications of the meshes are shown in table 4.

TABLE 4: PROPERTIES OF STEEL MESHES.

| Mesh Type | Mesh Size (mm) | Thickness (mm) | Weight (Kg/ m2) | Es (GPa) | σy (MPa) | σu (MPa) |
|---|---|---|---|---|---|---|
| Expanded | 33 x 16.5 | 1 | 1.3 | 120 | 200 | 320 |
| Welded | 12 x 12 | 1 | 0.3 | 170 | 350 | 550 |

**Es**: Modulus of elasticity of steel meshes, **σy**: Yield strength, **σu**: Ultimate strength

The universal testing machine used in conducting the steel tensile tests for meshes was equipped with internal extensometer. Bearing in mind the inherent difficulties in testing thin sheet specimens in direct tension, the test specimens were especially designed to ensure failure away from the grips and the ends of the specimen. The dimensions of the test specimens were chosen with the guidance of the method proposed by ACI. All the specimens had the same matrix with the mix properties of 1: 2: 0.35 (cement: sand: water) by weight.

### *2.2 Mortar matrix*

The concrete mortar used for casting plates was designed to get an ultimate compressive strength at 28-days age of (350 kg/cm2), 35 MPa. The mix proportions by weight were (2:1) for (fine aggregate: cement) and the water- cement ratio was (0.35).

As mentioned before, a super plasticizer was used with all mixes as 1.5% of weight of cement to maintain suitable workability to ensure ease of the process of casting. The mix properties for mortar matrix were chosen based on the (ACI committee 549 report: 1988).

For all mixes, mechanical mixer in the laboratory used mechanical mixing with capacity of 0.05 m3, where the volume of the mixed materials was found to be within this range. The constituent materials were first dry mixed; the mix water was added and the whole patch was re-mixed again in the mixer. The mechanical compaction was applied for all specimens. Mix properties by weight are given below in Table 5.

TABLE 5: FERROCEMENT MORTAR MIX PROPERTIES BY WEIGHT.

| Materials | Type | Wight per m3 of the mix (kg) |
|---|---|---|
| Sand | Fine sand passing sieve # 4 | 1330 |
| Cement | Ordinary cement type (I) | 665 |
| Water | Potable water | 260 |
| Mineral | Silica fume | 80 |
| Superplasticizer | Sikament 163- high range water-reducer | 11.175 |
| Fibers | Polypropylene fibers | 1.4 |

### *2.3 Test specimens of mortar matrix*

Slump and compressive strength tests were conducted on every patch of the mortar according to ASTM. 3 cubes samples of dimensions 100x 100 x100 mm were cast for each mix. The cubes were left 24 hours before curing to allow the concrete mix to harden. The compressive strength was measured at age (3, 7, and 28 -days). The average of three samples was taken for each date.

