CHAPTER 9

TEST RESULTS AND DISCUSSIONS

9.1 GENERAL

Test methods used to study the characteristics of fresh concrete include slump flow test, U – box, V – funnel and L – box test. These tests had been conducted to determine the filling ability, passing ability and resistance to segregation of the SCC mix.

9.2 FRESH CONCRETE

Test methods used to study the characteristics of fresh concrete include slump test, U – box V – funnel and L – Box. These tests had been conducted to determine the filling ability, passing ability and resistance to segregation of the SCC mix. The results of workability tests on fresh SCC mixes M1 to M8 are listed in Table A1.1 to Table A1.8 in the appendix.

Without steel fibres, for mix M4 with 100 % sand + 0 % copper slag, the slump flow was 665 mm and for mix M4 with 0 % sand + 100 % copper slag, the slump flow was 700 mm. With the addition of steel fibres, for mix M4 with 100 % sand + 0 % copper slag, the slump flow was 665 mm and for mix M4 with 0 % sand + 100 % copper slag, the slump flow reduced to 681 mm. The workability of SCC increases with the increase in copper slag percentage. Moderate bleeding without segregation was noticed for SCC mixes with 80 % to 100 % copper slag. Addition of steel fibres, reduced the flowability and passing ability but satisfying the suggested limits for SCC.
Copper slag has water absorption 0.28% and fine aggregate has water absorption 1.05%. Hence when the percentage of copper slag increases, the free water content in SCC mix also increases, resulting an increase in the workability of the concrete. The increase in free water content in the SCC mix could be the reason for the moderate bleeding noticed for SCC mixes with 80% to 100% of copper slag. The variation of workability for SCC mixes M1 to M8 with copper slag proportions without steel fibres is shown in Figure 9.1. The variation of workability for SCC mixes M1 to M8 with copper slag proportions and with steel fibres is shown in Figure 9.2

![Figure 9.1 Variation of workability with copper slag proportions for SCC mixes M1 to M8 (without steel fibres)](image-url)
9.3 HARDENED CONCRETE

9.3.1 Density

Figure 9.3 shows the variation of density of SCC mixes M1 to M8. Without steel fibres, for mix M4 with 100 % sand + 0 % copper slag, the density was 24.83 kN/m³ and for mix M4 with 0 % sand + 100 % copper slag, the density increased to 25.57 kN/m³.
Figure 9.3 Variation of density with copper slag proportions for SCC mixes M1 to M8 on 28th day in MPa (without steel fibres)

With the addition of steel fibres, for mix M4 with 100 % sand + 0 % copper slag, the density was 25.33 kN/m³ and for mix M4 with 0 % sand + 100 % copper slag, the density increased to 26.41 kN/m³. The variation of density with copper slag proportions for SCC mixes M1 to M8 with steel fibres is shown in Figure 9.4.

Due to the addition of steel fibres, the density of SCC mixes increase approximately 2% to 3.5%. Copper slag has a specific gravity of 3.68, higher than that of OPC (3.09) and fine aggregate (2.78), replacement of FA with copper slag leads to the increase in density of concrete cubes.
Figure 9.4 Variation of density with copper slag proportions for SCC mixes M1 to M8 on 28th day in MPa (with steel fibres)
9.3.2 Compressive Strength

Three cubes, each measuring 150 x 150 x 150 mm had been tested for each of the SCC mixes M1 to M8 to determine the compressive strength on 1, 3, 7, 14, 28, 56 and 90 days. Test results are given in Table A1.9 to Table A1.16 in the appendix.

Without steel fibres, for mix M4 with 100 % sand + 0 % copper slag, compressive strength on 28th day was 60.8 MPa. Replacing FA with copper slag, the compressive strength increased up to 65.73 MPa for Mix M4 with 70% sand and 30% copper slag. Compressive strength increased approximately by 8%. Further replacement of FA with copper slag resulted in reduction of compressive strength. For Mix M4 with 0% sand and 100% copper slag, the compressive strength was 49.72 MPa. The reduction in compressive strength was 18% when compared with the compressive strength of mix M4 with 100 % sand + 0 % copper slag. Figure 9.4 shows the variation of compressive strength of SCC mix M4 with different copper slag proportions. Table A1.9 to Table A1.16 in the appendix shows the variation of compressive strength of SCC mix M1 to M8 with different copper slag proportions (without steel fibres).
Figure 9.5 Variation of compressive strength with copper slag proportions for SCC Mix M4 (without steel fibres)

