Advances in Concrete Construction, *Vol. 6, No. 5 (2018) 545-560*
DOI: https://doi.org/10.12989/acc.2018.6.5.545

Copper or ferrous slag as substitutes for fine aggregates in concrete

Job Thomas*, Nassif N. Thaickavil[a] and Mathews P. Abraham[b]

Department of Civil Engineering, Cochin University of Science and Technology, Kochi, Kerala, India

(Received January 7, 2018, Revised October 24, 2018, Accepted October 25, 2018)

Abstract. The ever-increasing cost of natural sand and the environmental impacts of extracting manufactured sand (quarry sand) calls for exploring the potential to use alternative materials as fine aggregates in concrete. Copper slag and ferrous slag are industrial by products obtained from the smelting process of copper and iron respectively. A large quantity of copper slag and ferrous slag end up being disposed as waste in landfills and this poses a serious threat to the environment. Copper slag and ferrous slag have similar physical and chemical properties as natural sand and also exhibit pozzolanic activity. This paper studies the technical feasibility of industrial by-products such as copper slag and ferrous slag to replace the fine aggregate in concrete by evaluating the workability, strength and durability characteristics of concrete. The test results indicate that the strength properties are not affected by 40% or 100% replacement of quarry sand with iron slag or copper slag. However, 40% replacement of quarry sand with iron slag or copper slag in concrete is recommended considering the durability aspects of concrete.

Keywords: slag; concrete; replacement; strength; durability; fine aggregate

1. Introduction

Excessive mining of river sand for construction activities is a cause of serious environmental concern. The non-availability of natural sand and its increasing cost have led the construction industry to adopt alternate fine aggregate materials such as manufactured sand. Unrestricted quarrying for extracting aggregates causes quick depletion of naturally available resources and also results in large scale pollution of the environment. A sustainable solution for this problem is the utilization of waste materials to replace fine aggregates in concrete. Copper slag and ferrous slag are two industrial by-products having similar particle size and characteristics as that of natural sand.

Copper slag is a by-product material produced during the process of extracting copper from its ore. Around 33 million tonnes of copper slag is generated every year and India alone contributes around 6.0-6.5 million tonnes annually (Dash *et al.* 2016). Although copper slag is widely used in the sand blasting industry and in the manufacturing of abrasive tools, the balance is disposed off

∗Corresponding author, Professor, E-mail: job_thomas@cusat.ac.in
[a]Ph.D. Student
[b]Former M. Tech. Student

http://www.techno-press.org/?journal=acc&subpage=7 ISSN: 2287-5301 (Print), 2287-531X (Online)

without any further reuse or reclamation. Its excellent soundness characteristics, good abrasion resistance and good stability (Gorai *et al*. 2002) make it suitable for substituting fine aggregates in concrete.

Ferrous slag is another industrial by-product generated during the separation of the molten ferrous metal in steel-making furnaces. Ferrous slag constitutes about 15% of the total steel output (Patra and Mukharjee 2016) and India currently produces around 12 million tons of ferrous slag per annum (Indian Bureau of Mines 2015). Ferrous slag aggregates generally possess the desirable properties of soundness, strength, shape, abrasion resistance and gradation. Copper slag and ferrous slag are alternatives that have been considered for replacing sand in concrete.

The objective of this study is to evaluate the technical feasibility of using materials such as copper slag and ferrous slag to replace manufactured sand fine aggregates in concrete. The workability, strength and durability of concrete made with copper slag fine aggregates and ferrous slag fine aggregates are evaluated in this paper.

2. Literature review

Over the recent decades, intensive research has been carried out to explore the possibility of employing different industrial by-product materials including copper slag and ferrous slag as alternative fine aggregates in concrete. Mavroulidou (2017) investigated the effect of partial replacement as well as full replacement of fine aggregate in concrete with water cooled copper slag for two different water-cement ratios. It was reported that there was no significant effect on the strength of concrete whereas the durability was found to be similar to or better than the control mix in some cases.

Dhir *et al*. (2017) conducted a meta-analysis of the published literature on the use of copper slag as fine aggregate in concrete and studied the effects on consistence, strength, deformation resistance, permeation, durability, setting time and bleeding rate of concrete. It was observed that replacement of fine aggregates with up to 50% copper slag showed an improvement in the strength properties, modulus of elasticity, creep and shrinkage. It was reported that the addition of copper slag did not affect the durability properties of concrete except its acid resistance.

Al-Jabri *et al*. (2011) studied the effect of using copper slag as a fine aggregate on the properties of cement concrete of grade M30. The workability, density, compressive strength, tensile strength, and flexural strength of concrete with different proportions of copper slag ranging from 0% (for the control mixture) to 100% as fine aggregates replacement were evaluated. It was recommended that replacement of up to 40-50% of copper slag (by weight) of fine aggregates produced concrete with good strength and durability characteristics. Brindha *et al*. (2010) conducted investigations on M20 grade concrete by partially replacing sand with copper slag. The results of the compressive strength test and split tensile strength test indicated that the strength of concrete increases proportionally up to 40% replacement of sand with copper slag. Al-Jabri *et al*. (2009) investigated the performance of high strength concrete (M80) made with copper slag as a fine aggregate and recommended that 40% replacement of sand produces good quality high performance concrete.

