

Research Article

Flexural Behaviour of Chicken Mesh Ferrocement Laminates with Partial Replacement of Fine Aggregate by Steel Slag

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Bending tests were conducted on ferrocement laminates containing chicken mesh and steel slag. The fundamental goal of the examination was to investigate the effects of partial substitution of fine aggregate by steel slag in cement mortar combining chicken mesh of different volume fractions as reinforcement in thin ferrocement laminates. The following variables were investigated: (a) volume fraction of chicken mesh as 0.94%, 1.88%, 2.82%, and 3.77% and (b) level of steel slag substitution from 0% to 50% by weight fine aggregate. Results show that ferrocement laminates with chicken mesh of volume fractions of 3.77% and 30% substitution of fine aggregate with steel slag display better performance in terms of load deflection behaviour, first crack load, ultimate load, energy absorption, and ductility ratio when related with other specimens. An analytical model has been proposed to predict the ultimate moment carrying capacity of ferrocement laminates under flexure to validate the experimental results.

1. Introduction

Ferrocement is a special form of reinforced concrete construction where real composite action exists between the cement matrix and mesh [1]. The ferrocement may be reinforced with mesh made of metal or other materials. The fineness of mortar matrix and its composition should be in agreement with the mesh and the framework system it is meant to encapsulate. The mortar may contain discontinuous fibres [2]. The uniform spreading and high superficial area to volume ratio of its reinforcement result in better crack arrest mechanism. Volume fraction plays a vital role in ultimate strength carrying capacity. It is very popular as the raw material is readily available and can be prepared in any shape and it is fire resistant [3]. The properties of ferrocement are highly reliant on the type, amount, alignment, and strength properties of mesh and reinforcing rods [4]. Ferrocement laminates with chicken mesh, weld mesh, and

well-designed mortar can be an alternative and cost-effective technique in strengthening and repair of structural elements for improving load carrying capacity and ductility [5].

Ferrocement laminates under flexure and compression show higher performance with galvanised iron mesh when compared with ferrocement with polypropylene mesh. But laminates with polypropylene mesh exhibited improved ductility properties as compared to GI mesh panels. Increase in thickness of laminate and number of layers results in higher load carrying capacity [6]. Bamboo based ferrocement slab with 40 mm and 50 mm under flexure shows similar first crack load and ultimate load. The ultimate load has been found to be twice that of the first crack loads. Large ductility was observed before final failure under flexure [7]. Ferrocement with expanded metal mesh has higher energy captivation when compared with ferrocement with welded wire mesh or fiber glass mesh. Increase in number of layers increases energy absorption for beams made of Autoclaved Aerated Lightweight Brick Core

(AAC) [8]. Flexural performance of ferrocement increases when wire mesh is used with epoxy. With increase in number of layers of wire mesh flexural strength, cracking behaviour and energy absorption increase. Wire mesh-epoxy composites are more efficient than carbon fibres in flexural strength and ductility [9].

Ferrocement beams with welded wire mesh exhibit increase in shear capacity and less number of crack patterns compared with reference and expanded wire mesh [10]. Ferrocement slab with 10% rubber powder as replacement of cement was found to change the brittle failure to ductile failure with a small reduction in ultimate flexural strength [11]. Aerated slurry-infiltrated chicken mesh ferrocement exhibits ductile failure which can be used as a building construction material. Theoretical model developed confirms the experimental results [12]. Ferrocement containing perlite light weight aggregate (LWA) indicates flexural behaviour of light weight ferrocement increases with number of expanded rib lath layers [13]. Incorporation of 10% LECA in ferrocement leads to the increase of energy absorption by 48%, ductility index by 26%, and crack width by 106% [14]. Ferrocement with 4% of high calcium wood ash by weight of cement exhibited better structural performance when compared to control ferrocement without high calcium wood ash. Addition of HCWA in mortar increases the engineering performance and also contributes as potential binding material [15]. Cementitious matrices containing silica fume and fly ash in ferrocement have high strength, increased load carrying capacity, lateral confinement, and ductility [16]. Flexural strength of welded square mesh ferrocement of U shaped channel section mesh is higher than ferrocement channel section with woven square mesh. With increase in number of layers of mesh from 2 to 4, flexural strength and load carrying capacity increase [17].