With the addition of steel fibres, for mix M4 with 100 % sand + 0 % copper slag, compressive strength on 28th day was 61.88 MPa. Replacing FA with copper slag, the compressive strength increased upto 64.81 MPa for Mix M4 with 70% sand and 30% copper slag. Compressive strength increased approximately by 5%. Further replacement of FA with copper slag resulted in reduction of compressive strength. For Mix M4 with 0% sand and 100% copper slag, the compressive strength was 53.92 MPa. The reduction in compressive strength was 13% when compared with the compressive strength of mix M4 with 100 % sand + 0 % copper slag. Figure 9.6 shows the variation of compressive strength of SCC mix M4 with different copper slag proportions. Table A1.9 to Table A1.16 in the appendix shows the variation
of compressive strength of SCC mix M1 to M8 with different copper slag proportions (with steel fibres).

![Graph showing variation of compressive strength with copper slag proportions for SCC Mix M4](image)

**Figure 9.6** Variation of compressive strength with copper slag proportions for SCC Mix M4 (with steel fibres)

When the percentage of copper slag increases, the free water content in SCC mix also increases. This may lead to reduction in compressive strength of the SCC cubes.
9.3.3 Flexural Strength

Three prisms, each measuring 100 x 100 x 500 mm had been tested for each of the SCC mixes M1 to M8 to determine the flexural strength on 1, 3, 7, 14, 28, 56 and 90 days. Test results are given in Table A1.17 and Table A1.24 in the appendix.

Without steel fibres, for mix M4 with 100 % sand + 0 % copper slag, flexural strength on 28th day was 5.63 MPa. Replacing FA with copper slag, the flexural strength increased up to 5.91 MPa for Mix M4 with 70% sand and 30% copper slag. Flexural strength increased approximately by 5%. Further replacement of FA with copper slag resulted in reduction of flexural strength. For Mix M4 with 0% sand and 100% copper slag, the flexural strength was 4.85 MPa. The reduction in flexural strength was 14% when compared with the flexural strength of mix M4 with 100 % sand + 0 % copper slag. Figure 9.7 shows the variation of flexural strength of SCC mix M4 with different copper slag proportions. Table A1.17 to Table A1.24 in the appendix shows the variation of flexural strength of SCC mix M1 to M8 with different copper slag proportions (without steel fibres).
Figure 9.7 Variation of flexural strength with copper slag proportions for SCC Mix M4 (without steel fibres)

With the addition of steel fibres, for mix M4 with 100 % sand + 0 % copper slag, flexural strength on 28th day was 5.70 MPa. Replacing FA with copper slag, the flexural strength increased up to 6.00 MPa for Mix M4 with 70% sand and 30% copper slag. Flexural strength increased approximately by 5.3%. Further replacement of FA with copper slag resulted in reduction of flexural strength. For Mix M4 with 0% sand and 100% copper slag, the flexural strength was 4.91 MPa. The reduction in flexural strength was 14% when compared with the flexural strength of mix M4 with 100 % sand + 0 % copper slag. Figure 9.8 shows the variation of flexural strength of SCC mix M4 with different copper slag proportions. Table A1.17 to Table A1.24 in the appendix shows the variation of flexural strength of SCC mix M1 to M8 with different copper slag proportions (with steel fibres).
9.3.4 Split Tensile Strength

Three cylinders, each measuring 150 mm diameter and 300 mm long had been tested for each of the SCC mixes M1 to M8 to determine the split tensile strength on 1, 3, 7, 14, 28, 56 and 90 days. Test results are given in Table A1.25 to Table A1.32 in the appendix.

