CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 GENERAL

In this chapter, the results based on the experimental investigations which were carried out on optimized mortar matrix are discussed. The flexural and impact characteristics of ferrocement laminates, with different proportion of fly ash and silica fume together with cement, reinforced with chicken mesh of volume fraction 0.943%, 1.880%, 2.823%, 3.770% and weld mesh of volume fraction 0.586%, 1.174%, 1.761% and 2.348% are presented. The results are compared with conventional mortar specimens of ferrocement laminates. The experimental investigation on strengthened reinforced concrete beams with ferrocement laminates of conventional mortar and optimized mortar containing silica fume, fly ash and cement reinforced with galvanized weld mesh of volume fraction of 1.761% and 2.348% are also presented. The experimental results in flexural capacity of ferrocement laminates and strengthening of reinforced concrete beams are compared with the proposed analytical model.

5.2 OPTIMIZATION OF MORTAR MIX

The cement was replaced with silica fume at three proportions (3%, 5% and 7%) and a dosage of super plasticizer ranging from 0% - 1% by the weight of total binder with an increment of 0.2% was adopted. 5% silica fume as a cement replacement showed a good increase in compressive
strength at 28 days (Thomas et al 1999). Hence the addition of 5% silica fume with different fly ash replacements was adopted. Water cement ratio of ferrocement elements should be between 0.3 to 0.4 by weight (ACI 549 R, 1997). Hence the water cement ratio of 0.32, 0.35 and 0.38 was adopted.

The compressive strength of cement mortar at 28 days containing different mixes 1:2, 1:2.5 and 1:3, different water binder ratio, 0.32, 0.35 and 0.38 partial replacement of cement with fly ash varying from 10% to 30% (with 5% incremental) together with a constant 5% silica fume at different dosages of the super plasticizer are discussed.

5.2.1 Optimization of Super Plasticizer

Figures 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8 and 5.9 depict the compressive strength vs dosage of super plasticizer. It is obvious that the compressive strength increased with an increase in the dosage of super plasticizer, only for OPC mortars. For other mixes, with different water binder ratios, the compressive strength has shown increase of up to 0.6% and it was maximum at 0.6% dosage. This trend may be attributed to the slow hydration process caused by high dosage of super plasticizer. Thus, it is deduced that the dosage of super plasticizer can be optimized at 0.6% of the total binder by weight.
Figure 5.1  Compressive strength vs super plasticizer dosage 1:2 mix, w/b 0.32

Figure 5.2  Compressive strength vs super plasticizer dosage 1:2 mix, w/b 0.35
Figure 5.3  Compressive strength vs super plasticizer dosage 1:2 mix, w/b 0.38

Figure 5.4  Compressive strength vs super plasticizer dosage 1:2.5 mix, w/b 0.32
Figure 5.5  Compressive strength vs super plasticizer dosage 1:2.5 mix, w/b 0.35

Figure 5.6  Compressive strength vs super plasticizer dosage 1:2.5 mix, w/b 0.38
Figure 5.7  Compressive strength vs super plasticizer dosage 1:3 mix, w/b 0.32

Figure 5.8  Compressive strength vs super plasticizer dosage 1:3 mix, w/b 0.35
Figure 5.9  Compressive strength vs super plasticizer dosage 1:3 mix, w/b 0.38

5.2.2 Optimization of Water Binder Ratio

The compressive strength was seen to have increased as w/b ratio was varied. For 1:2 mortar mix with 0.35 water binder ratio was observed graphically from Figures 5.10, 5.11 and 5.12. There was 8.5% to 42% increase in compressive strength for 0.35 water binder ratio compared to conventional mortar. When water binder ratio varied from 0.32 to 0.35, the compressive strength at 28 days increased to a maximum value and then decreased at 0.38 water binder ratio. Hence it is evident that the mortar mix 1:2 with water binder ratio 0.35 is suitable for casting ferrocement elements.
Figure 5.10  Compressive strength vs specimen for 1:2 mix with w/b 0.32, 0.35 and 0.38

Figure 5.11  Compressive strength vs specimen for 1:2.5 mix with w/b 0.32, 0.35 and 0.38
Figure 5.12 Compressive strength vs specimen for 1:3 mix with w/b 0.32, 0.35 and 0.38

5.2.3 Optimization of Mortar Mix

When cement sand ratio was varied from 1:2 to 1:3, compressive strength of mix at 28 days increased to a maximum value with cement sand ratio of 1:2 which can be observed graphically from Figures 5.10, 5.11 and 5.12. From Figure 5.10, it looks apparent that the compressive strength 78MPa was reached for mortar 1:2, with 20% fly ash, 5% silica fume and 0.6% super plasticizer with w/b ratio of 0.35. The compressive strength increased to about 42% compared to conventional mortar. From Figure 5.11, the compressive strength increased to 46% for mortar 1:2.5, with 20% fly ash, 5% silica fume and 0.6% super plasticizer with w/b ratio of 0.35 compared to conventional mortar. From Figure 5.12, the compressive strength increased to 28% for mortar 1:3, with 20% fly ash, 5% silica fume and 0.6% super plasticizer with w/b ratio of 0.35 compared to conventional mortar.

In Figure 5.10, it is noted that the compressive strength of mix with 1:2 cement sand ratio, and 0.35 water binder ratio was found to be
significantly higher in comparison with cement sand ratio of 1:2.5 and 1:3. It is observed from Figure 5.12 that sand rich mortar mix with cement sand ratio of 1:3 consistently exhibited the lowest compressive strength when compared to the other mixes. Due to the balanced combination of cement sand ratio in the mix 1:2, a higher compressive strength was achieved. It was clear that a higher compressive strength was obtained for a mortar mix of 1:2 and 0.35 water binder ratio. With the use of this cement sand ratio in the production of structural grade mortar mix in fabrication of ferrocement structural elements, the consumption of cement binder would be economized. So there are potential savings in terms of material and production cost of mortar mix for the construction industry (Chean Chee Ban & Mahyuddin Ramli 2010).