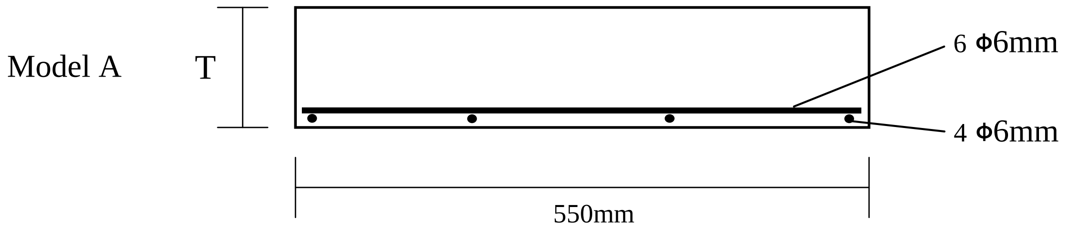
### *2.4 Preparation of Test Specimens*

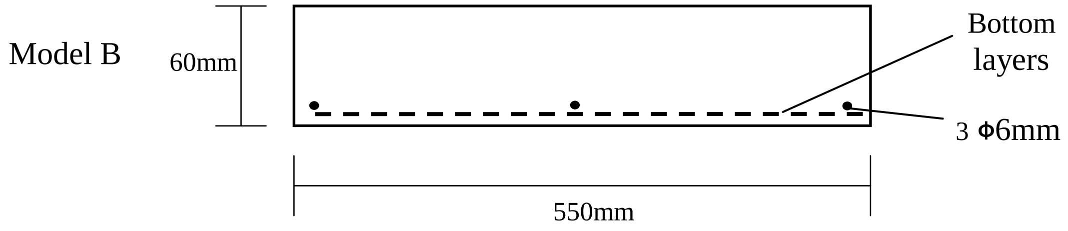
Five models comprise eighteen reinforced concrete plates were cast and tested. All plates have same length (1100mm), and width (550mm) and with different thicknesses were 60, 80 and 100 mm. Table 6 show all plates casted and its models and properties. The plates were cured for 28 days before testing. The five models of reinforcement were chosen as follow in figure 1.

### *2.5 Test Setup*

After 28 days, the specimens were painted with white paint to facilitate the crack detection during testing process. A set of four "demec" points was placed on one side of the specimen to allow measuring the strain versus load during the test. Demec points were located as shown in Figure 2.

The specimen was laid on a universal testing machine of maximum capacity of 100kN, where the test was conducted under a three-lines loading system as shown in Figure 3. The specimen was centered on the testing machine, where the span between the two supports was kept constant at 1000mm. A dial gauge with an accuracy of 0.01 mm was placed under the specimen at the center to measure the deflection versus load. Load was applied at 5kN increments on the specimen exactly at the center. The horizontal distance between each pair of demec points was recorded by using a mechanical strain gauge reader. Concurrently, the plate deflection was determined by recording the dial gauge reading at each load increment. Cracks were traced throughout the sides of the specimen and then marked with colored markers. The first crack-load of each specimen was recorded. The load was increased until complete failure of the specimen was reached.





