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Studies on High Strength Self-Compacting Concrete With Copper Slag

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Abstract

This paper presents the results of an experimental investigation on the use of copper slag as a replacement of fine aggregate in High Strength Self-Compacting Concrete (SCC). The ten series of tests, involving various copper slag proportions ranging from 0% to 100% were used to prepare SCC specimens. Test procedures selected to verify the characteristics of SCC in fresh state include Abrams slump flow, L – Box, U – tube and V – funnel test. Properties of SCC in hardened state like density, compressive, flexural, split tensile strength and modulus of elasticity were studied. Test Results show an increase in workability, compressive and flexural strength with increase in copper slag percentage. Copper slag up to 30% replacement as fine aggregate resulted in an increase of 11% in compressive strength, 5% in flexural strength and 16% in split tensile strength when compared with that of control mix. The above strengths reduced on further additions of copper slag. Results indicate that copper slag can be effectively used as a fine aggregate replacement in producing sustainable durable self-compacting concrete.

Keywords: Self-compacting concrete, workability, segregation, strength, filling ability, passing ability, water-powder ratio, recycled aggregates, fly ash, copper slag

Introduction

The construction of modern and complicated civil engineering structures has become a part of today's fast developing world. Concrete known for its high compressive strength, workability and durability plays a vital role in construction. In order to construct strong and durable structures, it is necessary to improve the performance of concrete. Continuous research is being done throughout the world to improve the

properties of concrete to meet the above challenges, leading to the invention of high performance concrete (HPC). Self-Compacting Concrete (SCC) is a high performance concrete that has very low viscosity and high resistance to segregation, doesn't require mechanical vibration during casting. Hence SCC has been widely accepted in the construction industry.

Copper slag is a by-product during the smelting and refining process of copper ore. It contains highly toxic elements like arsenic, barium, cadmium, copper, lead and zinc. Copper slag can release these elements into the environment causing pollution of soils, atmospheric air, surface waters and groundwater. Copper smelter releases copper selenium. They are highly toxic if present overabundant. They contaminate the soil in the vicinity of smelters, destroying the vegetation. For every ton of copper produced, roughly 3 tons of copper slag gets generated. Copper slag is used for several purposes, mainly for land filling and grid blasting. This process consumes about 15% to 20% of the slag generated [15]. Several researchers have already investigated the use of copper slag in the manufacture of cement mortar and concrete. Although there are research works on the use of copper slag as fine aggregate or coarse aggregate to manufacture concrete, there has been little research on using copper slag as fine aggregates particularly to manufacture SCC.

Research Significance

In the recent times, construction activity has increased several times in many parts of the world. Fast growth in the construction industry relies on the use of natural resources for infrastructure development. Large-scale production of portland cement and the rapid exploitation of the environment for aggregates in the last few decades, have a dramatic impact on the environment. This leads to change in climatic conditions, depletion of ground water table and irregular rain fall pattern. The availability of natural resources is reducing, slowing down the growth in construction activity.

In day to day life, several types of byproducts and waste materials are generated through commercial, industrial activities. These waste materials need to be effectively recycled or safely disposed. The utilization of such materials in concrete not only makes it economical but also helps in reducing disposal problems [13]. Hence a suitable technology is needed to know their optimum use in concrete. Utilizing these waste materials for the manufacture of SCC, makes SCC economical, reduces disposal problems and eliminates our dependence on new raw materials for the manufacture of SCC.

A fine example of using waste materials for the manufacture of concrete would be the use of copper slag. Khalifa S. Al-Jabri et al (2009) [12] investigated the use of copper slag as fine aggregate replacement in High Strength Concrete (HSC) and recommended that up to 40–50% (by weight of sand) of copper slag can be used as a replacement for fine aggregates in order to obtain a concrete with good strength and durability requirements and concluded that the use of copper slag as sand substitution improves strength and durability characteristics of HSC. Wei Wu et al (2010) [14] investigated the mechanical properties of high strength concrete incorporating copper

slag as a fine aggregate and concluded that less than 40% copper slag as sand substitution can achieve a high strength concrete that is comparable or better to the control mix, beyond which its strength properties decreased significantly. Ayano and Sakata [17] reported that the smaller size of copper slag particles cause longer delay in the setting time.