U-shaped ferrocement with 98 expanded steel mesh exhibits higher first crack load, ultimate load, and serviceability load when compared with beams reinforced with EX156 expanded steel mesh and then specimens reinforced with woven mesh [18]. The beams with lightweight brick have higher first crack load and ultimate load when compared with conventional beams with welded wire mesh. Similarly, use of light weight brick resulted in reduction of serviceability load and energy absorption [19]. This paper presents the experimental results of ferrocement laminates under flexure with chicken mesh and partial replacement of fine aggregate by steel slag and proposes an analytical model to determine the ultimate moment carrying capacity of ferrocement laminates under flexure.

2. Properties of Materials Used

2.1. Cement. Ordinary Portland cement of 53 grades was used in this investigation and its physical properties were tested in accordance with Indian standards [20]. Specific gravity was 3.15 and initial and final setting time was 35 minutes and 10 hours, respectively. The test results comply with the requirements as per Indian Codal Provisions [21].

2.2. Fine Aggregate

2.2.1. Sand. Fine aggregate passing through 2.36 mm sieve having specific gravity 2.68 under Zone II as per the

recommendations of IS 383, 1970, ACI 549 1R-93, 1999, and Ferrocement Model Code (FMC) 2001 was used [22–24].

2.2.2. Steel Slag. Steel slag is a byproduct acquired in basic oxygen furnace (BOF) during change of iron to steel or in electric arc furnace (EAF) during softening of scrap to make steel. Steel slag is defined as a nonmetallic item, comprising basically of calcium silicates and ferrites joined with intertwined oxides of iron, aluminum, manganese, and calcium that are grown at the same time with steel in essential oxygen, electric curve, or open hearth heaters [25]. Steel slag could be used as substitute material for normal sand in mortar either mostly or completely [26]. Steel slag with specific gravity 2.95 with a division going through 2.36 mm sieve was utilized for cement mortar for fabrication of ferrocement laminates. The chemical composition of steel slag is usually expressed in terms of simple oxides calculated from elemental analysis determined by Le Chatelier method [27]. Table 1 arrays the chemical composition of steel slag from a typical base oxygen furnace [25].

2.3. Water. Water fit for drinking is generally fit for casting ferrocement laminate and water used is free of acids, oils, alkalis, and other organic impurities and its pH value is 7 ± 1 .

2.4. Reinforcement for Ferrocement Laminate. The properties of chicken mesh are on par with the steel reinforcing bars used in reinforced concrete [2]. Chicken mesh with diameter 0.5 mm and yield strength of 312 N/mm^2 as per the manufacturer data was used.

3. Experimental Investigations on Ferrocement Laminates

The mortar mix proportion was taken as 1 : 2, w/c ratio 0.40 [28]. Steel slag replacement from 0% to 50% by weight of fine aggregate in increments of 10% was adopted for experimental investigation of ferrocement laminate under flexural loading.

3.1. Flexural Behaviour of Ferrocement Laminates. The experimental work involves casting and testing of ferrocement laminates [23] of size $150 \text{ mm} \times 25 \text{ mm} \times 500 \text{ mm}$ with partial replacement of fine aggregate by steel slag from 0% to 50% by weight of fine aggregate in increments of 10% in mortar matrix under flexure by closed mould method of bundling of chicken meshes.

For the study, a total number of 72 specimens were cast of size $150 \text{ mm} \times 25 \text{ mm} \times 500 \text{ mm}$, and volume fractions of 0.94%, 1.88%, 2.82%, and 2.377% for 1 layer, 2 layers, 3 layers, and 4 layers were used. The cross section of the specimen is shown in Figure 1. The details of the specimen with chicken mesh are arrayed in Table 2. The designation refers to the number of layers of mesh reinforcement, ferrocement, type of mesh, and percentage of replacement of steel slag for fine aggregate. For example, 1FCC0 refers to 1

TABLE 1: Chemical composition of steel slag.