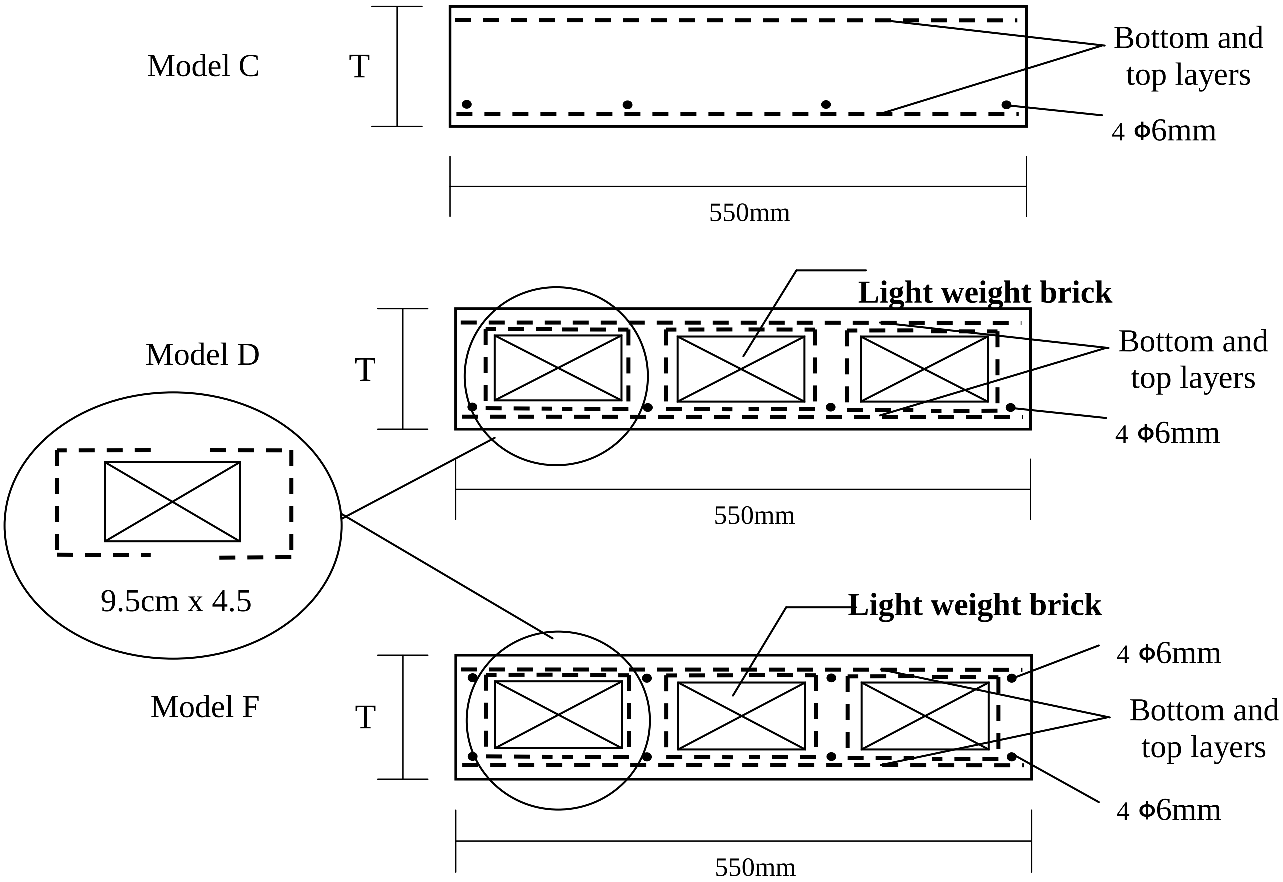


Figure 1 : models of plate's reinforcement

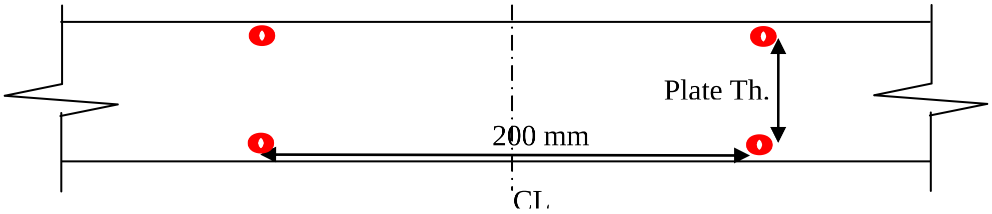


Figure 2: Locations of the demec points

Figure 3: Test setup

TABLE 6 : PLATES CASTED AND ITS MODELS AND PROPERTIES.

| Plate model | Plate thick cm | Reinf. mesh type | Number of layers | Plate code | Volume fraction Vr% | Surface area Cm2 | Specific surface Sr |
|---|---|---|---|---|---|---|---|
| A | 6 | ------- | 0 | A6S1* | 0.592 | 1263 | 3.9 |
| | 6 | ------- | 0 | A6S1 | 0.592 | 1263 | 3.9 |
| | 8 | ------- | 0 | A8S1 | 0.444 | 2245 | 2.92 |
| | 10 | ------- | 0 | A10S1 | 0.355 | 1264 | 2.34 |
| B | 6 | Welded | 3 | B6W3 | 0.74 | 5971 | 18.43 |
| | 6 | Expanded | 1 | B6E1 | 0.71 | 4152 | 12.82 |
| C | 8 | Expanded | 2 X 2 | C8E2 | 1.6 | 15100 | 34.96 |
| | 10 | Expanded | 2 X 2 | C10E2 | 1.3 | 15100 | 27.97 |
| D | 8 | Expanded | 2 X 2 | D8E2 | 1.96 | 21078 | 69.4 |
| | 10 | Expanded | 2 X 2 | D10E2 | 1.57 | 21078 | 51.2 |
| | 8 | Welded | 4 X 4 | D8W4 | 1.6 | 18174 | 29.83 |
| | 10 | Welded | 4 X 4 | D10W4 | 1.28 | 18174 | 44.14 |
| F | 6 | Welded | 3 X 3 | F6W3 | 1.8 | 15322 | 78.28 |
| | 8 | Welded | 2 X 2 | F8W2 | 1.1 | 11717 | 38.58 |
| | 10 | Welded | 2 X 2 | F10W2 | 0.89 | 11717 | 28.46 |
| | 6 | Expanded | 1 X 1 | F6E1 | 2 | 14661 | 74.89 |
| | 8 | Expanded | 1 X 1 | F8E1 | 1.53 | 14661 | 48.26 |
| | 10 | Expanded | 1 X 1 | F10E1 | 1.22 | 14661 | 35.6 |