Patra and Mukharjee (2017) investigated the effects of partial replacement of fine aggregate in concrete by granulated blast furnace slag (GBS) on the mechanical and durability properties of concrete. Three different fine aggregate replacement levels of 20%, 40% and 60% were considered. The compressive strength, modulus of elasticity and chloride penetration resistance were found to increase with the increase in percentage of GBS in the mix. Devi and Gnanavel (2014) studied the effect of partially replacing coarse and fine aggregates with steel slag on various strength and durability properties of M20 concrete and recommended that optimum percentage for replacement of fine aggregate is 40%. The strength and durability characteristics were found to be comparable to the control mix at 40% replacement of fine aggregate with steel slag. Khajuria and Siddique (2014) observed that the strength of concrete increased when 30% of the fine aggregates were replaced with iron slag. Hiraskar and Patil (2013) investigated the effect of using blast furnace slag as fine aggregates in concrete on the compressive strength, flexural strength and split tensile strength of concrete. The use of blast furnace slag as fine aggregates was recommended after concluding that the properties of blast furnace slag were similar to natural aggregates.

The possibility of using materials such as copper slag and ferrous slag as a partial replacement for fine aggregate in concrete has been investigated in different studies as indicated in the literature study. However studies on the potential of copper slag or ferrous slag to completely replace natural or manufactured sand in concrete are limited. Likewise, the durability aspects of concrete made with copper slag and ferrous slag also needs to be addressed. This paper explores the possibility of replacing the fine aggregate in concrete with alternative materials like copper slag and ferrous slag by studying the workability, strength and durability characteristics of concrete.

The novelty in this paper is the separate investigation and comparison of the effects of replacing manufactured sand fine aggregates with copper slag and ferrous slag on the strength and durability properties of normal concrete and high strength concrete.

3. Experimental investigation

The strength and durability of concrete specimens with copper slag and ferrous slag as fine aggregate replacement were studied separately. The strength parameters considered are compressive strength and split tensile strength. Sulphate attack test, sulphuric acid attack test, bulk diffusion test and rapid chloride permeability test were conducted to ascertain the durability characteristics. The variables considered in the study are grade of concrete and percentage replacement of fine aggregate.

3.1 Materials

Ordinary Portland Cement (OPC) conforming to IS: 12269 (1987) was used throughout the study. Laboratory tests were conducted on cement and the properties are recorded in Table 1.

Table 1 Properties of cement

Sl. No.	Property	Magnitude
1.	Specific gravity	3.11
2.	Fineness	4%
3.	Standard consistency	31%
4.	Initial setting time	186 minutes
5.	Final setting time	396 minutes
6.	Compressive strength (7 days)	39.2 MPa
7.	Compressive strength (28 days)	55.7 MPa

Table 2 Chemical composition of copper slag

Sl. No.	Chemical constituent	Copper slag
1.	Fe_2O_3	68.59%
2.	SiO_2	27.28%
3.	CaO	0.65%
4.	CuO	1.20%
5.	Al_2O_3	0.22%
6.	Na_2O	0.58%
7.	MgO	0.48%
8.	TiO_2	0.41%
9.	K_2O	0.23%
10.	SO_3	0.11%
11.	Sulphide Sulphur	0.25%

Table 3 Chemical composition of ferrous slag

Sl. No.	Chemical constituent	Ferrous slag
1.	SiO_2	37.34%
2.	CaO	37.73%
3.	Al_2O_3	14.42%
4.	MgO	8.71%
5.	Fe_2O_3	1.11%
6.	MnO	0.02%
7.	Sulphide Sulphur	0.50%

Sieve analysis and fineness modulus determination for all the aggregates were conducted as per IS: 383 (2016). The specific gravity of the fine aggregates was determined in accordance with the provisions of IS: 2386 Part III (1963).

The fine aggregate used in the study is manufactured sand (M-sand) having a specific gravity of 2.6. The fineness modulus of M-sand was obtained as 2.67 and was found to conform to Zone II. The M-sand grains are of angular shape.

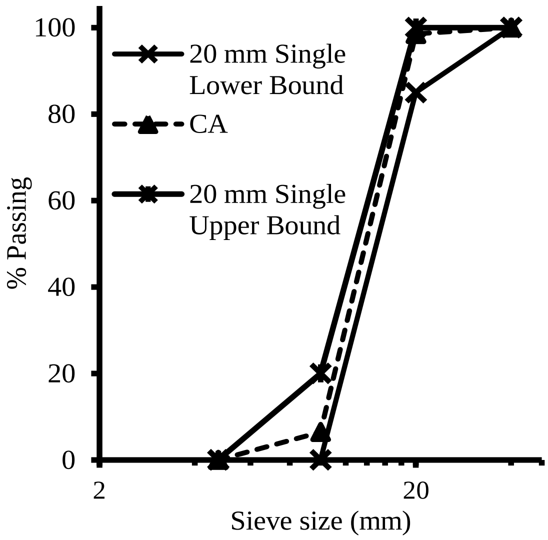
Copper slag used in the study is air-cooled slag. The slag was found to have a black glassy texture. The shape of the copper slag particles is angular in nature. The physical properties of copper slag were determined by laboratory tests. The grading pattern of copper slag was determined by sieve tests and the sample was found to be well graded. The specific gravity was obtained as 3.3 and the fineness modulus as 2.84. The higher fineness modulus of copper slag indicates that the particles are coarser than M- sand. Table 2 gives the chemical composition of copper slag used in the study.

Air-cooled blast furnace ferrous slag was used for the study. It has a black/grey glassy appearance and has a similar particle size as that of sand. The ferrous slag particles have an angular shape. The physical properties were determined by laboratory tests. The specific gravity was recorded as 2.63 and the fineness modulus as 2.12. The sieve analysis of ferrous slag showed that the sample is well graded and has a lower fineness modulus compared to M- sand. Table 3 gives the chemical composition of ferrous slag used in the study. Fig. 1 shows the surface texture of copper slag and ferrous slag.