5.2.4 Effect of Fly Ash and Silica Fume

The results showed that an increase in the compressive strength was obtained for the mortars with 1:2 mix, 0.35 water binder ratio and partially replaced cement with fly ash varied between 10% to 30% (with 5% incremental) together with a constant 5% silica fume ranging between 8.5% to 42% over conventional mortar at optimized 0.6% dosage of super plasticizer. The increase in the compressive strength of optimally replaced mortar is due to the following reasons: The specific gravity of silica fume and fly ash were lower than that of cement. Fly ash proved to be extremely fine. The silica fumes exhibited pozzolanic reaction and packing effect. The pozzolanic reaction between fly ash with silica fume had resulted in the formation of a greater amount of secondary calcium silicate hydrate and refinement in the pore structure of the resultant cementitious composites. (Langan et al 2002).

From Figures 5.10, 5.11 and 5.12, it is observed that the replacement of cement with 20% fly ash and 5% silica fume in mortars has improved compressive strength. It ranged from 3% to 44% over control OPC mortars at various dosages of the super plasticizer in all the three mixes for all
water binder ratios. Beyond this, increasing the fly ash content decreased the compressive strength slightly. Excessive addition of fly ash in the system showed no reaction. This can be attributed to the lower effectiveness of SiO$_2$ present in fly ash.

The slow rate strength gain of cement can be overcome by a ternary mix. The blend of silica fume in addition to fly ash in the mortar accelerated the initial strength as well as the long term strength compared to conventional mortar. Fly ash compensated for increased water demand of silica fume. During hydration of cement mortars, the fly ash and silica fume in the cement mortar caused conditions to bind CH and produced new (pozzolanic) C-S-H gel and so the strength increased (Langan et al 2002).

From Figure 5.10, it looks apparent that the compressive strength 78MPa was reached for mortar 1:2, with 20% fly ash, 5% silica fume and 0.6% super plasticizer with w/b ratio of 0.35. The compressive strength increased to about 42% compared to conventional mortar. It was due to the hydration and pozzolanic reaction of the fly ash and silica fume.

In this work, an optimum mortar mix was developed for studying the flexural and impact behaviour of ferrocement specimens. This study led to the development of a criterion for an optimum mortar mix to cast thin ferrocement elements ideally suited for structural repair or retrofit. The optimum mortar mix was found to have a composition of 1:2 mortar mix, 0.35 water binder ratio, 0.6% dosage of the super plasticizer with partial replacement of cement with fly ash varying from 10% to 30% (with 5% increments) together with a constant 5% silica fume.
5.3 FLEXURAL BEHAVIOUR OF FERROCEMENT LAMINATES

The results and discussions presented are based on the experimental investigations carried out on ferrocement specimens of size 150 mm x 25 mm x 500 mm as in Figure 3.5, with 1:2 mix ratio, 0.35 water binder ratio, partial replacement of cement with fly ash content varying from 10%, 15%, 20%, 25% and 30% together with a constant 5% silica fume by weight of cement and the dosage of super plasticizer used was 0.6% by weight of the total binder.

5.3.1 First Crack Load and Ultimate Load

To determine optimum replacement, flexural test was conducted with loads applied at one third points. It indicated that all the specimens had flexural failure. The first cracking was defined as the instance when the first crack became visible. The first crack load and ultimate load were found to be directly related to the volume fraction of reinforcement in loading direction. The first crack load and ultimate load for the ferrocement specimens with galvanized square weld mesh and chicken mesh of different volume fraction are shown graphically. From Figures 5.13, 5.14, 5.15 and 5.16 it may be seen that for all the specimens reinforced separately with weld mesh and chicken mesh, the first crack load and ultimate load varied linearly with the volume fraction of reinforcement.
Figure 5.13  Comparison of first crack load for laminates reinforced with weld mesh

Figure 5.14  Comparison of first crack load for laminates reinforced with chicken mesh
Figure 5.15  Comparison of ultimate load for laminates reinforced with weld mesh

Figure 5.16  Comparison of ultimate load for laminates reinforced with chicken mesh
It is evident from the graphs that for both the meshes, the first crack load and ultimate load were found to be maximum at a higher volume fraction and at partial replacement of 20% fly ash together with a constant 5% silica fume by weight of cement. The first crack load and ultimate load gradually increased for the replacement proportion of constant 5% silica fume, and fly ash varied from 0% to 20% and decreased with fly ash proportion of 25% and 30%. The first crack load and ultimate load attained maximum at 20% fly ash and 5% silica fume for both the meshes. This was due to the bonding characteristic of mesh with optimized mortar being good and adequate in flexure.

Specimen 4FWFA20SF reinforced with weld mesh of volume fraction 2.348% and 4FCFA20SF reinforced with chicken mesh of volume fraction 3.770% had the maximum first crack load at 2.4kN and 1.65kN respectively. The maximum first crack load was 50% greater than 4FW0 and 18% greater than 4FC0. The maximum ultimate load for the specimen 4FWFA20SF was 5.2kN and for 4FCFA20SF was 3.6kN. It was 37% greater than 4FW0 and 20% greater than 4FC0.

Maximum first crack load for specimen 3FWFA20SF reinforced with weld mesh of volume fraction 1.761% was 2.1kN and for specimen 3FCFA20SF reinforced with chicken mesh of volume fraction 2.823% .It was 1.5kN. It is 40% greater when compared to 3FW0 and 25% greater when compared to 3FC0. The maximum ultimate load for specimen 3FWFA20SF was 4.2kN and for specimen 3FCFA20SF. It was 2.9kN. It is 28% greater compared to 3FW0 and 26% greater compared to 3FC0.

Specimen 2FWFA20SF reinforced with weld mesh of volume fraction 1.174% and 2FCFA20SF reinforced with chicken mesh of volume fraction 1.880% had the maximum first crack load at 1.9kN and 1.4kN respectively. It is 46% greater than 2FW0 and 40% greater than 2FC0. The
maximum ultimate load for the specimen 2FWFA20SF was 3.1kN and for 2FCFA20SF. It was 2.25kN. It is 41% more than 2FW0 and 2FC0 specimens.