Constituent	Composition (%)	Composition (%) as per ACI 233 R-03
CaO	32.5	32 to 45
SiO ₂	34	32 to 42
Fe ₂ O ₃	0.3	0.1 to 0.5
MgO	9	5 to 15
Al ₂ O ₃	22	7 to 16
P ₂ O ₅	0.56	—
SO ₃	0.7	—

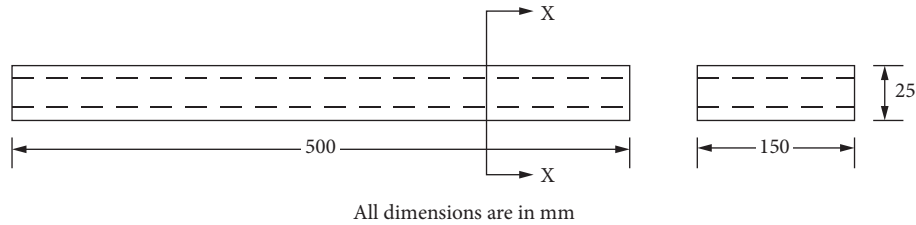


FIGURE 1: Cross section of the ferrocement laminates.

TABLE 2: Details of test specimen with chicken mesh for flexure test.

Type of mesh	Designation	No. of layers	Volume fraction V_r (%)	Steel slag (%)	No. of specimens
Chicken mesh	1FCC0	1	0.94	0	3
	1FCC10			10	3
	1FCC20			20	3
	1FCC30			30	3
	1FCC40			40	3
	1FCC50	50	3		
	2FCC0	2	1.88	0	3
	2FCC10			10	3
	2FCC20			20	3
	2FCC30			30	3
	2FCC40			40	3
	2FCC50	50	3		
	3FCC0	3	2.82	0	3
	3FCC10			10	3
	3FCC20			20	3
	3FCC30			30	3
	3FCC40			40	3
	3FCC50	50	3		
	4FCC0	4	3.77	0	3
	4FCC10			10	3
	4FCC20			20	3
	4FCC30			30	3
	4FCC40			40	3
	4FCC50	50	3		

layer of mesh reinforcement in ferrocement with weld mesh and 0% steel slag replacement for fine aggregate.

The ferrocement laminates were subjected to flexure test under the simply supported span of 400 mm with loads at one third points. In the present investigation, deflection at the midpoint for each 0.5 kN load was noted with the help of dial gauge of the least count of 0.01 mm/divisions. During testing, observations were made for (a) deflection at the midpoint for each 0.5 kN increment of loading, (b) load at first crack, (c) ultimate load, and (d) mode of failure of all specimens.

4. Analytical Investigation on Ferrocement Laminates

4.1. Prediction of Ultimate Moment for Ferrocement Laminates. An analytical model for determining ultimate moment carrying capacity of ferrocement using plastic moment approach is presented. The proposed stress strain block for ferrocement laminate is shown in Figure 2.

In this investigation, the following assumptions were made:

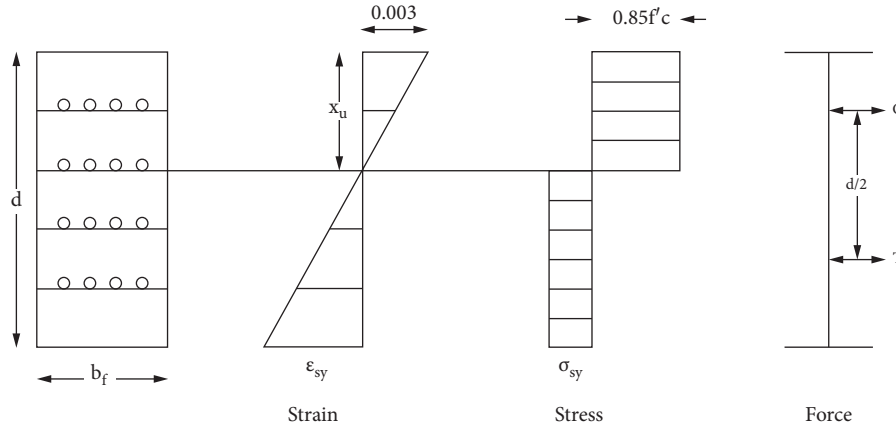


FIGURE 2: Stress strain block for ferrocement laminate.