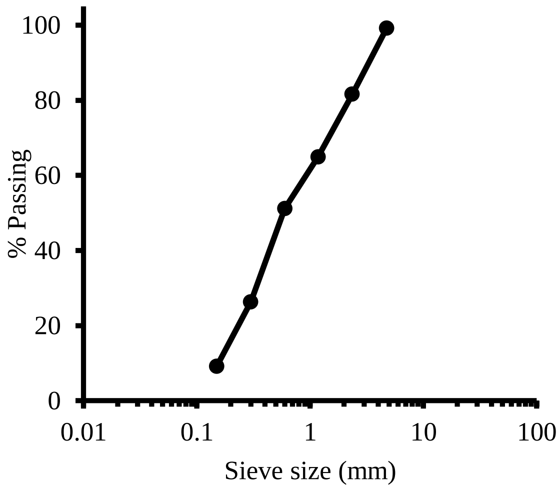
(a) Copper slag

(b) Ferrous slag

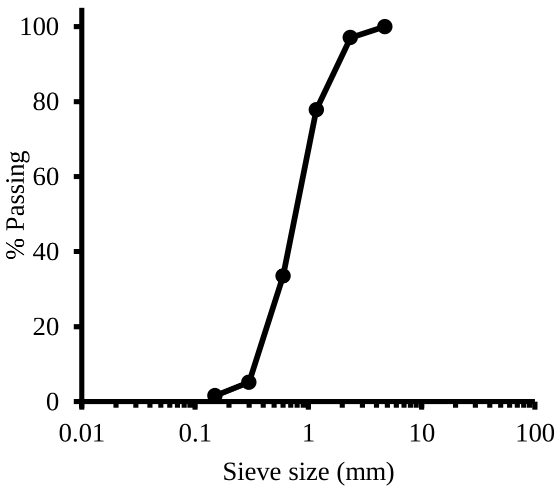
Fig. 1 Surface texture



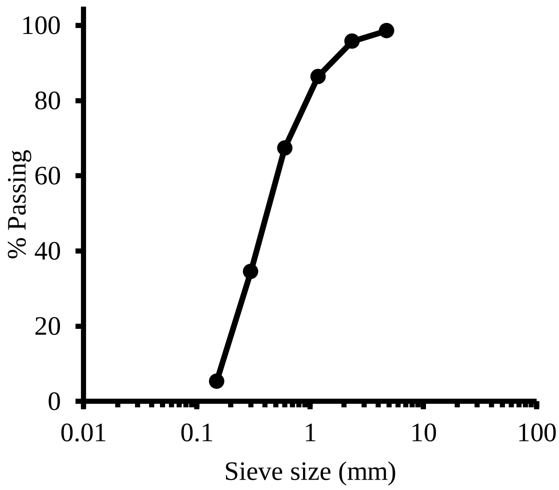
(a) Coarse aggreagates



(b) Manufactured sand from quarry



(c) Copper slag



(d) Ferrous slag

Fig. 2 Particle size distribution curves

Table 4 Concrete mix proportions

Sl.No.	Mix	A kg/m^3	Water kg/m^3	Cement kg/m^3	SF kg/m3	MS kg/m^3	CS kg/m^3	FS kg/m^3	CA kg/m^3
1	M40 CC	3.01	154	430	-	720	-	-	1200
2	M40 CS40	3.01	154	430	-	432	361	-	1200
3	M40 CS100	3.01	154	430	-	-	904	-	1200
4	M40 FS40	3.01	154	430	-	432	-	296	1200
5	M40 FS100	3.01	154	430	-	-	-	740	1200
6	M70 CC	9	125	450	50	839	-	-	1042
7	M70 CS40	9	125	450	50	503	421	-	1042
8	M70 CS100	9	125	450	50	-	1053	-	1042
9	M70 FS40	9	125	450	50	503	-	344	1042
10	M70 FS100	9	125	450	50	-	-	861	1042

Crushed natural stone of maximum size 20 mm was used as coarse aggregate. The specific gravity was obtained as 2.6. The coarse aggregates used are of irregular shape.

Silica fume of specific gravity 2.22 was used in M70 concrete to achieve high strength. The specific gravity of silica fume was determined as per IS: 1727 (1967). A Sulphonated Naphthalene Formaldehyde based super-plasticizer was used to enhance the workability of fresh concrete. The particle size distribution of the fine aggregates and coarse aggregates are given in Fig. 2(a)-(d).

3.2 Mix design

The grades of concrete considered for the control mix are M40 and M70 with manufactured sand as the only fine aggregate. Mix design of the M40 mix (M40 CC) was done by the density method as per IS: 10262 (2009) and the design of the M70 mix (M70 CC) was done by the density method as per ACI 211 (2002). The mix proportions obtained for each of the two control mixes were checked by laboratory trials and were found to be satisfactory. The strength and durability properties of the concrete were studied by considering 40% and 100% replacements (by weight) of fine aggregate with copper slag or ferrous slag. The control concrete mixes were hence modified when copper slag or ferrous slag was used as partial replacement for fine aggregate as per the method in Thomas (2015). The mixes for M40 grade with copper slag replacement were designated as M40 CS40 and M40 CS100 with 40% and 100% replacement of fine aggregate respectively. The first term in the designation denotes the grade of concrete, the second term denotes the material used for replacement and the percentage of fine aggregate replaced. Similarly, the mixes for M70 grade concrete with copper slag replacement were designated as M70 CS40 and M70 CS100. The mixes with ferrous slag replacement were designated as M40 FS40 and M40 FS100 for M40 grade concrete and M70 FS40 and M70 FS100 for M70 grade concrete following the same designation system. Thus, a total of ten mixes including two control mixes are considered in this study. Table 4 gives the mix proportions for the mixes where 'A' represents admixture, 'SF' represents silica fume, 'FA' represents fine aggregates, 'MS' represents manufactured sand, 'CS' represents copper slag, 'FS' represents ferrous slag and 'CA' represents coarse aggregates.