* Without fibers.
Surface area of expanded layer = 3587 cm2 / m.l
Surface area of welded layer = 1802 cm2 / m.l
Surface area of Φ6mm bar = 188.5 cm2 / m.l

## 3. Results and Discussion

The test results are listed in Table 7. The table shows the obtained experimental results for each specimen as well as the ultimate failure load, the first crack load, ductility ratio, and energy absorption for each group. Ductility ratio is defined in this investigation as the ratio between the mid-span deflection at ultimate load to that at the first crack load, while the energy absorption is defined as the area under the load-deflection curve. Service load, or flexural serviceability load, is defined as the load corresponding to a deflection equal to span/100.

The load-deflection curves of the test specimens are shown in Figure 4. The load-deflection relationship can be divided into three regions: a) Linear relationship up to first cracking of concrete, b) Transition region, where the relation deviated from linearity due to continuous cracking of the beam and c) Large plastic deformation due to yielding of the reinforcing steel bars and the steel mesh.

The load at which the load-deflection relationship started to deviate from the linearity and the extent of the plastic deformation varied with the type of steel mesh in the ferrocement plates.

### *3.1 Cracking Behavior*

Figure 5 shows the cracking patterns of the different test groups. For the control specimens, cracking started at mid-span. As the applied load increased, the developed cracks propagated rapidly from the tension side towards the compression side and spread along the plate span.

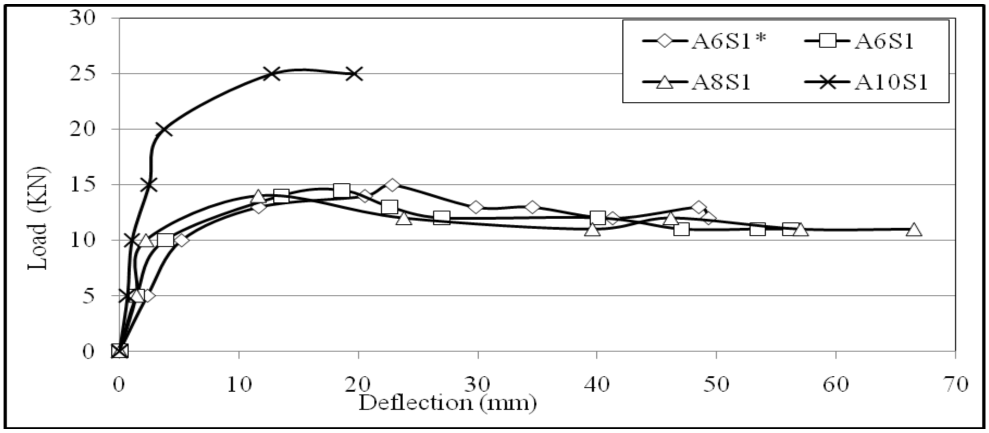
For the ferrocement plates, the first crack occurred nearly at mid-span. The first crack load varied with the variation of the steel mesh type as shown in Table 7. As the load increased, new cracks were developed at both sides of the first crack, while the first crack propagated vertically. New cracks developed with the additional increase of the load, while the previously developed cracks propagated nearly vertically. This pattern of crack development continued till failure of the plates. The number of the developed cracks varied with the variation of the steel mesh type.