- (1) The compressive stress in mortar was represented by a rectangular stress block with stress intensity of $0.85f'_c$ and depth equal to neutral axis depth
- (2) Perfect bond existed between the steel mesh and mortar
- (3) The material was considered as a homogenous material
- (4) Plane section remained plane even after bending
- (5) The maximum usable compressive strain in mortar was 0.003
- (6) The properties in tension were predicted by assuming all steel layers are in the plastic range
- (7) The depth of plastic neutral axis was determined by equating compressive force equal to tensile force
- (8) The distribution of reinforcement was uniform throughout the section

The behaviour of laminate was assumed similar to that of RC beams [29]. Therefore, the total force due to compression is equal to total force due to tension. From the stress strain block in Figure 2, the equations for compressive and tensile forces were obtained as

$$\begin{aligned} C &= 0.85f'_c b_f x_u, \\ T &= \sigma_{cy} b_f (d - x_u). \end{aligned} \quad (1)$$

The tensile strength of the composite σ_{cy} was obtained from assuming all the steel layers in the plastic range:

$$\begin{aligned} \sigma_{cy} &= \eta V_r \sigma_{ry} \\ &= X. \end{aligned} \quad (2)$$

Moment due to compressive force is

$$M_c = 0.425f'_c \cdot b_f d^2 \frac{X}{0.85f'_c + X}. \quad (3)$$

Moment due to tensile force is

$$M_T = 0.5b_f \cdot d^2 \times \left(1 - \frac{X}{0.85f'_c + X}\right). \quad (4)$$

Final moment is

$$M = M_c \text{ or } M_T, \quad (5)$$

where x_u is the depth of neutral axis, V_r is the volume fraction of mesh reinforcement, M_c is the moment due to compressive force, M_T is the moment due to tensile force, f'_c is the compressive strength of mortar (N/mm^2), b_f and d are the breadth and thickness of the ferrocement laminate (mm), σ_{ry} is the yield strength of mesh reinforcement (N/mm^2), σ_{cy} is the tensile strength of composite, and η is the efficiency factor for reinforcement.

5. Results and Discussion

5.1. First Crack Load and Ultimate Load. In the case of ferrocement laminates with chicken mesh, the first crack load is shown in Figure 3; for specimens 1FCC30 with volume fraction 0.94% and 2FCC30 with volume fraction 1.88%, the first crack load is enhanced about 40% and 25%, respectively, when compared to 1FCC0 and 2FCC0. For the specimens 3FCC30 reinforced with volume fraction 2.82% and 4FCC30 reinforced with volume fraction 3.77%, first crack load increased by 29% and 77%, respectively, when compared to 3FCC0 and 4FCC0.

From Figure 4 for specimens 1FCC30 and 2FCC30, the ultimate load increased about 91% and 63%, respectively, when compared to 1FCC0 and 2FCC0. In regard to the specimens 3FCC30 and 4FCC30, the ultimate load enhanced about 22% and 36%, respectively, when compared to 3FCC0 and 4FCC0.

It is clear that, for ferrocement laminates, first crack load and ultimate load gradually increased from 0% to 30% replacement of steel slag by weight of fine aggregate and decreased for 40% and 50% replacement irrespective of the volume fraction and type of mesh reinforcement. This is due to the good bonding characteristics of mesh reinforcements with 30% replacement of steel slag by weight of fine aggregate (optimised % replacement). There are only marginal variations in first crack load for all the specimens with different volume fractions and different replacement levels. The first crack load and ultimate load achieved by the specimens with chicken mesh of volume fraction 1.88% with 30% steel slag replacement are higher than those of the

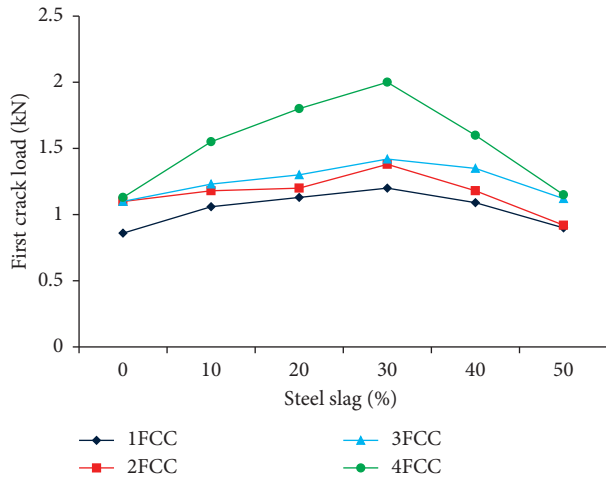


FIGURE 3: First crack load for different levels of steel slag replacement and volume fractions of chicken mesh ferrocement laminates.