Fig. 3 Cube specimen before testing

3.3 Testing

The workability of the fresh concrete was determined by the slump test as given in IS: 1199 (1959). The density of concrete was determined by using cube specimens of size 150 mm×150 mm×150 mm in the wet condition. The density, compressive strength and split tensile strength were determined in accordance with the provisions of IS: 516 (1959).

The compression test was done on cubes of size 150 mm×150 mm×150 mm in a compression testing machine of capacity 2000 kN. The cube compressive strength was determined at 7 and 28 days of curing period. The load was applied gradually at a rate of 14 N/mm^2 per minute. The failure load was noted and the compressive strength was calculated. Fig. 3 shows testing of a specimen for compression.

Split tensile tests were conducted on cylinder specimens of size 150 mm diameter and 300mm height after 28 days of curing. The test was carried out by placing the cylindrical specimens horizontally between the loading surfaces of compression testing machine and the load was applied until the specimen split into two along the vertical diameter.

The effect of sulphuric acid on the control concrete and concrete with copper slag and ferrous slag were assessed by conducting tests based on ASTM C267 (2012). Cube specimens of size 150 mm× 150 mm×150 mm were used in the study to measure the reduction in compressive strength and mass loss on exposure to 5% sulphuric acid solution. The specimens so prepared were compared with the normally cured specimens. The surface colour change, surface deterioration, weight loss and strength loss were studied.

The resistance to sulphate attack was determined as per ASTM C452 (2015) by immersing cubes of size 150 mm×150 mm×150 mm into sulphate solution prepared by adding 5% Sodium sulphate (Na_2SO_4) and 5% Magnesium sulphate ($MgSO_4$) by weight to water. The specimens were weighed after 28 days to measure the mass loss and then the cubes were tested to determine the reduction in compressive strength when compared to the normally cured specimens.

The resistance to chloride penetration was evaluated by conducting bulk diffusion test and rapid chloride penetration test (RCPT) on concrete specimens. Bulk diffusion test was conducted on cylinder specimens of size 150 mm diameter and 300 mm height as per UNI 9944 (1994) by immersing the specimens in a chloride solution of 1.8M NaCl solution for 28 days. The specimens were taken out at 28 days and were subjected to splitting along the vertical diameter. After splitting, 0.1M $AgNO_3$ solution was sprayed on to the split face of the cylinder specimen to observe for any white precipitate on the edges of the split surface. The depth of penetration was found by the method suggested by Basheer (2001).

RCPT test was conducted according to ASTM C1202 (2010) on concrete disc specimens of size 100mm diameter and 50mm thickness. The test setup consisted of two compartments or cells (cathode and anode) with a central hole of diameter 100 mm and the disc specimen was placed firmly in between the two cells with the help of rubber washer. The cathode compartment was filled with 3% NaCl solution and anode compartment is filled with 0.3 M NaOH solution. Electrode dipped in NaCl was connected to negative terminal of the power supply and that of NaOH to the positive terminal. A potential difference of 60V DC was maintained across the ends of the specimen using a DC power source between the anode and cathode. The current was monitored up to 6 hours at an interval of 30 minutes. The total charge passing through the specimen gives a measure of resistance of the specimen to chloride ion penetration.

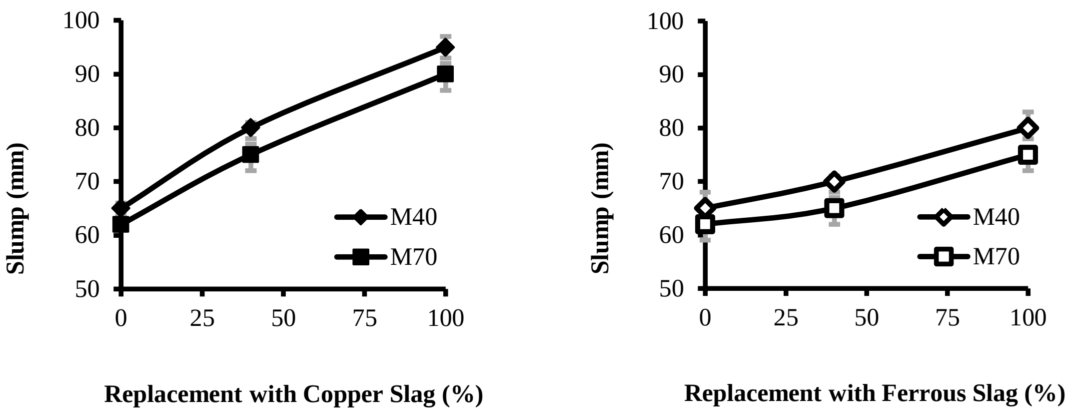
Three specimens were tested for each of the above tests for each of the ten mixes. The average values of the strength and durability parameters obtained by testing the three specimens for each mix are reported as the results.

4. Results and discussion

The results of the experimental study on the effect of replacement of fine aggregate with copper slag and ferrous slag on the workability, strength and durability properties of concrete are presented in the subsequent sections.