TABLE 7: TEST RESULTS

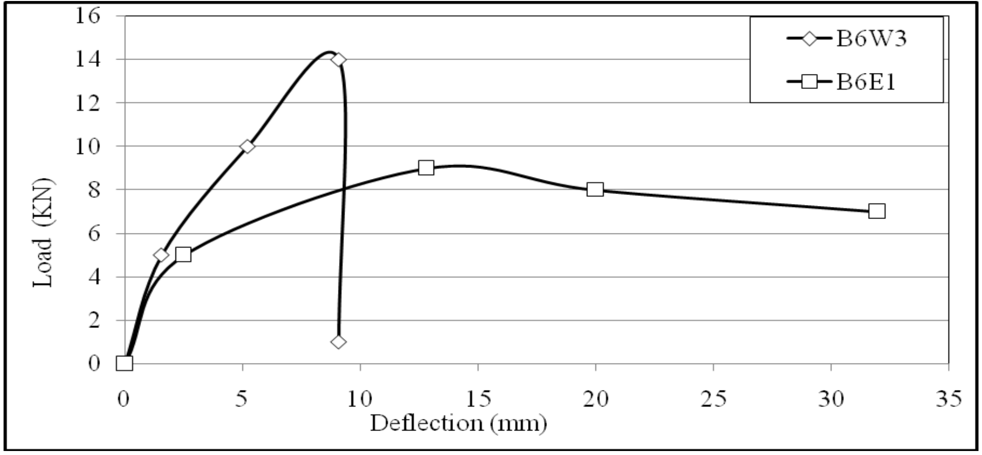
| Plate model | Plate | Volume fraction Vr% | Specific Surface area Cm-1 | First crack load .KN | Pu KN | Ductility Index | Energy Absorption KN.mm |
|---|---|---|---|---|---|---|---|
| A | A6S1* | 0.592 | 0.0348 | 5 | 13 | 17.46 | 177.15 |
| | A6S1 | 0.592 | 0.0348 | 5 | 14 | 6.23 | 232.78 |
| | A8S1 | 0.444 | 0.0464 | 10 | 14 | 20.16 | 203.305 |
| | A10S1 | 0.355 | 0.0209 | 15 | 25 | 14.81 | 407.2 |
| B | B6W3 | 0.74 | 0.1645 | 5 | 14 | 4.33 | 141.085 |
| | B6E1 | 0.71 | 0.1144 | 5 | 9 | 14.06 | 135.905 |
| C | C8E2 | 1.6 | 0.3120 | 10 | 18 | 8.22 | 272.225 |
| | C10E2 | 1.3 | 0.2496 | 15 | 25 | 8.84 | 278.55 |
| D | D8E2 | 1.96 | 0.4355 | 10 | 19 | 9.04 | 418.365 |
| | D10E2 | 1.57 | 0.3484 | 10 | 20 | 12.11 | 147.725 |
| | D8W4 | 1.6 | 0.3755 | 10 | 20 | 17.72 | 153.6 |
| | D10W4 | 1.28 | 0.3004 | 15 | 40 | 9.48 | 509.1 |
| F | F6W3 | 1.8 | 0.4221 | 5 | 18 | 20.39 | 217.355 |
| | F8W2 | 1.1 | 0.2421 | 5 | 15 | 9.51 | 241.5 |
| | F10W2 | 0.89 | 0.1937 | 10 | 25 | 2.83 | 208.35 |
| | F6E1 | 2 | 0.4039 | 5 | 15 | 18.01 | 326 |
| | F8E1 | 1.53 | 0.3029 | 10 | 23 | 4.05 | 366.31 |
| | F10E1 | 1.22 | 0.2423 | 10 | 25 | 2.02 | 292.75 |