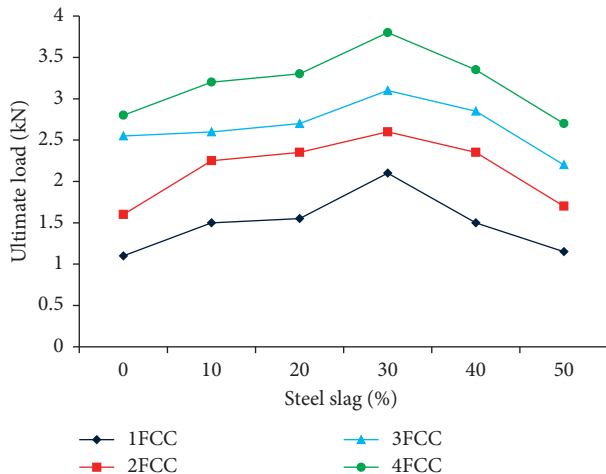


FIGURE 4: Ultimate load for different levels of steel slag replacement and volume fractions of chicken mesh ferrocement laminates.

specimens with chicken mesh of volume fraction 3.77% without replacement. It shows that the addition of steel slag has considerable effect on increasing the load carrying capacity.

Moreover, first crack load and ultimate load were maximum for ferrocement laminates with volume fraction of 3.77% because of increased moment arm due to increase in the depth of mesh layers from the neutral axis of the section [30].

5.2. Load-Deflection Characteristics. An experimental load-deflection curve of ferrocement with their transition points (i.e., cracking, yielding, and ultimate) is discussed using Figures 5–8. It is observed that the ferrocement laminates exhibit linear elastic behaviour up to the first crack load. Figures 5 and 6 depict the load deflection behaviour of specimens with chicken mesh reinforced with volume fractions 0.94% and 1.88%. The specimen started to yield

when the load was 0.86 kN, 1.2 kN, 1.1 kN, and 1.38 kN for the specimens 1FCC0, 1FCC30, 2FCC0, and 2FCC30, respectively. On further increment of load, the specimens reach an ultimate load of 1.1 kN, 2.1 kN, 1.6 kN, and 2.6 kN for specimens 1FCC0, 1FCC30, 2FCC0, and 2FCC30, respectively.

Figures 7 and 8 show the load-deflection behaviour of specimens with chicken mesh with volume fractions 2.82% and 3.77%. Initially, as the load is increased, the transition point of cracking is obtained for specimens 3FCC0, 3FCC30, 4FCC0, and 4FCC30 when the load is at 1.1 kN, 1.42 kN, 1.13 kN, and 2 kN, respectively. When the static load is further increased, the yielding of mesh reinforcement occurs and specimens reach the ultimate load of 2.55 kN, 3.1 kN, 2.8 kN, and 3.8 kN, respectively. The ultimate load of 4FCC30 was found to be 49% higher than the control specimen.

5.3. Energy Absorption Capacity. Energy absorption is the area under the load-deflection curve. The energy absorption capacity of specimens with chicken mesh is manifested in Figure 9.

Figure 9 shows that, for the specimens with chicken mesh reinforced with volume fraction 0.94%, 1.88% maximum energy absorption was obtained for the specimens 1FCC30 and 2FCC30 which was about 67% and 51% higher than 1FCC0 and 2FCC0. For the specimen 3FCC30 reinforced with volume fraction 2.82%, the energy absorption increased about 21% when compared to control specimen. Energy absorption of the specimen 4FCC30 reinforced with volume fraction 3.77% increased about 79% compared to control specimen.

5.4. Ductility Ratio. Ductility ratio is the ratio of deflection at ultimate load to that at the onset of yielding. The ductility ratio shown in Figure 10 increased about 46% for the specimen 1FCC30 which is reinforced with the volume fraction 0.94%. The specimens 2FCC30 and 3FCC30 increased about 27% and 9%, respectively, when compared to control specimen. The specimen 4FCC30 increased about 19% when compared with control specimen. It is clear that a specimen with optimum percentage of replacement of steel slag (i.e., 30 percent) by weight of fine aggregate has produced higher ductility strength.

5.5. Effect of Mortar Matrix. From the test results, it is clear that the addition of steel slag in the mortar matrix, which was used for ferrocement laminates, has considerably reduced the deflection. The mortar matrix with 30% steel slag by weight of fine aggregate has influenced the initial strength as well as long-term strength in ferrocement laminates which in turn increases the first crack load and ultimate load. The specimens with 30% steel slag by weight of fine aggregate gave sufficient warning before failure. So this, in turn, represents that 30% replacement of steel slag by weight of fine aggregate is the optimum percentage of replacement for fine aggregate.