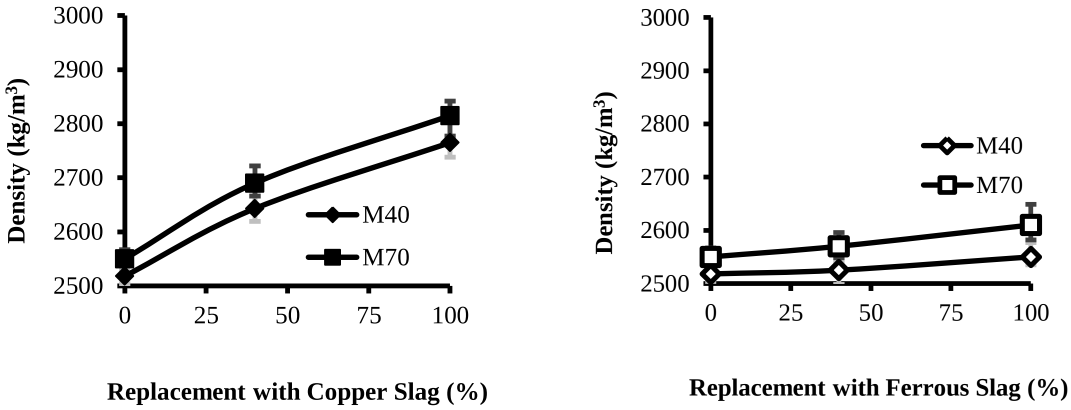
4.1 Effect on workability

The replacement of fine aggregate with copper slag and ferrous slag increases the workability of concrete as seen from Fig. 4. The slump test is a measure of the consistence of concrete and represents the ease of placing concrete. It can be observed that addition of copper slag significantly increases the workability of concrete by 46% when compared to the control mix. The addition of ferrous slag causes an increase in workability of 20% with respect to the control mix. The improvement of workability may be due to reduction in friction between the particles due to the glassy texture of copper slag particles. The available surface water also increases as the content of



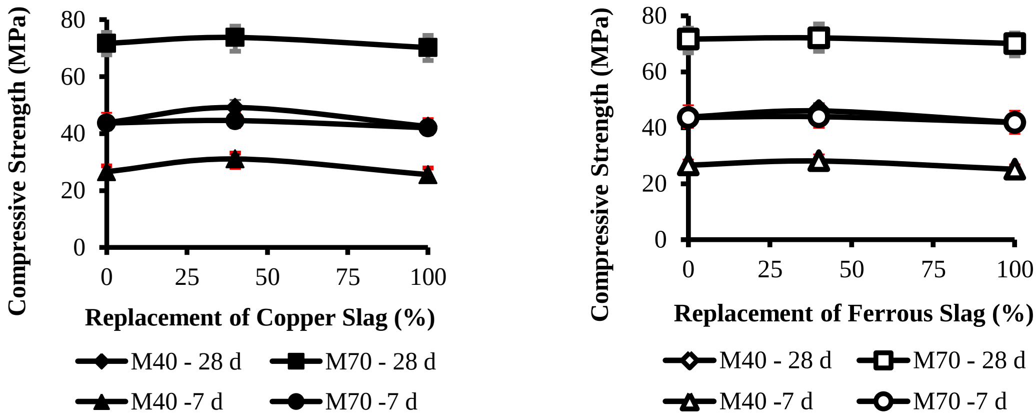
(a) Copper slag (b) Ferrous slag

Fig. 4 Effect on workability



(a) Copper slag (b) Ferrous slag

Fig. 5 Effect on density



(a) Copper slag (b) Ferrous slag

Fig. 6 Effect on compressive strength

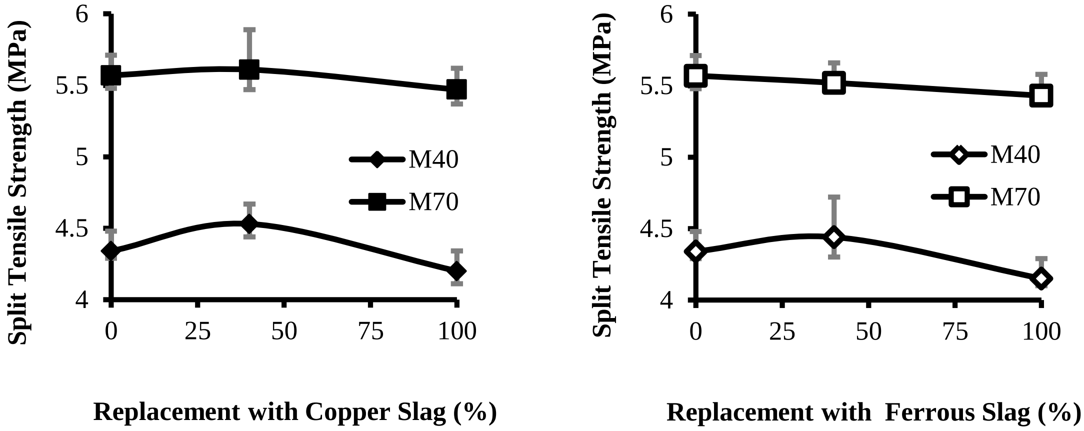
copper slag aggregates in concrete increases. Replacing sand with copper slag or ferrous slag for fine aggregate in concrete is hence beneficial to make the concrete more workable.

4.2 Effect on density of concrete

The density of concrete depends on the bulk density of its constituents. The increase in density is only marginal in the case of replacement with ferrous slag as seen from Fig. 5. However, the specific gravity of copper slag being much higher than sand results in concrete of higher density than the control mix. The increase in density was about 5% for 40% replacement with copper slag and about 10% for 100% replacement with copper slag when compared to the control concrete.

4.3 Effect on compressive strength

Compared to the control mix, the compressive strength of concrete was found to increase



(a) Copper slag (b) Ferrous slag

Fig. 7 Effect on split tensile strength

slightly when 40% fine aggregate is replaced with copper slag or ferrous slag as seen from Fig. 6.

With the increase in slag content, the compressive strength can be seen to decrease marginally. Compared to the control mix, both 7 day and 28 day strength of concrete remains almost same when the fine aggregates are fully replaced with copper slag or ferrous slag.