The maximum first crack load for specimen 1FWFA20SF reinforced with weld mesh of volume fraction 0.586% was 1.7kN and for specimen 1FCFA20SF reinforced with chicken mesh of volume fraction 0.943%. It was 1.2kN. It was 42% and 50% greater than 1FW0 and 1FC0 respectively. The maximum ultimate load was 2.5kN and 1.65kN for specimens 1FWFA20SF and 1FCFA20SF respectively which were 56% and 50% greater compared to 1FW0 and 1FC0.

In the case of first crack load analysis, marginal variation was found in all the specimens with different volume fraction and different replacement levels. But a significant variation was found in the case of ultimate load for both meshes. This indicated that the flexural strength of the mortar was increased with an increase in volume fraction of mesh. The increased depth of mesh layers from the neutral axis of the section resulted in increasing the moment arm, leading to an increase in flexural strength (Jamal Shannag 2008). It was observed that the volume fraction has a pronounced effect on ultimate load.

5.3.2 Load Deflection Characteristics

Load deflection curves for ferrocement panels tested under flexure for different volume fraction of weld mesh and chicken mesh are shown in Figures 5.17, 5.18, 5.19, 5.20, 5.21, 5.22, 5.23 and 5.24.
Figure 5.17  Load vs Deflection plot for laminates reinforced with weld mesh of volume fraction 0.586% for different replacement levels of fly ash

Figure 5.18  Load vs Deflection plot for laminates reinforced with weld mesh of volume fraction 1.174% for different replacement levels of fly ash
Figure 5.19  Load vs Deflection plot for laminates reinforced with weld mesh of volume fraction 1.761% for different replacement levels of fly ash

Figure 5.20  Load vs Deflection plot for laminates reinforced with weld mesh of volume fraction 2.348% for different replacement levels of fly ash
Figure 5.21 Load vs Deflection plot for laminates reinforced with chicken mesh of volume fraction 0.943% for different replacement levels of fly ash

Figure 5.22 Load vs Deflection plot for laminates reinforced with chicken mesh of volume fraction 1.880% for different replacement levels of fly ash
Figure 5.23 Load vs Deflection plot for laminates reinforced with chicken mesh of volume fraction 2.823% for different replacement levels of fly ash

Figure 5.24 Load vs Deflection plot for laminates reinforced with chicken mesh of volume fraction 3.77% for different replacement levels of fly ash
Figures 5.17 and Figure 5.21 show the load deflection curves for specimens with weld mesh of volume fraction 0.586% and chicken mesh of volume fraction 0.943%. It is linearly elastic up to load 1.2kN, 1.7kN, 0.8kN, 1.2kN for specimens 1FW0, 1FWFA20SF, 1FC0 and 1FCFA20SF respectively.

Figures 5.18 and Figure 5.22 show the load deflection curves for specimens reinforced with weld mesh of volume fraction 1.174% and chicken mesh of volume fraction 1.880%. From the curves, it is observed that the curve deviated from linearity gradually after the first crack load occurred at a load of 1.9kN, 1.3kN, 1.4kN, 1kN for specimens 2FWFA20SF, 2FW0, 2FCFA20SF and 2FC0 respectively.

Figures 5.19 and Figure 5.23 show the load deflection curves for specimens reinforced with weld mesh of volume fraction 1.761% and chicken mesh of volume fraction 2.823%. From the curves, it is observed that the specimens 3FW0, 3FWFA20SF, 3FC0, and 3FCFA20SF indicated the linearity up to static load of 1.5kN, 2.1kN, 1.2kN and 1.5kN respectively. Then, it began to curve towards yielding a maximum of 3.3kN, 4.2kN, 2.3kN, and 2.9kN for specimens 3FW0, 3FWFA20SF, 3FC0, and 3FCFA20SF respectively.

Figures 5.20 and Figure 5.24 show the load deflection curves for specimens reinforced with weld mesh of volume fraction 2.348% and chicken mesh of volume fraction 3.77%. From the curves, it is seen that initially, as the load increased, the deflection also increased linearly. The linearity in the curves is up to a load of 2.4kN, 1.6kN, 1.6kN, 1.4kN for the specimens 4FWFA20SF, 4FW0, 4FC0, and 4FCFA20SF respectively indicating the initiation of cracks in the specimens. As the static load continued to increase, the slope of the curve became less steep towards the yield point.
From the load deflection curves, it is evident that the specimen 4FWFA20SF reached a maximum load of intensity 5.2kN with a corresponding deflection of 12.5mm whereas specimen 4FCFA20SF reinforced with chicken mesh reached a maximum load of 3.6kN with corresponding deflection of 17mm.

From the load deflection curves, it is inferred that the ultimate load carrying capacity of laminate with optimum replacement of 20% fly ash together with constant 5% silica fume reinforced with weld mesh and chicken mesh is greater than those of conventional mortar specimens with different volume fraction.

5.3.3 Energy Absorption Capacity

The area under the load deflection curve is known as energy absorption capacity of the specimens. The entire area under the load deformation diagram consisting of both ascending and descending parts was taken into account. Variation of energy absorption capacity with volume fraction is shown in Figure 5.25 and 5.26 for different replacement of specimens. The ability of the composites to undergo large deformations before failure is the toughness index. From Figures 5.25 and 5.26 it is noted that the toughness of the various ferrocement specimens increased with an increase in the volume fraction of reinforcement.
Figure 5.25  Comparison of energy absorption for laminates reinforced with weld mesh

Figure 5.26  Comparison of energy absorption for laminates reinforced with chicken mesh
The energy absorption capacity of specimens 4FWFA20SF and 4FCFA20SF was increased by 23% and 16% for galvanized square weld mesh of volume fraction 2.348% and chicken mesh with volume fraction 3.770% respectively when compared with 4FW0 and 4FC0.

Specimens 3FWFA20SF and 3FCFA20SF exhibited an increase in energy absorption capacity of 16% and 15.5% for galvanized square weld mesh of volume fraction 1.761% and chicken mesh with volume fraction 2.823% respectively when compared with specimens 3FW0 and 3FC0.