Without steel fibres, for mix M4 with 100 % sand + 0 % copper slag, split tensile strength on 28th day was 4.96 MPa. Replacing FA with copper slag, the split tensile strength increased up to 5.09 MPa for Mix M4 with 70% sand and 30% copper slag. Split tensile strength increased approximately by 3%. Further replacement of FA with copper slag resulted in
reduction of split tensile strength. For Mix M4 with 0% sand and 100% copper slag, the split tensile strength was 4.19 MPa. The reduction in split tensile strength was 16% when compared with the split tensile strength of mix M4 with 100% sand + 0% copper slag. Figure 9.9 shows the variation of split tensile strength of SCC mix M4 with different copper slag proportions. Table A1.25 to Table A1.32 in the appendix shows the variation of split tensile strength of SCC mix M1 to M8 with different copper slag proportions (without steel fibres).

![Graph showing variation of split tensile strength with copper slag content](image)

**Figure 9.9 Variation of split tensile strength with copper slag proportions for SCC Mix M4 (without steel fibres)**

With the addition of steel fibres, for mix M4 with 100% sand + 0% copper slag, split tensile strength on 28th day was 4.78 MPa. Replacing FA with copper slag, the split tensile strength increased up to 4.88 MPa for
Mix M4 with 70% sand and 30% copper slag. Split tensile strength increased approximately by 2%. Further replacement of FA with copper slag resulted in reduction of split tensile strength. For Mix M4 with 0% sand and 100% copper slag, the split tensile strength was 4.15 MPa. The reduction in split tensile strength was 14% when compared with the split tensile strength of mix M4 with 100 % sand + 0 % copper slag. Figure 9.10 shows the variation of split tensile strength of SCC mix M4 with different copper slag proportions. Table A1.25 to Table A1.32 in the appendix shows the variation of flexural strength of SCC mix M1 to M8 with different copper slag proportions (with steel fibres).

![Figure 9.10 Variation of split tensile strength with copper slag proportions for SCC Mix M4 (with steel fibres)](image)
9.3.5 Static Modulus of Elasticity

Figure 9.11 Variation of static modulus of elasticity with copper slag proportions for SCC Mix M4 (without steel fibres)

Three cylinders, each measuring 150 mm diameter and 300 mm long had been tested for each of the SCC mixes M1 to M8 to determine the static modulus of elasticity on the 28\textsuperscript{th} day. Test results are given in Table A1.33 in the appendix.

Without steel fibres, for mix M4 with 100 % sand + 0 % copper slag, static modulus of elasticity on 28th day was 38522 MPa. Replacing FA with copper slag, the static modulus of elasticity reduces. For Mix M4 with
0% sand and 100% copper slag, the static modulus of elasticity was 24885 MPa. The reduction in static modulus of elasticity was 35% when compared with the static modulus of elasticity of mix M4 with 100% sand + 0% copper slag. Figure 9.11 shows the variation of static modulus of elasticity of SCC mix M4 with different copper slag proportions. Table A1.33 in the appendix shows the variation of static modulus of elasticity of SCC mix M1 to M8 with different copper slag proportions (without steel fibres).

![Graph showing variation of static modulus of elasticity with copper slag proportions for SCC Mix M4 (with steel fibres)](image)

**Figure 9.12 Variation of static modulus of elasticity with copper slag proportions for SCC Mix M4 (with steel fibres)**

With the addition of steel fibres, for mix M4 with 100% sand + 0% copper slag, static modulus of elasticity on 28th day was
29601 MPa. Replacing FA with copper slag, the static modulus of elasticity reduces. For Mix M4 with 0% sand and 100% copper slag, the static modulus of elasticity was 25582 MPa. The reduction in static modulus of elasticity was 14% when compared with the static modulus of elasticity of mix M4 with 100% sand + 0% copper slag. Figure 9.12 shows the variation of static modulus of elasticity of SCC mix M4 with different copper slag proportions. Table A1.33 shows the variation of static modulus of elasticity of SCC mix M1 to M8 with different copper slag proportions (with steel fibres).