4.4 Effect on split tensile strength

The split tensile strength of concrete with copper or ferrous slag decreases for 100% replacement of fine aggregate as seen from Fig. 7. However slight improvement in tensile strength is seen for M40 grade concrete at 40% replacement. The maximum reduction in strength observed was for M40 FS100 with a reduction of 4.5% compared to the strength of the control mix. However, this decrease is marginal.

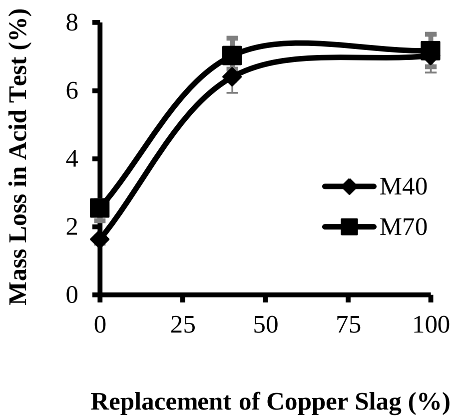
It can be noted that there is only a marginal reduction in the strength properties of concrete even after replacing the fine aggregates completely with copper slag or ferrous slag. This corroborates with the findings of Mavroulidou (2017), Patra and Mukharjee (2017).

4.5 Effect on durability

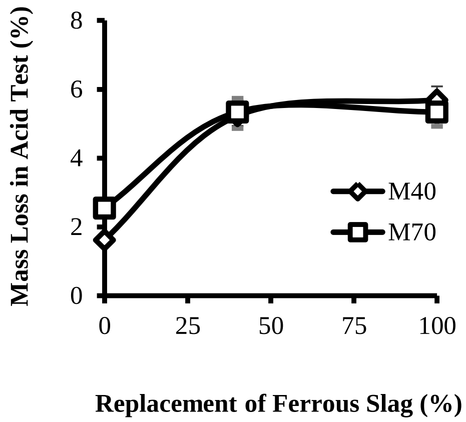
The durability of concrete is evaluated by studying the resistance to sulphuric acid, sulphate attack resistance and resistance to chloride penetration.

4.5.1 Effect on resistance to acid attack

It was found that all concrete specimens get affected by acid attack. The test result indicates that the concrete with copper slag and ferrous slag has lesser resistance to the H_2SO_4 solution than the control concrete. The outer portion of cubes gets destroyed and there is a maximum surface disintegration of 3 mm. About 5 to 6% loss in mass is observed for concrete containing copper slag or ferrous slag after exposure to the acid as seen from Fig. 8. Concrete prepared with copper slag showed relatively higher mass change compared to ferrous slag. Similarly, the specimens containing ferrous slag showed lower loss of compressive strength on acid attack when compared