Several investigators reported that the compressive and split tensile strength of concrete specimens made with copper slag fine aggregate are almost the same as that of normal concrete or even significantly more than control mixtures [16]. The evaluation of the effects of copper slag aggregate on the sulfate attack resistance and the depth of carbonation shows no significant attack and slower rate of carbonation by using copper slag [15,17]. To utilize copper slag in large volumes in the manufacture of concrete, experiments were carried out to investigate the possible utilization of copper slag in concrete as partial replacement for fine aggregate upto 50%. Tests were carried out to determine the strength and durability properties. These investigations demonstrate that copper slag can be effectively used in concrete.

This study aims to develop an economical procedure for utilizing copper slag to produce SCC and its optimum dosage.

Experimental Program

In the present investigation, a self-compacting concrete mix, proportioned for a characteristic strength of 50 MPa had been studied with different proportions of copper slag ranging from 0% to 100%. Super plasticizer and viscosity modifying agent were used to obtain the SCC characters at fresh state. Density, compressive, tensile, flexural strength and modulus of elasticity of the SCC mix were investigated to determine the optimum proportion of copper slag that could be added to the SCC mix without affecting the workability and strength of the SCC mix.

Materials

Ordinary Portland cement OPC – 53 grade, confirming to ASTM C150 / C150M – 12[34] was used for casting the specimen. Locally available river sand with a maximum size of 4.75 mm, confirming to ASTM C33 / C33M – 13[31] was used as fine aggregate. Crushed blue granite, 12.5 mm size, angular shape confirming to ASTM C33 / C33M – 13 was used as coarse aggregate. Potable water as per ASTM C1602 / C1602M – 12[39], suitable for drinking was used for casting as well curing. A polycarboxylic ether based Superplasticizer – Glenium B233 and Viscosity Modifying agent – Glenium Stream II were used to improve the workability.

Cement

Ordinary Portland cement OPC – 53 grade with the following properties. Fineness (wt of residue) 7%, Specific Gravity 3.09, Initial setting time 35 min, Final setting time 235 min, Soundness 3.6 mm, Compressive Strength of 31.5 MPa on 3rd day, 46 MPa on 7th day, 58 MPa on 28th day.

Fine Aggregate
Natural river sand, Specific Gravity 2.78, Fineness Modulus 2.65, water absorption 1.05%, Density 2.3 gm/cm^3, Dry rodded Bulk Density 1610 kg/m^3, Loose Bulk Density 1430 kg/m^3, free from clay / organic matter.

Coarse Aggregate
Crushed blue granite, 12.5 mm size, angular shape, Specific Gravity 2.61, Fineness modulus 5.9, Dry rodded bulk density 1480 kg/m^3, Loose bulk density 1290 kg/m^3

Flyash
Specific Gravity 2.20, Passing through 75 micron sieve, fineness 290 m^2/kg, light grey in color, SiO_2 69.13%, Na_2O 0.36%, CaO 0.91%, Fe_2O_3 3.72 %, Al_2O_3 21.29%, K_2O 0.19%, SO_3 0.08%, MgO 3.82%

Copper Slag
Black in color, bulk density 2.25 gm/cm^3, Specific Gravity 3.68, water absorption 0.28%, fineness modulus 3.17, SiO_2 31.40%, Fe_2O_3 4.36%, CaO 54.25%, Al_2O_3 4.30%, MgO 2.41%, SO_3 1.79 %, K_2O 0.79%

Water
Potable water as per ASTM C1602 / C1602M – 12[39] specifications.

Super Plasticizer
Light brown Color with Specific Gravity 1.2, Relative Density at 25°C is 1.09 ± 0.0, Chloride iron content < 0.2%, pH > 6.

Viscosity Modifying Agent
Colorless free flowing liquid with Specific Gravity 1.2, Relative Density at 25°C is 1.01 ± 0.0, Chloride iron content < 0.2%, pH > 6.

Sieve analysis was conducted to obtain the gradation of sand and copper slag. Both materials satisfied the particle size requirements of zone 1 grading limits [40].