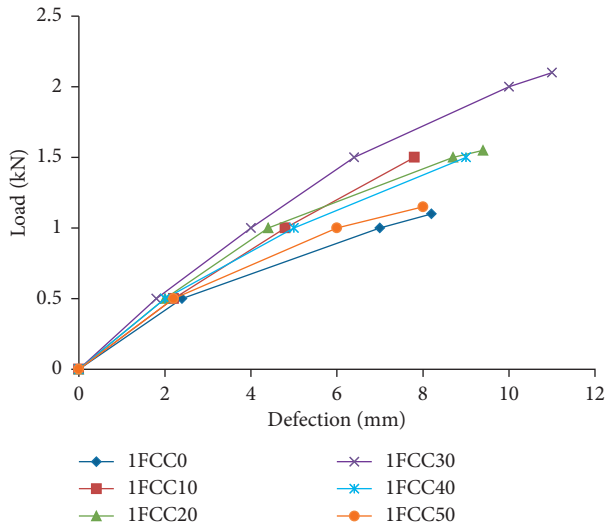


FIGURE 5: Load vs. deflection for ferrocement laminates with volume fraction 0.94%.

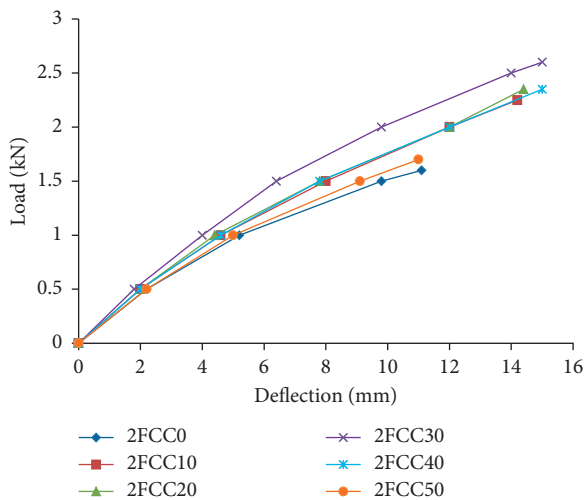


FIGURE 6: Load vs. deflection for ferrocement laminates with volume fraction 1.88%.

5.6. Effect of Number of Wire Mesh Layers. It is evident from the graphs that the strength increases with an increase in the number of layers of mesh. The number of layers is attributed to the increase in passive confining pressure which in turn is dependent on the volume fraction of transverse wires [31]. Therefore, the chicken mesh with 0.5 mm diameter and the mesh opening have direct influence on the increase in strength of the specimen. The specimens with 3 layers and 4 layers are equally spaced and distributed within the depth. The transverse wires in meshes provided a better anchorage for a bond with cement matrix and a better restraint against lateral expansion of the matrix in the compression zone [31]. The chicken mesh with higher volume fraction of mesh reinforcement provided better crack control mechanism by the formation of a large number of well distributed cracks.

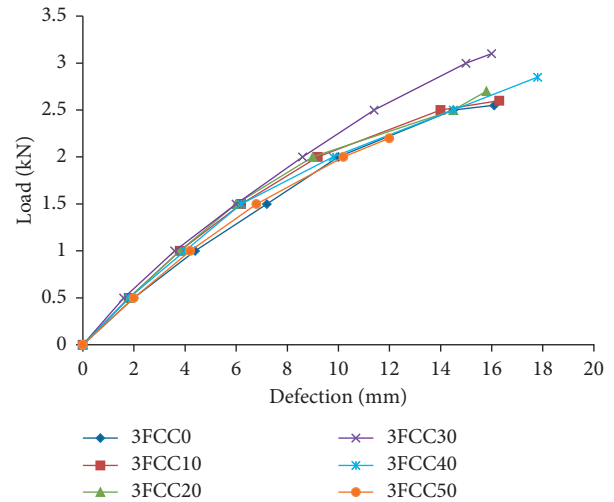


FIGURE 7: Load vs. deflection for ferrocement laminates with volume fraction 2.82%.

5.7. Mode of Failure. Flexural pattern failure was observed for all specimens. Most of the cracks were generated near the centre on increase in loads. The crack pattern for various specimens is displayed in Figure 11.