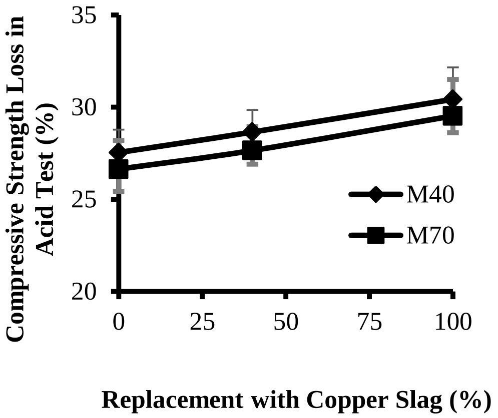


(a) Copper slag

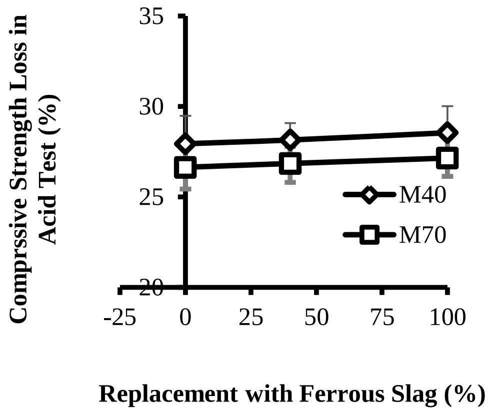


(b) Ferrous slag

Fig. 8 Mass loss on acid attack



(a) Copper slag



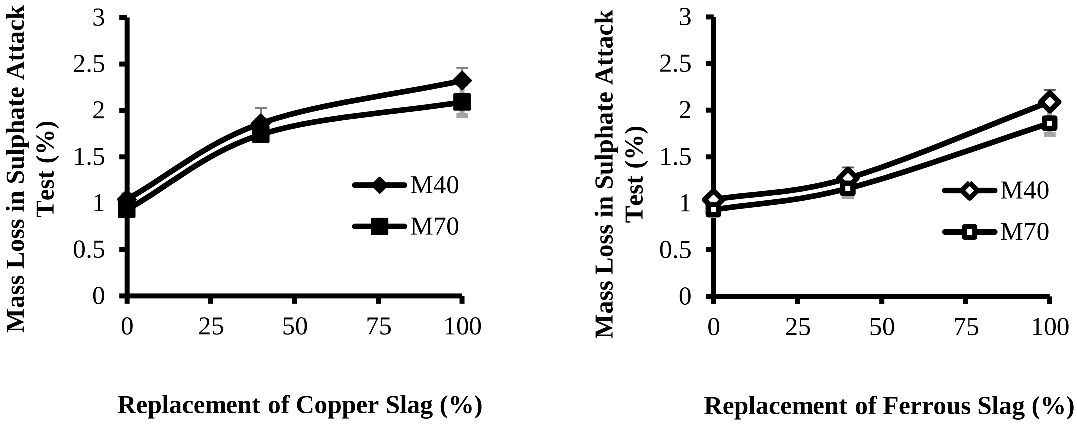
(b) Ferrous slag

Fig. 9 Strength loss on acid attack

Fig. 10 Specimens subjected to acid attack

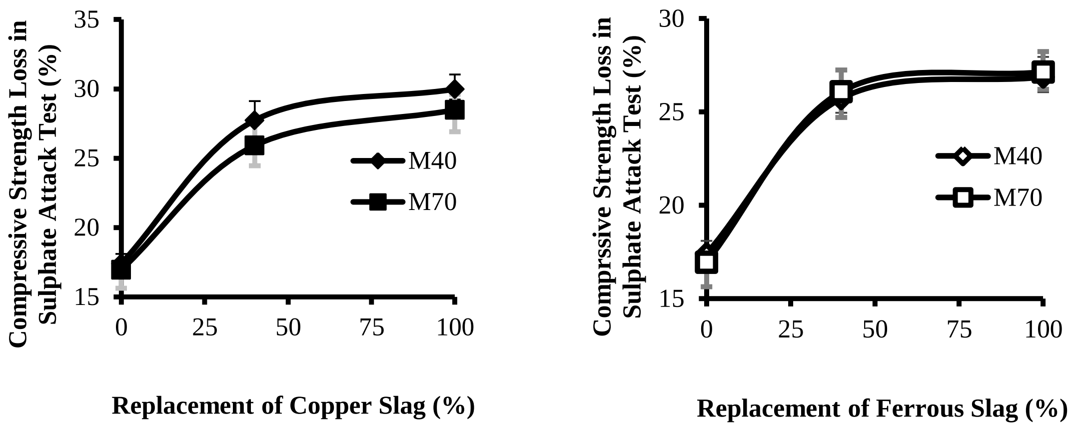
to specimens containing copper slag as seen from Fig. 9.

Copper slag contains about 50% ferrous compounds. When the hardened concrete containing copper slag is immersed in sulphuric acid, the ferrous compounds in concrete gets converted into ferrous salts which disintegrate the concrete thereby causing loss in mass and strength.



(a) Copper slag (b) Ferrous slag

Fig. 11 Mass loss due to sulphate attack



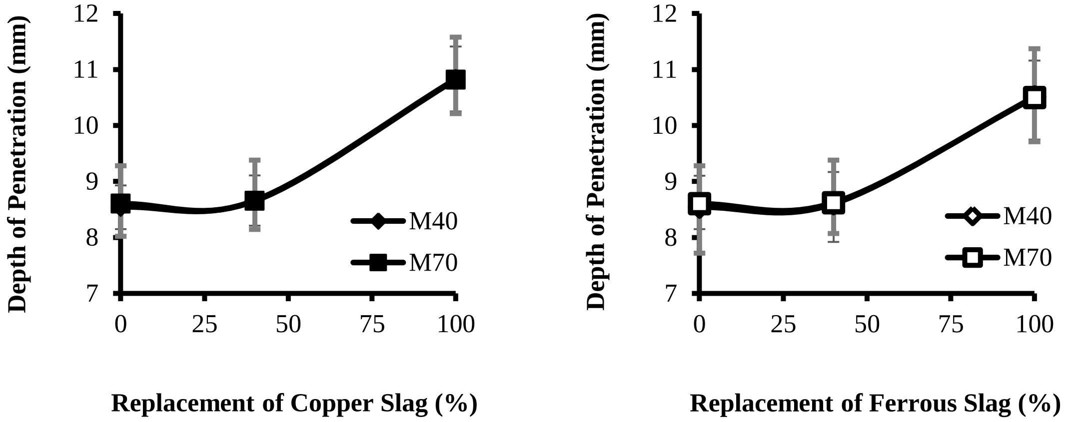
(a) Copper slag (b) Ferrous slag

Fig. 12 Strength loss due to sulphate attack

Ferrous slag contains sulphur compounds, alumina and ferric oxide which results in the formation of a weak acidic environment in the presence of moisture and oxygen. Ferrous slag also contains lime and magnesia which produce a strongly alkaline environment in the presence of moisture and oxygen. This alkaline environment neutralizes the acidic environment due to sulphuric acid. Hence concrete with ferrous slag has higher resistance to acid attack when compared to concrete containing copper slag. Fig. 10 shows specimens subjected to acid attack after 28 days.

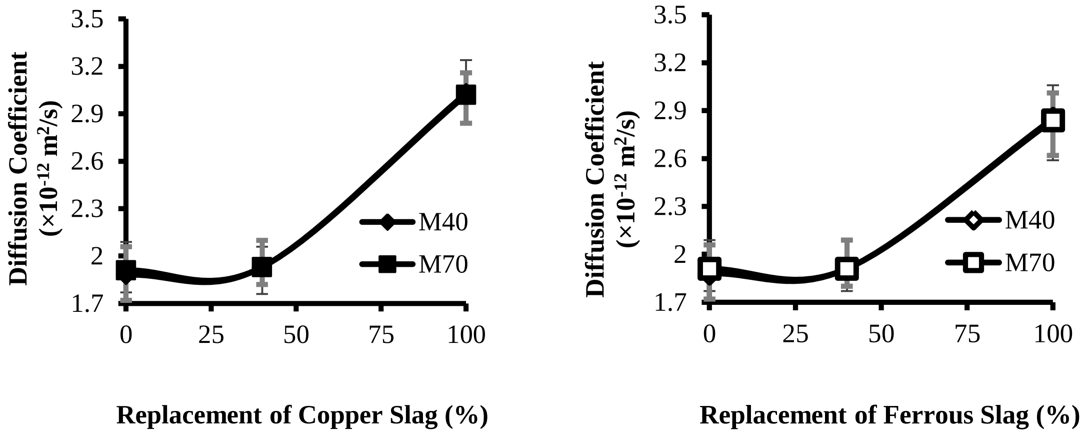
4.5.2 Effect on resistance to sulphate attack