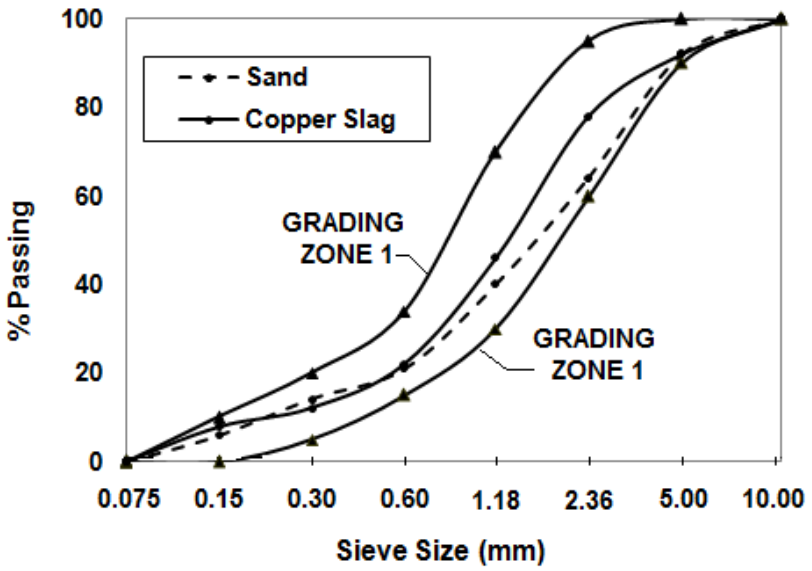

Figure 1: Sieve analysis of sand and copper slag

Mix Proportioning

The SCC mix had been proportioned for a characteristic strength of 50 MPa. The mix proportioning of SCC was obtained by changing the paste volume (i.e. powder and water content) with a constant volume of coarse and fine aggregate.

The four-stage mix design method for SCC has been developed at UPC, Spain is as follows.

- Determination of optimum super plasticizing dosage
- Determination of filler dosage
- Determination of the aggregate skeleton
- Determination of paste cement based on the requisites at self-compaction and strength.

The mix proportion was arrived based on the EFNARC guidelines. The coarse aggregate contains 8~10 mm and 12.5 mm in the ratio 9:6. The total powder content has been fixed in between 400-600 Kg/m^3. Water content generally does not exceed 200 lt/m^3. The mix design details of self-compacting concrete are given in Table 1

Table 1: Mix Proportioning of Self Compacting Concrete

Mix Proportioning of Self Compacting Concrete							
Cement	**Fly ash**	**Fine Aggregate**	**Coarse Aggregate**		**Water**	**Super Plasticizer**	**Viscosity Modifying Agent**
			8~10 mm	**12.5 mm**			
(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)	(kg/m^3)
372	**225**	**863**	**447**	**297**	**181**	**1.55**	**0.76**

Preparing and Casting the test specimens

To prepare the concrete mix, coarse aggregate was placed inside the concrete mixer followed by fine aggregate. Then 20% of the total quantity of water was added. The concrete mixer was allowed to rotate a few times after which fly ash and cement were added. Approximately 40% of the total quantity of water was poured into the concrete mixer and the materials were mixed for 1 minute. Superplasticizer and VMA were added to the remaining quantity of water and added to the mixer. Mixing was continued for another 2 minutes.

Tests on Fresh Concrete

After mixing, tests were conducted to determine the properties of fresh concrete as per EFNARC Guidelines. Slump flow test, L – Box test, U – Box test, V funnel test were used to evaluate the fresh concrete properties of SSC.

Curing The Specimen

After casting, the specimens were given a smooth finish with a steel trowel. The specimens were stored in room temperature approximately 26°C for 24 hours. After hardening, the specimens were demoulded, placed in potable water for curing. After necessary curing, specimens were taken out from the curing tank, allowed to dry and tested.

Tests on Hardened Concrete

After the necessary curing period, the concrete specimens were tested as follows.

Table 2: Test Details on Hardened Concrete

S. No	Type of test	Specimen details	Reference
1	Compressive strength (3^{rd}, 7^{th}, 14^{th}, 28^{th}, 56^{th} and 90^{th} days)	Cube – 150 x 150 x 150 mm	Tests carried out as per BS 1881: Part 116 [41]
2	Split tensile strength (3^{rd}, 7^{th}, 14^{th}, 28^{th}, 56^{th} and 90^{th} days)	Cylinder – 150 mm diameter and 300 mm long	Tests carried out as per ASTM C496-96 [37]
3	Flexural strength (3^{rd}, 7^{th}, 14^{th}, 28^{th}, 56^{th} and 90^{th} days)	Prism – 100x 100 x 500 mm	Tests carried out as per ASTM C78-94 [32]
4	Modulus of elasticity – on 28th day	Cylinder – 150 mm diameter and 300 mm long	Tests carried out as per ASTM C469-14 [36]
5	Change in density – on 28th day	Cube – 150 x 150 x 150 mm	-

Test Results and Discussion

Fresh Concrete

Test methods used to study the characteristics of fresh concrete include slump test, U – tube, 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 are listed in Table 3.