The specimens with volume fraction 0.943% showed a single major crack at the middle of the specimen. Due to the increase in the cover of mesh reinforcement, the ferrocement laminates failed suddenly after reaching the ultimate load. The specimens reinforced with chicken mesh of volume fraction 1.880% showed a formation of cracks not far from loading points of the specimen. For the specimens reinforced with volume fraction 2.82%, the parallel cracks were well distributed at the middle of the specimen. For the specimens with volume fraction 3.77%, the cracks were well distributed at the centre and it was observed that no separation of specimen occurred even after failure, but it was attached by mesh.

5.8. Analytical Investigation on Ferrocement Laminates

5.8.1. Correlation of Analytical and Experimental Ultimate Moment. The analytical model developed to determine the ultimate moment capacity of ferrocement laminates is discussed. The ultimate moment capacity of every specimen was experimentally calculated by testing the laminates under loads at one third points. The experimentally calculated ultimate moment values were compared with that of predicted analytical moment values determined using equations (3) or (4). From the comparison of results, it was clearly established that the proposed analytical equation for the calculation of ultimate moment capacity of ferrocement laminates with partial and without substitution of fine aggregate by steel slag goes hand in hand with experimental values. The variation in analytical and experimental moment value is checked for $\pm 20\%$ accuracy.

The correlation of analytical and experimental moments is shown in Figure 12. All the specimens reinforced with volume fractions 1.88%, 2.82%, and 3.77% fall within the

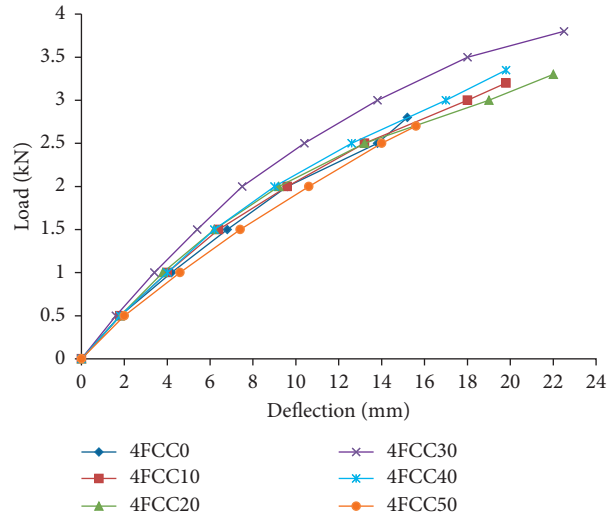


FIGURE 8: Load vs. deflection for ferrocement laminates with volume fraction 3.77%.

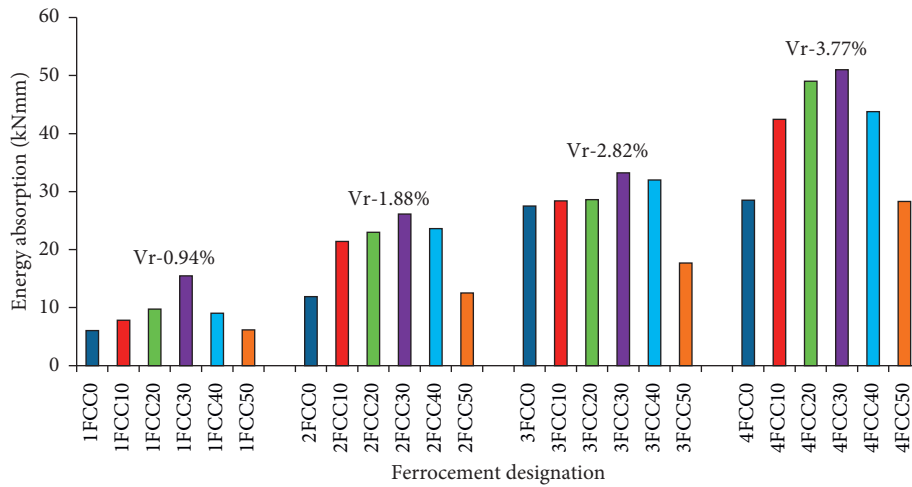


FIGURE 9: Energy absorption for different levels of steel slag replacement and volume fractions of chicken mesh ferrocement laminates.