After exposure to sulphate solution, white patches were found on the surface of all the concrete specimens. This was more pronounced in concrete with 100% replacement of fine aggregate. There was only a loss of about 1 to 2% in the mass of specimens after exposure to sulphate solution for 28 days as seen from Fig. 11. The surface deterioration of concrete exposed to



(a) Copper slag (b) Ferrous slag

Fig. 13 Chloride penetration depth



(a) Copper slag (b) Ferrous slag

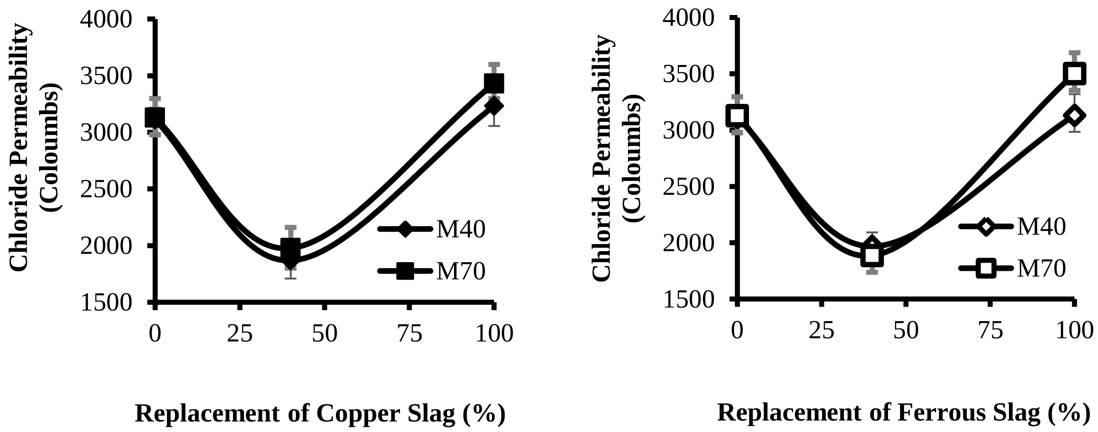
Fig. 14 Chloride diffusion coefficient

sulphate was also not severe. But it was found that compressive strength of all concrete specimens gets affected by sulphate attack. About 17 to 28% loss in compressive strength was observed for concrete containing copper slag or ferrous slag as observed from Fig. 12.

The test result indicates that the control specimens have higher resistance to sulphate attack. The concrete prepared with ferrous slag showed relatively higher resistance to sulphate attack when compared to that with copper slag. Sulphate attack causes the paste to expand due to the formation of reaction products. The massive formation of gypsum and ettringite formed during the external sulphate attack may cause the concrete to crack and scale.

4.5.3 Effect on resistance to chloride attack

Chloride penetration is a cause for concern, especially in coastal areas. Chloride initiated corrosion occurs at points of disruption in the passive oxide layer which protects the steel reinforcement from corrosion (Ashish *et al*. 2016). From Fig. 13 and Fig. 14 it can be inferred that



(a) Copper slag (b) Ferrous slag

Fig. 15 Chloride permeability from RCPT

the depth of chloride penetration in the bulk diffusion test increases for all concrete specimens with the increase in the percentage replacement of fine aggregate. Concrete with replacement of 40% slag showed better resistance to chloride ions compared to the case of 100% replacement. With the increase in content of slag the free water available in the mix increases. The presence of more voids and capillary channels may be the reason for increase in permeability, in the case of 100% replacement of fine aggregate.

From Fig. 15 it can be noted that the chloride permeability was minimum for concrete with 40% replacement of fine aggregate with copper slag or ferrous slag. This may be due to partial filling of voids as a result of improved packing of the fine aggregate and slag particles there by making concrete less permeable. With the increase in slag content the voids increases resulting in lower concrete durability. The angular shape of the slag particles results in poorer packing. The microstructure of concrete is therefore affected resulting in a permeable interfacial zone leading to lower durability. The specimens containing 40% of copper slag and ferrous slag were graded as concrete of ‘low permeability’ according to ASTM C1202 (2010). Concrete made with the control concrete mix and the mix containing 100% of copper slag and ferrous slag were graded as concrete of ‘moderate permeability’ according to ASTM C1202 (2010).

5. Conclusions

From the present study, the following conclusions have been arrived at:

• Copper slag and ferrous slag are industrial by-products that can be effectively utilized as alternatives for fine aggregates in concrete.

• When compared to the control mix, the strength and workability of concrete containing 100% copper slag or 100% ferrous slag as fine aggregates remain largely unaffected. 100% replacement of fine aggregates with copper slag or ferrous slag can be safely recommended in mild exposure conditions.

• Replacement of up to 40% by weight of fine aggregate in concrete can be recommended in moderate exposure conditions. The durability issues arising from the replacement with copper slag or ferrous slag can be addressed by proper surface treatments.

• The current Indian standard code IS: 383 (2016) allows fine aggregate replacement of up to 15% using ferrous slag and up to 35% using copper slag for RCC construction. The results of this study show that up to 40% fine aggregates in concrete can be safely replaced with copper slag or ferrous slag.

• The test results indicated that concrete containing ferrous slag shows slightly better durability in acidic environment when compared to the concrete containing copper slag.

The findings of the study encourage the increased utilization of waste materials such as copper slag and ferrous slag for manufacturing environment-friendly concrete, thereby promoting the idea of a sustainable and green future.

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