Table 3: Test results of fresh concrete properties of SCC

S. No	Detail	CM 100% S + 0% CS	M1 90% S + 10% CS	M2 80% S + 20% CS	M3 70% S + 30% CS	M4 60% S + 40% CS	M5 50% S + 50% CS	M6 40% S + 60% CS	M7 30% S + 70% CS	M8 20% S + 80% CS	M9 10% S + 90% CS	M10 0% S + 100% CS	Range
1	Slump flow by Abrams cone	665 mm	673 mm	675 mm	682 mm	684 mm	688 mm	690 mm	698 mm	699 mm	700 mm	700 mm	650 ~ 800 mm
2	T_{50cm} Slump flow	5 Sec	5 Sec	4 Sec	3 Sec	3 Sec	2 Sec	2 Sec	2 Sec	2 Sec	2 Sec	2 Sec	2 to 5 Sec
3	V funnel Test	13 Sec	10 Sec	10 Sec	10 Sec	8 Sec	8 Sec	7 Sec	7 Sec	7 Sec	7 Sec	7 Sec	8 to 12 Sec
4	V funnel at T_5 minutes)	16 Sec	13 Sec	13 Sec	12 Sec	11 Sec	10 Sec	9 Sec	9 Sec	9 Sec	9 Sec	9 Sec	0 to +3 Sec
5	L Box Test	0.79	0.84	0.83	0.87	0.89	0.9	0.91	0.91	0.91	0.91	0.91	h_2/h_1 = 0.8 to 1.0
6	U Box Test	27	26	26	24	24	23	21	21	21	21	21	$h_2 - h_1$ = 0 to 30 mm

CM = Control Mix (100% Sand + 0% Copper Slag), S = Sand, CS = Copper slag

Fig 2 shows the variation of slump flow with Copper Slag content. For the SCC mix **CM** (100 % sand, 0 % copper slag) the slump flow was 665 mm and for SCC mix **M10** (0 % sand, 100 % copper slag), the slump flow was 700 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.

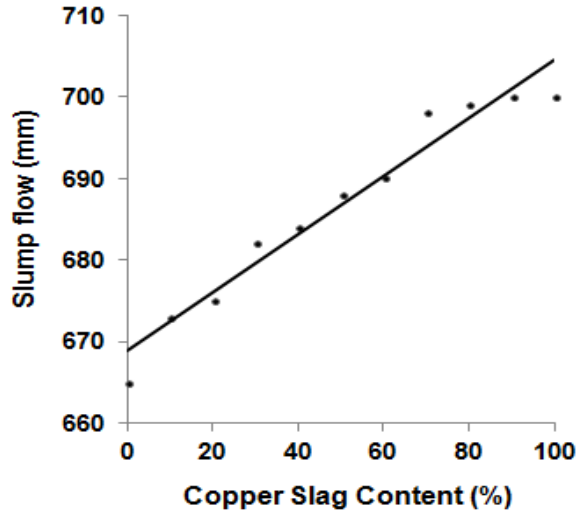

Figure 2: Variation of Workability with Copper Slag Proportions

Hardened Concrete

Density

The variation of the density of SCC with Copper Slag content is given in Table 4. For the SCC mix **CM** (100 % sand, 0 % copper slag), the density was 24.81 kN/m^3 and for SCC mix **M10** (0 % sand, 100 % copper slag), the density increased to 25.66 kN/m^3. The density of SCC increases with the increase in Copper Slag content. The density increased approximately by 4% when compared with the control mix.