The energy absorption capacity of 2FWFA20SF and 2FCFA20SF increased by 16% and 41% for galvanized square weld mesh of volume fraction 1.174% and chicken mesh with volume fraction 1.880% respectively when compared with specimens 2FW0 and 2FC0.

Specimens 1FWFA20SF and 1FCFA20SF exhibited an increase in energy absorption capacity of 39% and 21% for galvanized square weld mesh of volume fraction 0.586% and chicken mesh with volume fraction 0.943% respectively when compared with specimens 1FW0 and 1FC0.

From an overall assessment, energy absorption capacity of 4FWFA20SF and 4FCFA20SF was increased by 23% and 16% respectively when compared to 4FW0 and 4FC0 specimens. This is due to the increase in volume fraction of mesh and significant contribution of fly ash and silica fume in the cement mortar in improving the post cracking response of ferrocement specimen in flexure.

5.3.4 Effect of Matrix

It was observed that the incorporation of fly ash and silica fume as a partial substitute for cement has reduced the deflection and improved the
workability of the mix. The incorporation of silica fume in addition to the fly ash in the ferrocement mortar specimen accelerated the initial strength and the long term strength compared to a conventional mortar specimen (Thomas et al., 1999). Due to the above phenomenon, the maximum first crack load for specimens 4FWFA20SF and 4FCFA20SF with 4 layers of reinforcement was at 2.4kN and 1.65kN respectively. The optimum replacement specimen reached ultimate load level after sufficient warning before failure. Hence partial replacement of cement with 20% fly ash together with constant 5% silica fume was the optimal replacement for casting ferrocement laminates.

5.3.5 Ductility Factor

Ductility factor is computed as the ratio of deflection at ultimate load to that at the onset of yielding. It is an important factor which indicates the overall strength of various structural components. The ductility factor is given in equation 5.1.

\[
\text{Ductility factor} = \frac{\delta_u}{\delta_y}
\]  

(5.1)

where \( \delta_u \) - deflection at ultimate load (mm)
\( \delta_y \) - deflection at yield load (mm)

It varied from 1.375 to 3.472 for weld mesh and from 1.16 to 3.035 for chicken mesh. The variance of the ductility factor with volume fraction is shown in Figures 5.27 and 5.28 for different replacement of specimens.

The ductility factor of 4FWFA20SF and 4FCFA20SF was increased by 9.18% and 25.2% respectively when compared to 4FW0 and 4FC0 specimens. The ductility factor of the 3FWFA20SF and 3FCFA20SF was increased by 4.5% and 12% respectively when compared to 3FW0 and 3FC0 specimens. The ductility factor of the 2FWFA20SF and 2FCFA20SF
was increased by 24% and 26% respectively when compared to 2FW0 and 2FC0 specimens. The ductility factor of the 1FWFA20SF and 1FCFA20SF was increased by 41% and 47% respectively when compared to 1FW0 and 1FC0 specimens.

The ductility factor of 4FWFA20SF and 4FCFA20SF was 3.472 and 3.77 for weld mesh of volume fraction 2.348% and chicken mesh with volume fraction 3.770% respectively. It can be inferred that optimum replacement produced higher ductility strength. Due to its higher ductility, it can be effectively used in earthquake prone areas.

**Figure 5.27**  Comparison of ductility factor for laminates reinforced with weld mesh
First crack stress for each specimen was estimated, based on the equation 5.2 arrived at from (Mathews MS et al 1991).

\[ f_{cr} = 2V_r + 3.5f'_c \]  

where \( V_r \) is the volume fraction of reinforcement and \( f'_c \) is the compressive strength of mortar cube. The variance of the first crack stress with volume fraction is shown in Figures 5.29 and 5.30 for different replacement of specimens. The first crack stress increased with an increase in volume fraction of meshes as the first crack stress in bending test was a linear function of the percentage of steel reinforcement. This phenomenon is noticed in all percentages of cement replacement used in this investigation.
Figure 5.29  Comparison of first crack stress for laminates reinforced with weld mesh

Figure 5.30  Comparison of first crack stress for laminates reinforced with chicken mesh
The first crack stress of 4FWFA20SF and 4FCFA20SF specimens was increased by 16% and 15% respectively when compared to 4FW0 and 4FC0. The first crack stress of 4FWFA20SF and 4FCFA20SF was increased by 17% and 16% when compared to 3FW0 and 3FC0 specimens. The first crack stress of 2FWFA20SF and 2FCFA20SF was increased by 24% and 17% respectively when compared to 2FW0 and 2FC0 specimens. The first crack stress of 1FWFA20SF and 1FCFA20SF was increased by 18% when compared to 1FW0 and 1FC0 specimens.

5.3.7 Effect of Number of Wire Mesh Layers

It is evident from the plots that the strength was increased by increasing the number of mesh layers. The number of layers basically is attributed to the increase in passive confining pressure which in turn is dependent on the volume fraction of transverse wires (Waliuddin & Rafeeqi 1994). Therefore, the diameter of the wires and the mesh opening have direct bearing on the increase in strength of the specimen. In this study, 4 layers of both meshes reinforced in the ferrocement specimen with optimum replacement of 20% fly ash together with constant 5% silica fume by weight of cement showed considerable result. The specimens with 4 layers and 3 layers are equally spaced and distributed within the depth. The transverse wires in meshes provided a better anchorage for a bond and a better restraint against lateral expansion of the matrix in the compression zone strengthened the matrix (Waliuddin & Rafeeqi, 1994). The mesh wires were found to be more effective in increasing the margin between first crack load and ultimate load. From this observation it is understood that a higher volume fraction of mesh reinforcement provided better crack control mechanism by the formation of many well distributed cracks. Typical load deflection curves indicated the effect of the number of mesh layers.
5.3.8 Moment Curvature Curves