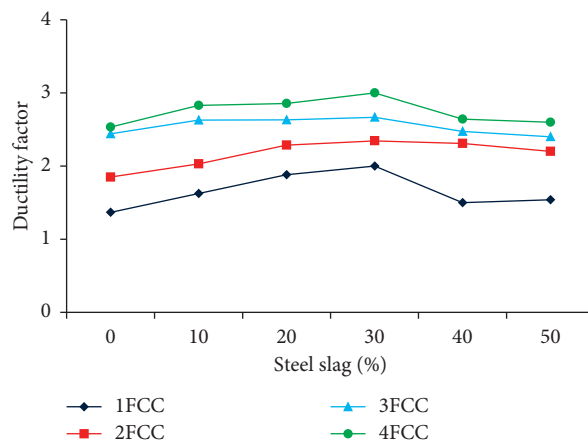


FIGURE 10: Ductility ratio for different levels of steel slag replacement and volume fractions of chicken mesh ferrocement laminates.

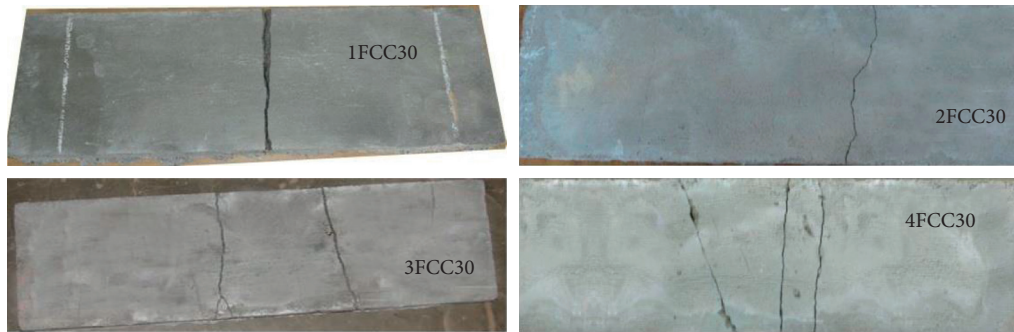


FIGURE 11: Crack pattern of ferrocement laminates under flexure.

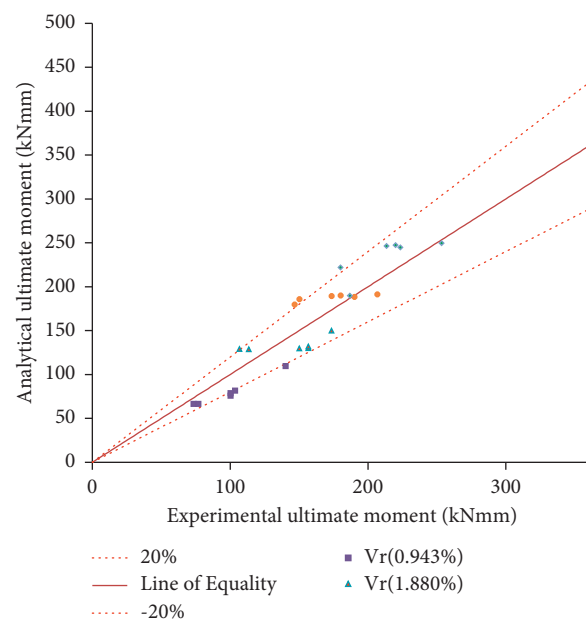


FIGURE 12: Correlation between analytical moment and experimental moment for ferrocement laminates.

$\pm 20\%$ accuracy whereas the specimens reinforced with volume fraction 0.94% had variation in the specimens with 10%, 20%, 30%, and 40% substitution of steel slag by weight of fine aggregate.

6. Conclusions

The following conclusions can be drawn from experimental and analytical investigations:

- (1) The first crack load and ultimate load were found to be maximum for specimens with volume fraction 3.77%, i.e., 4 layers, and 30% replacement of steel slag by weight of fine aggregate
- (2) Addition of steel slag of 30% and chicken mesh of volume fraction 3.77% in ferrocement laminates has reduced the deflection when compared to other specimens

(3) From an overall assessment, i.e., the maximum first crack load, ultimate load, deflection, and energy absorption, optimum results were obtained for ferrocement laminates with a volume fraction of 3.77% and steel slag replacement of 30%

(4) The ultimate moment capacity of ferrocement laminates obtained from the proposed analytical model was found to be in good agreement with the experimental values and accuracy fell within $\pm 20\%$

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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