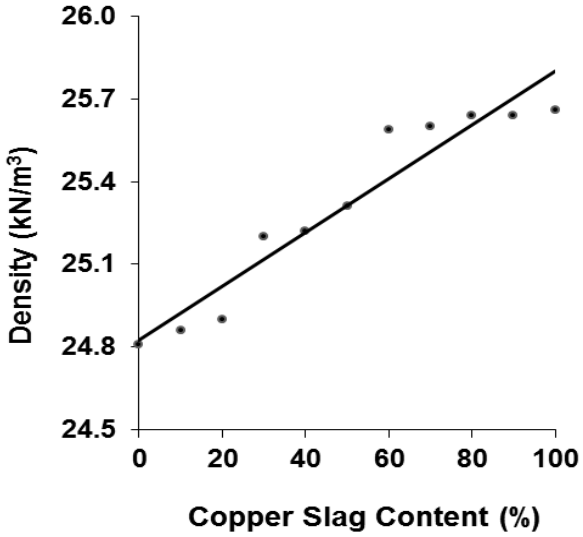

Figure 3: Variation of density of SCC with copper slag content

Table 4: Test results of hardened concrete property – Density of SCC

S. No	Detail	CM 100% S + 0% CS	M1 90% S + 10% CS	M2 80% S + 20% CS	M3 70% S + 30% CS	M4 60% S + 40% CS	M5 50% S + 50% CS	M6 40% S + 60% CS	M7 30% S + 70% CS	M8 20% S + 80% CS	M9 10% S + 90% CS	M10 0% S + 100% CS
1	Density @ 28 days (kN/m^3)	24.81	24.86	24.90	25.20	25.22	25.31	25.59	25.60	25.64	25.64	25.66

CM = Control Mix (100% Sand + 0% Copper Slag), S = Sand, CS = Copper slag

Compressive Strength

Three cubes, each measuring 150 x 150 x 150 mm had been tested for each mix to determine the compressive strength on 3, 7, 14, 28, 56 and 90 days. The compressive strength on 28th day for the control mix (100% sand and 0% copper slag) was 52.6 MPa. With the replacement of FA with copper slag, the compressive strength increased upto 55.8 MPa for Mix M3 (70% sand and 30% copper slag). Compressive strength increased approximately by 11%. Further replacement of FA with copper slag resulted in a reduction of compressive strength. For Mix M10 (0% sand and 100% copper slag), the compressive strength was 45.43 MPa. The reduction in compressive strength was 13% when compared with the control mix. The variation of compressive strength of SCC with Copper Slag content is given in Table 5.

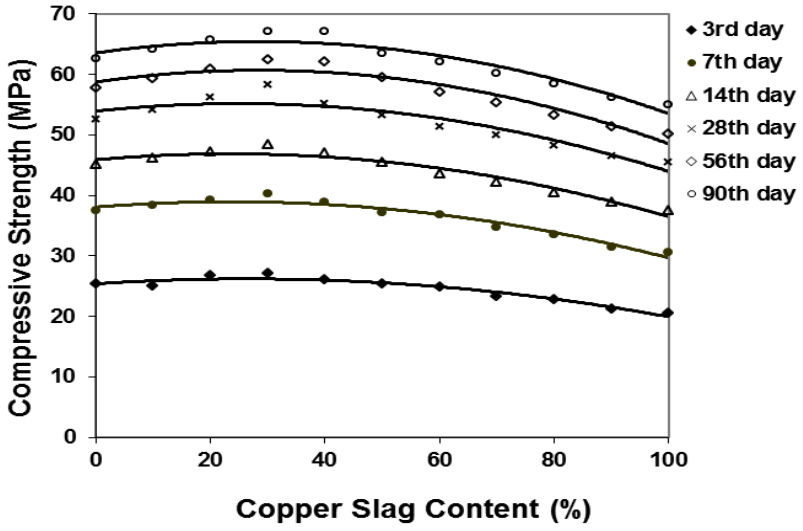

Figure 4: Variation of compressive strength of SCC with copper slag content

Table 5: Test results of hardened concrete property – Compressive strength of SCC

S. No	Detail	CM 100% S + 0% CS	M1 90% S + 10% CS	M2 80% S + 20% CS	M3 70% S + 30% CS	M4 60% S + 40% CS	M5 50% S + 50% CS	M6 40% S + 60% CS	M7 30% S + 70% CS	M8 20% S + 80% CS	M9 10% S + 90% CS	M10 0% S + 100% CS
1	Compressive Strength @ 28 days (MPa)	52.60	54.05	55.21	55.80	55.08	53.26	51.43	50.01	48.28	46.56	45.43