Moment curvature curves for ferrocement panels tested under flexure for different volume fraction of weld mesh and chicken mesh are shown in Figures 5.31, 5.32, 5.33, 5.34, 5.35, 5.36, 5.37 and 5.38. It can be observed from the Figures 5.31 to 5.38 that the shape of the curves is remarkably similar to the moment curvature curve exhibited by the reinforced concrete section. The moment curvature relation is linear for all the specimens in the pre-cracking stage. In a linear elastic portion both the reinforcement and the mortar matrix in compression remain linear elastic. Curvature increased with an increase in moment for all specimens. In a non linear portion, either or both materials are in their nonlinear range. The calculation of moment and curvature of the laminate 4FWFA20SF is presented in Appendix 1.

\[
\text{Moment at the center} = \frac{PL}{6} \tag{5.3}
\]

Curvature is the ratio of moment to flexural rigidity. The simplest formula to obtain curvature for the cracked section is given in equation 5.4 (Naaman 2000).

\[
\phi = \frac{M}{E_c I} \tag{5.4}
\]

Elastic modulus of composite is calculated from the equation 5.5.

\[
\delta_u = \frac{23PL^3}{1296E_c I} \tag{5.5}
\]

\[
I = \frac{bh^3}{24} \tag{5.6}
\]
$M$ - applied external moment

$E_c$ - elastic modulus of the composite

$\phi$ - curvature

$P$ - applied load

$\delta_u$ - deflection at the center

$L$ - length of the beam

$I$ - moment of inertia of cracked section

$b_f$ - breadth of the laminate

$h$ - thickness of the laminate

**Figure 5.31** Moment vs curvature plot for laminates reinforced with weld mesh of volume fraction 0.586% for different replacement levels of fly ash
Figure 5.32 Moment vs curvature plot for laminates reinforced with weld mesh of volume fraction 1.174% for different replacement levels of fly ash

Figure 5.33 Moment vs curvature plot for laminates reinforced with weld mesh of volume fraction 1.761% for different replacement levels of fly ash
Figure 5.34  Moment vs curvature plot for laminates reinforced with weld mesh of volume fraction 2.348% for different replacement levels of fly ash

Figure 5.35  Moment vs curvature plot for laminates reinforced with chicken mesh of volume fraction 0.943% for different replacement levels of fly ash
Figure 5.36  Moment vs curvature plot for laminates reinforced with chicken mesh of volume fraction 1.88% for different replacement levels of fly ash

Figure 5.37  Moment vs curvature plot for laminates reinforced with chicken mesh of volume fraction 2.823% for different replacement levels of fly ash
Figure 5.38  Moment vs curvature plot for laminates reinforced with chicken mesh of volume fraction 3.77% for different replacement levels of fly ash

Figures 5.31 and Figure 5.35 show the moment curvature curves for specimens with weld mesh of volume fraction 0.586% and chicken mesh of volume fraction 0.943% respectively. It is linearly elastic up to the 0.08kN.m, 0.113kN.m, 0.06kN.m, 0.08kN.m for specimens 1FW0, 1FWFA20SF, 1FC0 and 1FCFA20SF respectively.

Figures 5.32 and Figure 5.36 show the moment curvature curves for specimens reinforced with weld mesh of volume fraction 1.174% and chicken mesh of volume fraction 1.880%. The curve was linear up to 0.127kN.m, 0.087kN.m, 0.093 kN.m, 0.087 kN.m for specimens 2FW0, 2FWFA20SF, 2FC0 and 2FCFA20SF. Thereafter the curve deviated from linearity gradually.

Figures 5.33 and Figure 5.37 show the moment curvature curves for specimens reinforced with weld mesh of volume fraction 1.761% and chicken
mesh of volume fraction 2.823%. The specimens 3FW0, 3FWFA20SF, 3FC0, 3FCFA20SF indicated the linearity up to a moment of 0.1kN.m, 0.14kN.m, 0.08kN.m and 0.1kN.m. It then began to curve towards yielding and attaining a maximum of 0.22kN.m, 0.28kN.m, 0.153kN.m and 0.193kN.m for 3FW0, 3FWFA20SF, 3FC0, 3FCFA20SF respectively.

Figures 5.34 and Figure 5.38 show the moment curvature curves for specimens reinforced with weld mesh of volume fraction 2.348% and chicken mesh of volume fraction 3.77%. Initially, as moment increased, curvature also increased linearly up to about 0.16kN.m, 0.11kN.m, 0.11kN.m, 0.09kN.m for 4FW0, 4FWFA20SF, 4FC0, 4FCFA20SF. At that point, there was indication of cracks in the specimen. The moment continued to increase, because meshes started carrying additional loads and the slope of the curve became less steep towards its yield point.

From the moment curvature curves, it is noted that the ultimate moment carrying capacity of specimen 4FWFA20SF reached a maximum moment of intensity 0.35kN.m and specimen 4FCFA20SF reinforced with chicken mesh reached a maximum value of 0.24kN.m.

5.3.9 Mode of Failure

Flexural failure pattern was observed in all specimens. Most of the cracks were generated near the center and with an increase in loads, multiple cracks were generated at different locations. The failure patterns of ferrocement laminates are shown in Figure 5.39. The specimens reinforced with weld mesh of volume fraction 0.586% and chicken mesh of volume fraction 0.943% showed a single major failure crack forming in the pure moment region of the specimen.
Specimens reinforced with weld mesh of volume fraction 1.174% and chicken mesh of volume fraction 1.880% showed a formation of parallel cracks with respect to vertical direction in the middle of the specimen.

Figure 5.39 Failure pattern of ferrocement laminates
The ferrocement specimens of optimized mortar reinforced with weld mesh of volume fraction 1.761% and 2.348% were used for flexural strengthening of R.C beams in this study. The chosen weld mesh satisfies the general requirements for ferrocement applications. Square welded wire meshes perform better in bending than the other meshes (ACI 549 2R 1997). The above characteristics of weld mesh when used as mesh reinforcement are expected to influence the behavior of ferrocement panels under various loading conditions. Hence the weld mesh was used for flexural strengthening of R.C beams.