The relationship between compressive strength and flexural strength for plain concrete is given by

\begin{align}
\text{IS 456 : 2000} & \quad f_b = 0.7 (f_{ck})^{0.5} \quad (9.1) \\
\text{ACI 363R97} & \quad f_b = 0.94 (f'_c)^{0.5} \quad (9.2) \\
\text{ACI 318-08} & \quad f_b = 0.62 (f'_c)^{0.5} \quad (9.3)
\end{align}

where \( f_b \) = average flexural strength in MPa

\( f_{ck} \) = average cube compressive strength in MPa

\( f'_c \) = average cylindrical compressive strength in MPa

From the present investigation, for SCC mix M4 with 100% sand and 0% copper slag, the following equation relates compressive strength and flexural strength.

\[ f_b = 0.897 (f_{ck})^{0.452} \quad (9.4) \]

The observed results from the investigation are within the predicted values. The relationship between compressive strength and flexural
strength for SCC mixes M1 to M8 without copper slag and without steel fibres is shown in Figure 9.13.

\[ f_b = 0.868 (f_{ck})^{0.455} \]  \hspace{1cm} (9.5)

Figure 9.13 Variation of compressive strength with flexural strength for SCC Mix CM (M1 to M8) – without copper slag and without steel fibres

With the addition of steel fibres, from the present investigation, for SCC mix M4 with 100% sand and 0% copper slag, the following equation relates compressive strength and flexural strength.
The observed results from the investigation are within the predicted values. The relationship between compressive strength and flexural strength for SCC mixes M1 to M8 without copper slag and with steel fibres is shown in Figure 9.14

![Graph of compressive strength vs. flexural strength](image)

**Figure 9.14** Variation of compressive strength with flexural strength for SCC Mix CM (M1 to M8) – without copper slag and with steel fibres

The relationship between compressive strength and split tensile strength for plain concrete is given by

\[ f_{ct} = 0.7 \left( f_{ck} \right)^{0.5} \]  
\[ (9.6) \]

\[ f_{ct} = 0.59 \left( f'_{c} \right)^{0.5} \]  
\[ (9.7) \]
where \( f_{ct} \) = average split tensile strength in MPa

From the present investigation, for SCC mix M4 with 100% sand and 0% copper slag, the following equation relates compressive strength and split tensile strength.

\[
f_{ct} = 0.751 \left( f_{ck} \right)^{0.455}
\]

(9.8)

The observed results from the investigation are within the predicted values. The relationship between compressive strength and split tensile strength for SCC mixes M1 to M8 without copper slag and without steel fibres is shown in Figure 9.15.

![Graph showing the relationship between compressive strength and split tensile strength for SCC Mix CM (M1 to M8) without copper slag and without steel fibres.]

Figure 9.15 Variation of compressive strength with split tensile strength for SCC Mix CM (M1 to M8) – without copper slag and without steel fibres
With the addition of steel fibres, from the present investigation, for SCC mix M4 with 100% sand and 0% copper slag, the following equation relates compressive strength and split tensile strength.

\[ f_{ct} = 0.790 \left( f_{ck} \right)^{0.4371} \tag{9.9} \]

The relationship between compressive strength and split tensile strength for SCC mixes M1 to M8 without copper slag and with steel fibres is shown in Figure 9.16.

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**Figure 9.16**  Variation of compressive strength with split tensile strength for SCC Mix CM (M1 to M8) – without copper slag and with steel fibres
The static modulus of elasticity determines the behaviour of a material within the elastic region. It is affected by the quality of the mix, water-powder ratio, the type and quantity of the aggregates. The compressive strength of the mix influences the modulus of elasticity to a greater extent. For SCC mixes M1 to M8 without copper slag and without steel fibres, the relationship between static modulus of elasticity and the compressive strength is given in Figure 9.17 based on the experimental investigation.

\[ E = 3594.6f_{ck}^{0.5743} \]  
\( (9.10) \)

where \( E \) = Static modulus of elasticity in MPa  
\( f_{ck} \) = Cube compressive strength in MPa

The relationship between compressive strength and modulus of elasticity for SCC mixes M1 to M8 without copper slag and without steel fibres is shown in Figure 9.17
Figure 9.17 Variation of compressive strength with static modulus of elasticity for SCC Mix CM (M1 to M8) – without copper slag and without steel fibres

The static modulus of elasticity predicted by equation (9.10) differs very much with the relationship given by IS 456-2000, \( E = 5000\sqrt{f_{ck}}. \) This behaviour may be due to the slow development of cube compressive strength of the SCC mixes.