CM = Control Mix (100% Sand + 0% Copper Slag), S = Sand, CS = Copper slag

Flexural Strength

Three prisms, each measuring 100x 100 x 500 mm had been tested for each mix to determine the flexural strength on 3, 7, 14, 28, 56 and 90 days. The flexural strength on 28th day for the control mix (100% sand and 0% copper slag) was 9.24 MPa. With the replacement of FA with copper slag, the flexural strength increased upto 9.75 MPa for Mix M_3 (70% sand and 30% copper slag). Flexural strength increased approximately by 5%. Further replacement of FA with copper slag resulted in a reduction of flexural strength. For Mix M_{10} (0% sand and 100% copper slag), the flexural strength was 8.18 MPa. The reduction in flexural strength was 11% when compared with the control mix. The variation of flexural strength of SCC with Copper Slag content is given in Table 6.

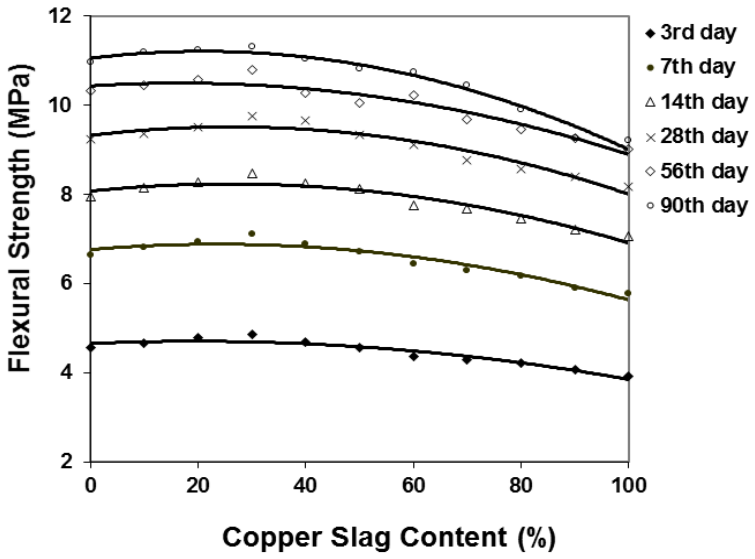

Figure 5: Variation of flexural strength of SCC with copper slag content

Table 6: Test results of hardened concrete property – Flexural strength of SCC

S. No	Detail	CM 100% S + 0% CS	M1 90% S + 10% CS	M2 80% S + 20% CS	M3 70% S + 30% CS	M4 60% S + 40% CS	M5 50% S + 50% CS	M6 40% S + 60% CS	M7 30% S + 70% CS	M8 20% S + 80% CS	M9 10% S + 90% CS	M10 0% S + 100% CS
1	Flexural Strength @ 28 days (MPa)	9.24	9.36	9.51	9.75	9.65	9.33	9.12	8.78	8.56	8.39	8.18

CM = Control Mix (100% Sand + 0% Copper Slag), S = Sand, CS = Copper slag

Split Tensile Strength

Three cylinders, each measuring 150 mm diameter and 300 mm long had been tested for each mix to determine the split tensile strength on 3, 7, 14, 28, 56 and 90 days. The split tensile strength on 28th day for the control mix (100% sand and 0% copper slag) was 4.58 MPa. With the replacement of FA with copper slag, the split tensile strength increased upto 5.34 MPa for Mix M_3 (70% sand and 30% copper slag). Split tensile strength increased approximately by 16%. Further replacement of FA with copper slag resulted in a reduction of split tensile strength. For Mix M_{10} (0% sand and 100% copper slag), the split tensile strength was 3.58 MPa. The reduction in split tensile strength was 21% when compared with the control mix. The variation of split tensile strength of SCC with Copper Slag content is given in Table 7.