An overall assessment by considering properties like the maximum first crack load, ultimate load, deflection, crack formation and energy absorption led to the conclusion that the specimens reinforced with galvanized square weld mesh of volume fraction 2.348% and chicken mesh of volume fraction 3.770% performed well and they can be used for producing high strength ferrocement laminates suitable for structural repair/retrofit of concrete elements. The high strength ferrocement laminates thus developed can be considered as promising material for maintenance and rehabilitation of concrete structures.

5.4 IMPACT RESISTANCE OF FERROCEMENT LAMINATES

The impact test results presented are based on the experimental investigation conducted on ferrocement specimens of size 300 mm x300 mm x25 mm reinforced with weld mesh of volume fraction 1.761% and 2.348% and chicken mesh of volume fraction 2.823% and 3.770%. Impact resistance, regarding energy absorbed for initiation of crack and failure are given for two support conditions (simply supported and sand bed condition). The ferrocement laminates under sand bed condition can be used for applications
like small canal lining, open terrace roof finish, tunnel lining and pavement slab etc. (sakthivel et al 2012).

5.4.1 Simply Supported Condition

The impact energy is calculated using the equation 5.7 based on (Jagannathan et al 2005).

\[
\text{Impact energy absorption in Joules} = n \times W \times h_1 \times 9.81 \quad (5.7)
\]

where 
- \( n \) - number of blows
- \( W \) - weight in kg
- \( h_1 \) - drop height in metres

There were increases in energy absorption of 40% and 30% at initial and at failure for the 3IWFA20SFSS specimen reinforced with weld mesh of volume fraction 1.761% compared to 3IW0SS specimen. There were increases in energy absorption of 29% and 65% at initial and at failure for the 3ICFA20SFSS specimen reinforced with chicken mesh of volume fraction 2.823% compared to 3IC0SS. The results are shown in Figures 5.40 and 5.41.

There were increases in energy absorption of 57% and 45% at initial and at failure for 4IWFA20SFSS specimen reinforced with weld mesh of volume fraction 2.348% compared to 4IW0SS. There were increases in energy absorption of 36% and 40% at initial and a failure for 4ICFA20SFSS reinforced with chicken mesh of volume fraction 3.770% compared to 4IC0SS specimen. The results are shown in Figures 5.42 and 5.43.
Figure 5.40 Variation of initial and final energy absorption for specimen reinforced with weld mesh (\(V_r=1.761\%\)) under simply supported condition.

Figure 5.41 Variation of initial and final energy absorption for specimen reinforced with chicken mesh (\(V_r=2.823\%\)) under simply supported condition.
Figure 5.42  Variation of initial and final energy absorption of specimen reinforced with weld mesh ($V_r = 2.348\%$) under simply supported condition.

Figure 5.43  Variation of initial and final energy absorption for specimen reinforced with chicken mesh ($V_r = 3.770\%$) under simply supported condition.
5.4.2 Sand Bed Condition

There was 69% and 33% increase in energy absorption at initial and at failure for 3IWFA20SFSB specimen reinforced with weld mesh of volume fraction 1.761% compared to 3IW0SB specimen. There was an increase in energy absorption 86% and 30% at initial and at failure for 3ICFA20SFSB specimens reinforced with chicken mesh of volume fraction 2.823% compared to 3IC0SB specimen. The results are shown in Figures 5.44 and 5.45.

There was an increase in energy absorption 42% and 22% at initial and at failure for 4IWFA20SFSB specimens reinforced with weld mesh of volume fraction 2.348% compared to 4IW0SB. There was an increase in energy absorption 95% and 38% at initial and a failure for 4ICFA20SFSB reinforced with chicken mesh of volume fraction 3.770% compared to 4IC0SB. The results are shown in Figures 5.46 and 5.47.

![Figure 5.44 Variation of initial and final energy absorption of specimen reinforced with weld mesh (V_r =1.761%) under sand bed condition.](image-url)
Figure 5.45  Variation of initial and final energy absorption of specimen reinforced with chicken mesh ($V_r=2.823\%$) under sand bed condition.

Figure 5.46  Variation of initial and final energy absorption of specimen reinforced with weld mesh ($V_r=2.348\%$) under sand bed condition.
Impact resistance under sand bed condition is higher than in the case of simply supported condition for all specimens, irrespective of the number of layers and type of mesh reinforcement used. There was an increase in energy absorption capacity with increase in volume fraction of mesh. This was due to the larger area of load transfer. Four layers of mesh were highly effective, with respect to the final energy absorbed for both meshes. While increasing mesh layers from 3 to 4, a positive jump in values for 4 layers showing effective energy absorption was observed and spalling area was smaller.

5.4.3 Failure Pattern

It was observed during testing that all the ferrocement specimens exhibited localized failure at the point of contact of the drop weight and that no fragments were detached from the specimens as the various layers of mesh
reinforcement held different fragments together. It can thus be inferred that meshes used as reinforcement play a major role in not only improving impact energy absorption, but also help to hold the various fragments together after the occurrence of full damage in the specimens due to impact loading. The failure patterns of bottom face of the laminates are shown in Figure 5.48.
From an overall assessment, higher impact resistance is obtained for sand bed condition. Thus, it can be inferred that the impact resistance is maximum for specimens with optimum replacement mortar reinforced with a galvanized weld mesh of volume fraction 2.348% and chicken mesh of volume fraction 3.770%. This was due to the better bonding property of mesh with optimized mortar matrix.

5.5 FLEXURAL STRENGTHENING OF R.C BEAMS WITH FERROCEMENT LAMINATES

The experimental results of control beam and strengthened beam with ferrocement laminates are discussed. Their behaviour throughout the static test to failure is described using recorded data on deflection behaviour and ultimate load carrying capacity.

5.5.1 First Crack Load

The first crack load of all the beams was observed and is shown in Figure 5.49. The increase in first crack load of all the strengthened beams with respect to control beam is shown in Figure 5.50. The first crack load for the beam SB1 was found to be 28kN increasing by 22%, 25%, 32% and 64% for beams SB3CM, SB3BM, SB4CM and SB4BM respectively compared to CB beam.
Figure 5.49 Comparison of first crack load for control beam and strengthened beam

Figure 5.50 Percentage increase in first crack load of strengthened beams
The first crack load of SB3BM beam was increased by 8% compared to SB3CM beam. The first crack load of the SB4BM was increased by 24% regarding SB4CM. This increase can be attributed to flexural rigidity of strengthened beams. It is thus clear that strengthening by ferrocement laminates with optimized mortar has beneficial effect even at the first cracking stage.