### *3.2 First Crack Load*

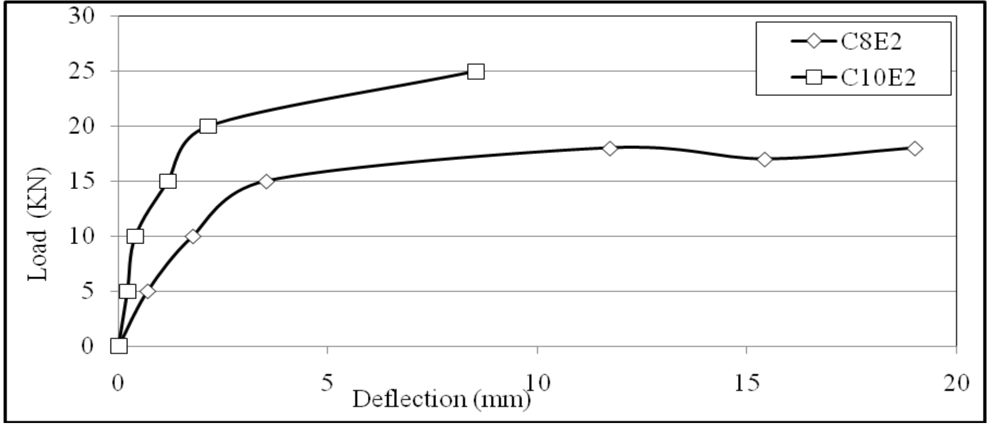
The first crack load was determined during the test, while the flexural serviceability load was determined for the test specimens shown in Table 7. The plates reinforced with expanded steel mesh had the highest serviceability load followed by those reinforced with expanded steel mesh. For the same type of steel mesh, plates with double steel mesh layers achieved higher first crack load and serviceability load than those with single steel mesh layer.



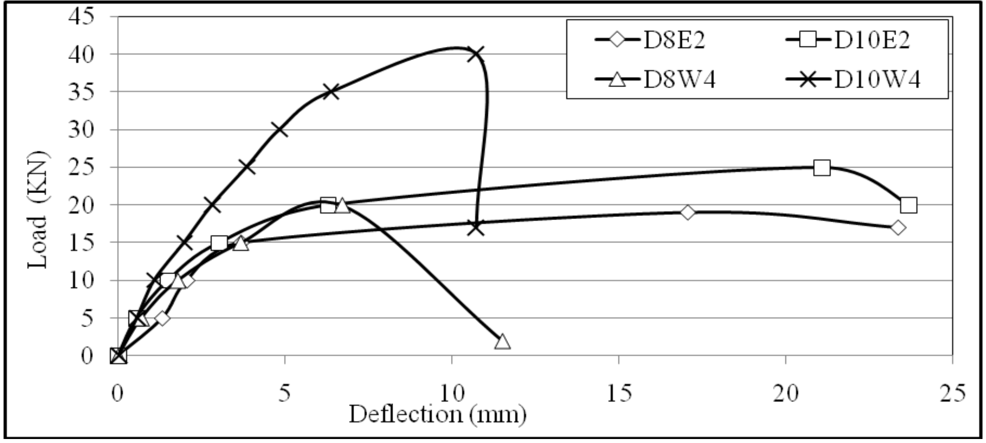
a) Load - Deflection curve of group A



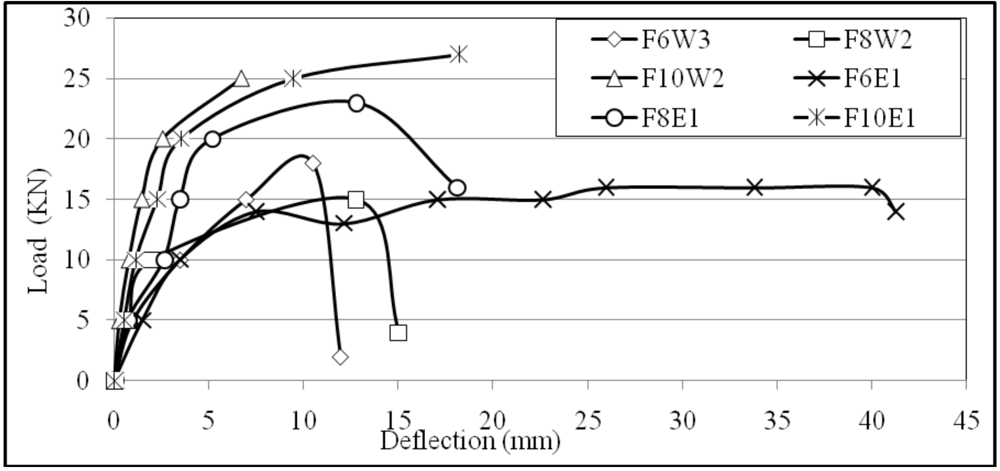
b) Load - Deflection curve of group B



c) Load - Deflection curve of group C



d) Load - Deflection curve of group D



e) Load - Deflection curve of group D

Figure 4: load – deflection curves of different groups

Group A: Control Specimen

B6E1 (Group B) C10E2 (Group C)