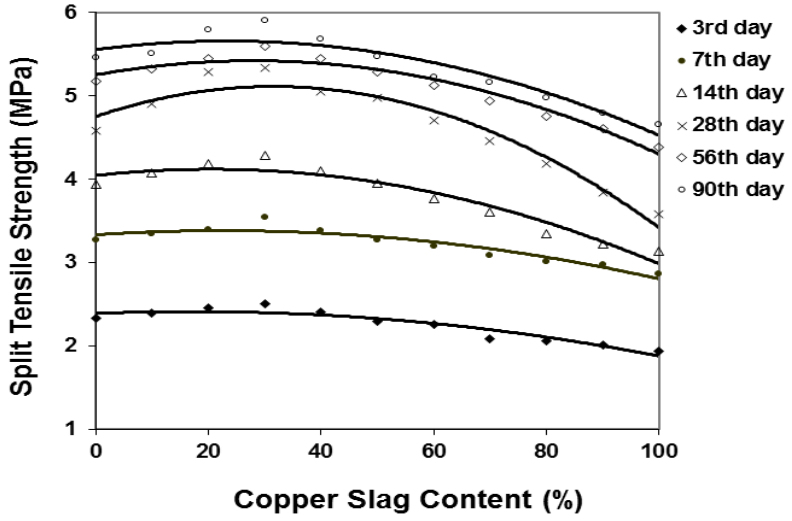

Figure 6: Variation of split tensile strength of SCC with copper slag content

Table 7: Test results of hardened concrete property – Split tensile strength of SCC

S. No	Detail	CM 100% S + 0% CS	M1 90% S + 10% CS	M2 80% S + 20% CS	M3 70% S + 30% CS	M4 60% S + 40% CS	M5 50% S + 50% CS	M6 40% S + 60% CS	M7 30% S + 70% CS	M8 20% S + 80% CS	M9 10% S + 90% CS	M10 0% S + 100% CS
1	Split Tensile Strength @ 28 days (MPa)	4.58	4.90	5.29	5.34	5.05	4.98	4.70	4.46	4.18	3.84	3.58

CM = Control Mix (100% Sand + 0% Copper Slag), S = Sand, CS = Copper slag

The variation of compressive strength and slump flow with Copper Slag content is shown in figure 7.

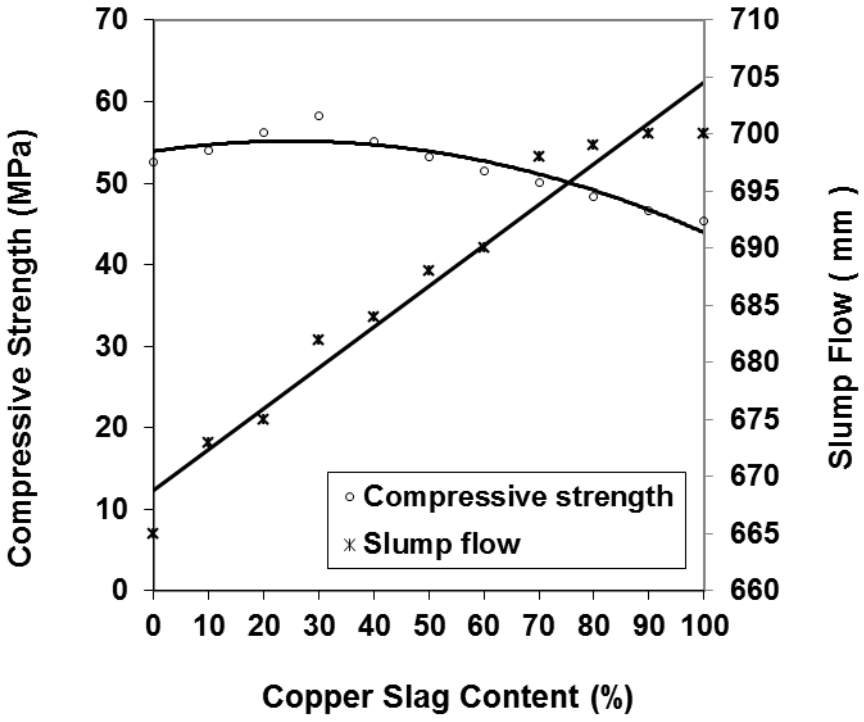

Figure 7: Variation of workability of SCC with copper slag content and compressive strength

Modulus of Elasticity

Three cylinders, each measuring 150 mm diameter and 300 mm long had been tested for each mix for determining the modulus of elasticity on 3, 7, 14, 28, 56 and 90 days.