5.5.2 Ultimate Load

The ultimate load carrying capacity of the control beam and strengthened beams were found and shown in Figure 5.51. The increase in ultimate load of all the strengthened beams with respect to control beam is shown in Figure 5.52. The ultimate load for CB beam was found to be 68kN. It was increased by 36%, 40%, 58% and 95% for beam SB3CM, SB3BM, SB4CM and SB4BM as compared to the CB beam. The ultimate load of SB3BM beam was increased by 36% compared to SB3CM beam. The ultimate load of SB4BM beam was increased by 31% with respect to SB4CM. The use of ferrocement laminate delayed initial cracks and any further crack development in the beam. Ferrocement laminate can be used to enhance flexural capacity of beams and to strengthen existing flexural members for increased flexural loads. The ultimate load of the strengthened beam was increased with increase in volume fraction of the mesh.
Figure 5.51 Comparison of ultimate load for control beam and strengthened beam

Figure 5.52 Percentage increase in ultimate load of strengthened beam
5.5.3 Load Deflection Characteristics

The load deflection of all the beams was recorded. The mid span deflection of each beam was compared with that of their respective control beams. It was noted that the behaviour of flexure when strengthened with ferrocement optimized blended mortar laminates was better than the corresponding conventional mortar beams. The mid span deflection was much lower when strengthened with ferrocement optimum blended mortar laminate with weld mesh of volume fraction 2.348%. The load deflection behavior of beams in flexure is shown in Figure 5.53. The use of ferrocement laminates delayed crack formation. The load deflection curves of all the beams were linear upto the first crack load and then the curve deviated from linearity upto the ultimate load.

At a load of 28kN, initial crack started appearing on the CB beam. With further increase in load, crack propagation took place. At the load of 60kN, the beam completely failed in flexure. For beam SB3CM, at a load of 34.2kN initial cracks appeared and reached an ultimate load of 81.5kN which is greater than that of beam CB. For beam SB3BM, at a load of 35.1kN, initial cracks started appearing and reached a greater ultimate load of 84.2kN compared to both beams CB and SB3CM. For beam SB4CM, at a load of 37kN initial cracks appeared and reached an ultimate load of 95kN which is greater than that of beam CB. For beam SB4BM, initial cracks started at 46kN and reached the greater ultimate load of 117kN compared to both beams CB and SB4CM. The descending order of the beams on the basis of deflection undergone was CB, SB3CM, SB3BM, SB4CM and SB4BM. Of these deflection undergone by the beam CB was the highest.
5.5.4 General Failure Characteristics

The reinforced concrete control beam failed due to yielding of tension steel followed by crushing of concrete at mid span. After failure, flexural cracks were observed in the beam throughout the span length. The typical appearance of control beam and strengthened beams after failure are shown in Figure 5.54. Flexural cracks observed were initiated randomly in the constant moment region. As the load was increased, cracks were observed along the entire length of the beam. The initial cracks started at higher load for beam SB4BM compared to CB and SB4CM. With further increase in loading, crack
propagation took place. Finally, the beam failure happened after flexure and crushing of concrete. In strengthening of beams till the failure, it has not delaminated. It is found to be intact. The difference in load deflection curves shows compatibility between RC beams and laminated beams. The application of ferrocement layer has given adequate confinement for the reinforced concrete beams. A flexible epoxy bonding system ensured that bond line in strengthened beam participated fully in the structural resistance of the strengthened beams and did not break before failure.

Figure 5.54 Crack pattern of control beam and strengthened beam
5.5.5  **Energy Absorption Capacity**

The energy absorption was calculated from the area under the load deflection curve. The beam SB3CM and SB4CM had 27% and 39% increase in energy absorption compared to control beam. The beam SB3BM had 35% and 65% increase in energy absorption compared to CB and SB3CM. Beam SB4BM had 41% and 21% increase in energy absorption compared to CB and SB4CM. The variation of energy absorption capacity with a specimen is shown in Figure 5.55. The increase in percentage of energy absorption capacity with respect to control beam is shown in Figure 5.56.

![Figure 5.55](image)

**Figure 5.55** Comparison of energy absorption for control beam and strengthened beam
Figure 5.56 Percentage increase in energy absorption of strengthened beam

5.5.6 Ductility Factor

The ductility factor is calculated based on the equation 5.1. The beam SB3CM and SB4CM had 9% and 34% increase in ductility factor compared to control beam. The beam SB3BM had 27% and 16% increase in ductility factor compared to CB and SB3CM. The beam SB4BM had 49% and 10% increase in ductility factor compared to CB and SB4CM. The variation of ductility factor is shown in Figure 5.57. The increase in percentage of ductility factor with respect to control beam is shown in Figure 5.58.
Figure 5.57 Comparison of ductility factor for control beam and strengthened beam

Figure 5.58 Percentage increase in ductility factor of strengthened beam

5.6.7 Overall Performance of Beams
The overall performance of beams is defined as the ratio of elastic forces in strengthened beam to that of control beam. The effectiveness factor of strengthened beams is shown in Figures 5.59 and 5.60 for energy approach and deflection approach, respectively.