With the addition of steel fibres, the relationship between static modulus of elasticity and the compressive strength is given in Figure 9.18 based on the experimental investigation.

\[
E = 4275.7f_{ck}^{0.4781} \quad (9.11)
\]

where \( E = \) Static modulus of elasticity in MPa
\[ f_{ck} = \text{Cube compressive strength in MPa} \]

The relationship between compressive strength and static modulus of elasticity for SCC mixes M1 to M8 without copper slag and with steel fibres is shown in Figure 9.15.

**Figure 9.18** Variation of compressive strength with static modulus of elasticity for SCC Mix CM (M1 to M8) – without copper slag and with steel fibres.
9.4 DURABILITY

9.4.1 Resistance to Sulphuric Acid

Three cubes, each measuring 150 x 150 x 150 mm had been tested for each of the SCC mixes M1 to M8 to determine the decrease in compressive strength on the 28th day. Test results are given in Table A1.35 in the appendix.

Without steel fibres, for mix M4 with 100 % sand + 0 % copper slag, compressive strength on 28th day was 60.8 MPa (not immersed in 5\% concentrated H$_2$SO$_4$), 49.85MPa (after immersing in 5\% concentrated H$_2$SO$_4$). For mix M4 with 0 \% sand + 100 \% copper slag, compressive strength on 28th day was 49.72 MPa (not immersed in 5\% concentrated H$_2$SO$_4$), 37.54 MPa (after immersing in 5\% concentrated H$_2$SO$_4$).

With steel fibres, for mix M4 with 100 \% sand + 0 \% copper slag, compressive strength on 28th day was 61.88 MPa (not immersed in 5\% concentrated H$_2$SO$_4$), 50.12 MPa (after immersing in 5\% concentrated H$_2$SO$_4$). For mix M4 with 0 \% sand + 100 \% copper slag, compressive strength on 28th day was 53.92 MPa (not immersed in 5\% concentrated H$_2$SO$_4$), 41.12 MPa (after immersing in 5\% concentrated H$_2$SO$_4$).

9.4.2 Resistance to Hydrochloric Acid

Three cubes, each measuring 150 x 150 x 150 mm had been tested for each of the SCC mixes M1 to M8 to determine the decrease in compressive strength on the 28th day. Test results are given in Table A1.36 in the appendix.
Without steel fibres, for mix M4 with 100 % sand + 0 % copper slag, compressive strength on 28th day was 60.8 MPa (without immersing in 5% concentrated H$_2$SO$_4$), 48.25 MPa (after immersing in 5% concentrated HCl). For mix M4 with 0 % sand + 100 % copper slag, compressive strength on 28th day was 49.72 MPa (without immersing in 5% concentrated HCl), 36.84 MPa (after immersing in 5% concentrated HCl).

With steel fibres, for mix M4 with 100 % sand + 0 % copper slag, compressive strength on 28th day was 61.88 MPa (without immersing in 5% concentrated HCl), 49.28 MPa (after immersing in 5% concentrated HCl). For mix M4 with 0 % sand + 100 % copper slag, compressive strength on 28th day was 53.92 MPa (without immersing in 5% concentrated HCl), 37.88 MPa (after immersing in 5% concentrated HCl).

9.5 COST ANALYSIS

Cost analysis has been done for the SCC mixes without copper slag, developed in the current investigation, to get a better understanding of the work. This cost analysis has been made as per the rates presently existing in Coimbatore. The following rates are considered in arriving final cost of each SCC mix.

Cost of cement  =  Rs 400 per bag

Cost of fly ash  =  Rs 1,000 per tonne

Cost of fine aggregate  =  Rs 1095/m$^3$ (Rs 3100/100cft)

Cost of coarse aggregate  =  Rs 810/m$^3$ (Rs 2300/100cft)

Cost of potable water  =  Rs 300/m$^3$
Cost of superplasticizer = Rs 400/litre
Cost of VMA = Rs 250/litre
Labour charges = 15% of the material cost
Transportation charges = Rs 7/m$^3$ per km. Charges have been worked out for 20 km as the transportation distance.
Operator’s profit = 40% of the material cost.

The cost analysis of the SCC mixes without copper slag is shown in Table A1.37 in the appendix.

9.6 CONCLUSIONS

The tested results are tabulated from Table A1.9 to Table A1.36 in the appendix. Based on the test results, the conclusions arrived are presented in the next chapter.