The modulus elasticity on 28th day for the control mix (100% sand and 0% copper slag) was 33135 MPa. With the replacement of FA with copper slag, the modulus of elasticity increased upto 33613 MPa for Mix M_4 (60% sand and 40% copper slag).

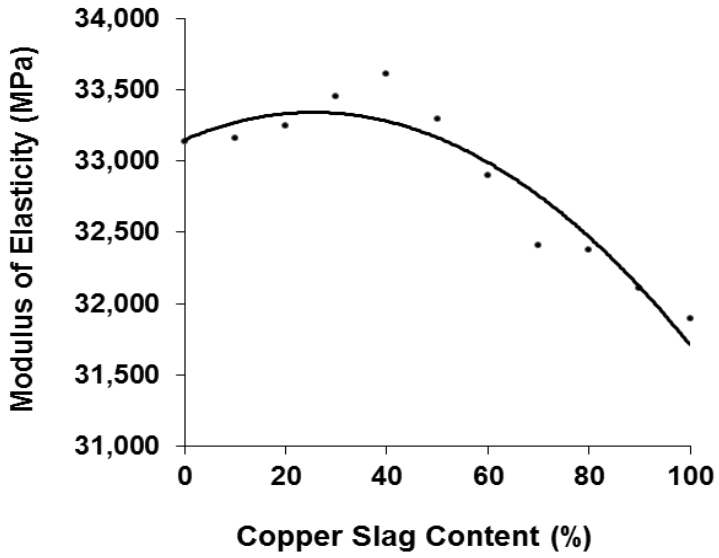

Figure 8: Variation of modulus of elasticity of SCC with copper slag content

Modulus of elasticity increased approximately by 1.5%. Further replacement of FA with copper slag resulted in a reduction of modulus of elasticity. For Mix M_{10} (0% sand and 100% copper slag), the modulus of elasticity was 31894 MPa. The reduction in modulus of elasticity was 4% when compared with the control mix. The variation of modulus of elasticity of SCC with Copper Slag content is given in Table 8.

Table 8: Test results of hardened property - Modulus of elasticity of SCC

S. No	Detail	CM 100% S + 0% CS	M1 90% S + 10% CS	M2 80% S + 20% CS	M3 70% S + 30% CS	M4 60% S + 40% CS	M5 50% S + 50% CS	M6 40% S + 60% CS	M7 30% S + 70% CS	M8 20% S + 80% CS	M9 10% S + 90% CS	M10 0% S + 100% CS
1	Modulus of Elasticity (MPa)	33135	33162	33245	33456	33613	33292	32896	32406	32375	32106	31894

CM = Control Mix (100% Sand + 0% Copper Slag), S = Sand, CS = Copper slag

Conclusions

Based on the experimental investigations, the following conclusions are drawn within the limitations of the test results.

- The test results of fresh concrete are within the limits of SCC i.e., flowability, passing ability and resistance against segregation. Moderate bleeding without segregation was noticed for SCC mixes with 80 % to 100 % copper slag.
- 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 increases, resulting an increase in the workability of the concrete. The workability increases with the increase in copper slag percentage as per Fig 2.
- 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.
- With the increase in copper slag percentage, the density of SCC increases as shown in Table 4. Copper slag has a specific gravity of 3.68, higher than that of OPC (3.09) and fine aggregate (2.78). Hence replacement of FA with copper slag leads to the production of SCC with higher density.
- Copper Slag up to 30% replacement as fine aggregate showed an increase of 11% in compressive strength, 5% in flexural strength and 16% in split tensile strength when compared with that of control mix. When copper slag is used in a concrete mix, it reacts with water, increasing Ca(OH)2 to form more calcium - silicate - hydrate (CSH) gel. The additional CSH densifies the concrete matrix, increasing the strength properties.
- Further additions of copper slag showed a decrease of the above strengths. When the percentage of copper slag increases, the free water content in SCC mix increases. This may lead to reduction in strength. Further research work may be undertaken with lesser water content particularly at higher copper slag proportions.
- The compressive, flexural and split tensile strengths of SCC increases, up to 30% addition of copper slag when compared with that of the control mix and further additions of copper slag showed a reduction in the above strengths as listed in Table 4. Hence 30% replacement of fine aggregate with copper slag may be considered as the optimum proportion for fine aggregate replacement.

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