The overall performance of the strengthened beams was evaluated by considering the equivalent elastic forces using energy and deflection approaches based on the equations arrived by (Rajkumar D et al 2010). The equivalent elastic forces $P_{e1}$ and $P_{e2}$ are computed from equations (5.8) and (5.9). The effectiveness factor $F_1$ and $F_2$ is computed from equations (5.10) and (5.11). The results are presented in Table 5.1.

\[
P_{e1} = \sqrt{\left(2A_e P_y \right)/\delta_y} \tag{5.8}
\]

\[
P_{e2} = P_y \left[ \frac{\delta_y}{\delta_y} \right] \tag{5.9}
\]

\[
F_1 = \frac{P_{e1(\text{strengthened})}}{P_{e1(\text{control})}} \tag{5.10}
\]

\[
F_2 = \frac{P_{e2(\text{strengthened})}}{P_{e2(\text{control})}} \tag{5.11}
\]

where,

$P_y$ - load on control beam at yield stage

$P_{e1(\text{control})}$ - equivalent elastic force of control beam using energy approach

$P_{e1(\text{strengthened})}$ - equivalent elastic force of strengthened beam using energy approach

$P_{e2(\text{control})}$ - equivalent elastic force of control beam using deflection approach
$$P_{e2(strengthened)}$$ - equivalent elastic force of strengthened beam using deflection approach

\(\delta_y\) - deflection of control beam at yield stage

\(\delta_u\) - deflection of control beam at ultimate stage

\(A_e\) - equivalent area

\(F_1\) - effectiveness factor by energy approach

\(F_2\) - effectiveness factor by deflection approach

The effectiveness factor of SB3BM beam when compared to SB3CM had 26% increase, based on energy approach and 34% increase based on deflection approach respectively. The effectiveness factor of the SB4BM compared to SB4CM had 46% increase based on energy approach and had 54% increase based on deflection approach respectively.

**Table 5.1 Effectiveness factor for control and strengthened beams**

<table>
<thead>
<tr>
<th>Beam designation</th>
<th>(A_e) mm²</th>
<th>(P_y) kN</th>
<th>(\delta_y) mm</th>
<th>(\delta_u) mm</th>
<th>(P_{e1}) kN</th>
<th>(P_{e2}) kN</th>
<th>(F_1)</th>
<th>(F_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>320</td>
<td>28</td>
<td>3.7</td>
<td>8</td>
<td>69.59</td>
<td>60.54</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>SB3CM</td>
<td>416</td>
<td>34.2</td>
<td>3.3</td>
<td>7.8</td>
<td>92.86</td>
<td>80.84</td>
<td>1.33</td>
<td>1.34</td>
</tr>
<tr>
<td>SB3BM</td>
<td>432.2</td>
<td>35.1</td>
<td>2.8</td>
<td>7.7</td>
<td>104.09</td>
<td>96.53</td>
<td>1.50</td>
<td>1.59</td>
</tr>
<tr>
<td>SB4CM</td>
<td>443.33</td>
<td>37</td>
<td>2.4</td>
<td>7.0</td>
<td>116.92</td>
<td>107.92</td>
<td>1.68</td>
<td>1.78</td>
</tr>
<tr>
<td>SB4BM</td>
<td>452.4</td>
<td>46</td>
<td>1.8</td>
<td>5.8</td>
<td>152.06</td>
<td>148.22</td>
<td>2.19</td>
<td>2.45</td>
</tr>
</tbody>
</table>
Figure 5.59 Comparison of effectiveness factor for control beam and strengthened beam by energy approach ($F_1$)

Figure 5.60 Comparison of effectiveness factor for control beam and strengthened beam by deflection approach ($F_2$)
Results from the test program showed that the ferrocement laminate with optimized mortar reinforced with the volume fraction of 2.348% was ideally suited for beam strengthening. The flexural capacity of beams was enhanced by using the optimized ferrocement laminate and hence to strengthen existing flexural members for increased flexural loads and so this method can be considered and adopted. The increasing availability of fly ash and silica fume provided a new opportunity for ferrocement to further expand its range of applications to new and undeveloped areas. Strengthening may be needed if additional mechanical equipment, filing systems, planters are added to the structure to improve the resistance to blast loading and due to a deficiency in the structure’s ability to carry the original design loads.

5.6 ANALYTICAL INVESTIGATION ON FERROCEMENT LAMINATES

The analytical model developed to compare the experimental ultimate moment of ferrocement laminates, reinforced separately with weld mesh and chicken mesh in flexure is now considered. Two methods were derived based on elastic theory and plastic analysis. The comparison results are plotted in Figures 5.61, 5.62, 5.63 and 5.64. From the comparison, it is clear that both elastic and plastic analysis methods fairly estimate the ultimate moment of the ferrocement specimens within ±20% variation in the calculated moment. It can be seen that calculated values are in close agreement with experimental values.
Figure 5.61  Comparison graph for weld mesh using plastic method

Figure 5.62  Comparison graph for chicken mesh using plastic method
From Figure 5.61 and Figure 5.63 the ultimate moments computed by plastic and elastic analysis, for ferrocement specimens reinforced with weld mesh of volume fraction 0.586, 1.174%, 1.761% and 2.348% are within 20% accuracy. Figure 5.62 and Figure 5.64 conveys that the ultimate
moments computed by plastic and elastic analysis for ferrocement specimens reinforced with chicken mesh of volume fraction and 0.943, 1.88%, 2.823% and 3.77% are within 20% accuracy. Calculation of ultimate moment of specimen 4FWFA20SF (4 layers of weld mesh with 20% fly ash and 5% silica fume) for plastic method and calculation of ultimate moment of specimen 4FWFA20SF (4 layers of weld mesh with 20% fly ash and 5% silica fume) for elastic method are presented in Appendix 2 and Appendix 3 respectively.

The ultimate moment carrying capacity of the ferrocement laminates determined by theoretical model developed by both elastic and plastic analysis matching with experimental results with ±20% variation.

5.7 ANALYTICAL INVESTIGATION ON FLEXURAL STRENGTHENING OF R.C BEAMS

The ultimate moment carrying capacity of the control beam and beams strengthened with ferrocement laminates obtained experimentally was compared with ultimate moment capacity calculated analytically. The proposed method is based on the elastic approach. The comparison results are presented in Figures 5.65. Therefore, the equation for finding ultimate moment carrying capacity of the control beam and strengthened beams were developed and validated with the experimental results. Calculation of ultimate moment of beam SB3BM (Beam with 20% fly ash together with constant 5% silica fume mortar laminate) is presented in Appendix 4.
Figure 5.65 Comparison of experimental moment with analytical moment