D10W4 (Group D)

F10E1 (Group F)
Figure 5: Cracking pattern of tested plates

### *3.3 Ultimate Load*

The measured load deflection response curves of the specimens in five models A, B, C, D, and F and the load deflection curves for all plates specimens are given in Figure 4. The difference in behavior between plates reinforced with 3 layers welded steel meshes and those reinforced with 1 expanded steel mesh, only one layer as a tensile reinforcement is shown in Figure 4.a. Figures 4.b shows the comparison between load-deflection curves for ferrocement slabs reinforced with two layers of welded steel mesh in two sides and effect of the thickness as shape C , Figure. 4.c. shows the difference between using two layers of expanded steel meshes and four layers welded steel meshes in two thicknesses 8,10 cm as shape D. Figure. 4.d show the comparison between load-deflection curves for ferrocement hollow core slabs with three box openings by light weight bricks and effected by many factors as shape F. The increase in the ultimate load for the ferrocement plates could be attributed to existence of lager area of steel, steel bars and steel mesh, on the tension side of the beams as compared to the control specimens which had steel bars only.

### *3.4 Ductility Ratio and Energy Absorption*

Table 7 shows the calculated ductility ratio and energy absorption for all tested groups. The average ductility ratio for the test groups ranged from 20.39 to 4.33 with the lowest individual result of 2.02. Although all ferrocement plates attained large deflection at failure, the increase of the first crack load and its corresponding deflection resulted in this reduction of the ductility ratio, as defined in this investigation, in comparison to the control plate. The energy absorption of the ferrocement plates was higher than that of the control. The percentage of the energy absorption relative to the control plates was about 93% and 58% when single layer of steel mesh was used.

## 4. Conclusions

Based on the results and observations of the experimental, the analytical study presented in this thesis and considering the relatively high variability and the statistical pattern of data, some conclusions can be drawn as follow:

1. Using two sides of reinforcing meshes did not significantly increase the bearing capacity due to lack of confining mortar. Although the reinforcement ratio was double, the increase in the bearing capacity was less than the improved associated with a smaller increase in the reinforcement ratio in the specimen reinforced with one side (tension side).

2. The cracking loads slightly increased as the reinforcement volume fraction increased. The cracking loads were independent of the mesh type.
3. The flexural capacity of the composite plates increased with the increase of the specific surface area of the mesh.
4. Plates witch reinforced by expanded steel meshes (B6E1) provided a larger number of cracks that were more for ultimate loads compared with plates witch reinforced by welded meshes (B6W3).
5. For the same specific surface area, plates witch reinforced by expanded steel meshes (C10E2) provided higher first crack loads by approximately 50% with respect to plates witch reinforced by welded meshes (F10W2), and same ultimate loads.
6. The welded steel mesh has higher tensile strength with respect to expanded mesh. But the specific surface area of expanded mesh is approximately double value of that for welded mesh, so comparing one layer of welded by one layer of expanded steel mesh used in this search , expanded meshes provided higher ultimate loads with respect to welded meshes.
7. For the same plate thickness and reinforcement type, the solid plates had lower values of Pu compared to three- openings hollow plates.
8. For the ferrocement plates with light weight brick core under flexural loading, increasing the number of openings leads to an increase in the ultimate load, energy absorption and ductility ratio.
9. The main disadvantages of welded mesh, In fact they show a linear elastic behavior in tension loading to a brittle failure type of failure without warning. Such disadvantages, which are quite critical for conventional reinforced concrete, seem to be less critical for ferrocement applications. This is because ductility is guaranteed in ferrocement composites by arrangement of the reinforcing system.

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