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Experimental investigations on substitution of natural sand in concrete with copper slag and blast furnace slag

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Abstract: The constant decrease in the availability of good quality natural sand across the globe has led to increasing investigations on the possibility of utilizing by-products obtained from different industries as a replacement for natural sand. Copper slag and blast furnace slag are by-products of metallurgical processes occurring during copper and pig iron production, respectively. The substitution of natural sand using copper slag and blast furnace slag in plain and reinforced concrete has been permitted in Indian Standard IS: 383-2016 up to a certain percentage as replacing natural sand in concrete. In the present study, investigations were carried out to check the feasibility of increasing copper slag and blast furnace slag as a substitution of natural sand in concrete. Conventional (Natural) sand was replaced (by volume) with copper slag (0%, 25%, 50% & 75%), Granulated Blast Furnace Slag (GBFS) (0%, 30%, 60% & 100%) and Air-Cooled Blast Furnace Slag (ACBFS) (0%, 30%, 60% & 100%). Concrete mixes were examined by substituting conventional sand with copper and blast furnace slag in different proportions and were evaluated for different mechanical properties and durability-related parameters. Leaching studies were also carried out on selected concrete samples.

Keywords: Natural sand, Copper Slag, Granulated Blast Furnace Slag, Air-Cooled Blast Furnace Slag, Durability

1. Introduction

Blast furnace slag consists of non-metallic material containing aluminosilicates and other compounds of manganese, sulfur, iron and several other trace elements. It is obtained in molten form, and its solidified form is further classified based on its methodology adopted to cool down the hot molten slag. When molten blast furnace slag is gradually cooled down (solidification) at ambient atmospheric conditions, resulting in crystalline mineral formation in the form of hard lumps, it is further crushed, screened, and called Air-Cooled Blast Furnace Slag (ACBFS). Whereas, when slag obtained in the molten state is rapidly quenched underwater, no crystallization occurs, and amorphous slag thus obtained is known as Granulated Blast Furnace Slag (GBFS). For every tonne of iron being produced, 300 kilograms of granulated slag is produced. In India, its annual generation is 17-18 Metric tonnes [1]. Copper slag is obtained during copper ore production and is further quenched using industrial or seawater. For every 1 tonne of copper produced, about 2.2 tonnes of copper slag is generated. In India, its annual generation is in the order 2-3 Metric tonnes [1].

At present, Indian Standard IS: 383-2016 [2] permits blast furnace slag and copper slag as an aggregate for concrete. Iron slag has been used up to 25% in reinforced concrete, 50% in plain concrete and 100% in lean concrete is replacing coarse and fine conventional aggregates. Copper slag has been used up to 35% in reinforced concrete, 40% in plain concrete, and 50% in lean concrete to replace conventional fine aggregates. Research work and studies to investigate the possibility of increasing the current permissible limits for utilization of blast furnace and copper slag aggregates as replacement of conventional aggregates in concrete (specially reinforced cement concrete) are being carried out all across the world. A few of those have been discussed below in detail, along with few other research studies in this area in other countries.

Khalifa et al. [3] investigated the properties of mortar and concrete mixes containing different proportions of copper slag ranging from 0 to 100% as a replacement of fine aggregates. Cement mortar mixes were evaluated for compressive strength, whereas concrete mixes were evaluated for their workability, density, compressive, tensile and flexural strength, and durability parameters. Khalifa et al. [3] showed a slight enhancement in density values of concrete with an increase in replacement percentages of copper slag. A significant increase in workability

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was observed with an increase in copper slag proportion. A substitution in the range of 40–50% copper slag as a sand replacement yielded comparable strength to that of control mix according to Khalifa et al. Study also indicated that replacement of copper slag beyond 50% resulted in a reduction of compressive strength due to the higher free water content in the mix. Sharma et al. [4] studied the durability-related parameters of self-compacting concrete substituting copper slag to replace fine aggregates. In the study by Sharma et al., six SCC mixes with different replacement percentages, i.e., 0%, 20%, 40%, 60%, 80% and 100% copper slag, were cast at fixed water to cement ratio of 0.45. SCC mixes were evaluated for fresh properties and hardened properties of concrete, including durability properties. Findings of the study indicated that fresh properties of concrete mix improved with enhancement in copper slag replacement. The maximum compressive strength was achieved for concrete mix with a replacement percentage of 20% copper slag. Studies related to sulfate exposure for concrete mixes containing copper slag indicated an increase in concrete weight and decreased compressive strength. Concrete mix with copper slag showed a significant reduction of carbonation phenomena. This study concluded that 60% replacement of copper slag as sand could be optimum as partial replacement to conventional sand for when the comparison is drawn for durability performance of SCC.

Baby et al. [5] conducted investigations to study the performance of concrete by substituting natural sand with copper slag as fine aggregate. In this study, M40 grade concrete was evaluated. In their experimental study, copper slag was used to replace 0 to 50% of fine aggregate (by weight) in concrete. The study's finding indicated that workability in terms of slump increases with an increase in replacement percentages of copper slag. The compressive strength and flexural strength were observed to be maximum at 40 % replacement. Selvi et al. [6] also studied M40 grade of concrete with copper slag as natural sand replacement. The replacement of natural sand by copper slag was done up to 100% in multiples of 20%. They found that 40% replacement of natural sand using copper slag is an optimum replacement. They also carried out non-destructive evaluation and found excellent concrete quality at 40% replacement levels. Rao et al. [7] conducted studies on the usage of ACBFS up to 50% replacement of natural sand in concrete which increases 15-20% strength of concrete, i.e., compressive strength, split tensile strength and flexural strength. Singh et al. [8] conducted a study on the use of GBFS up to 100 % substitution of natural sand, and it was concluded that the optimum replacement level of sand using GBFS comes in the range of 50-60%. Binici et al. [9] studied concrete mixes containing GBFS aggregate as a substitution of natural sand. The natural sand was replaced in three different replacement percentages, i.e., 5, 10 and 15%, by weight with GBFS aggregates. The results showed a reduction in the workability in terms of the slump and an increase in the compressive strength of hardened concrete with the substitution of GBFS sand to replace conventional (natural) sand. The study indicated that the increase in 28 days compressive strength was about 5.81%, 13.33% and 20.64%, with the substitution of 5%, 10%, and 15% GBFS as a replacement to conventional (natural) sand, respectively. Escalante Garia et al [10] replaced 0%, 30%, 40% and 50%. 90% silica sand in mortars by GBFS sand. Escalante Garia et al. found that GBFS sand was superior to natural silica sand compared to the strength and other mechanical parameters of concrete.

Pawar et al. [11] also studied the performance of concrete mixes with the substitution of conventional sand using copper slag as an aggregate. Findings of the study indicated that compressive strength increased by 8.11%, and flexural strength increased by 7.82% for concrete with copper slag replacement of 40 % compared to control concrete made with 100% conventional sand. As the percentage of copper slag increased, an increase in the workability of fresh concrete was observed. Thomas et al. [12] investigated copper and ferrous slag utilization to replace fine aggregates in concrete. The study indicated that the compressive strength and workability in terms of the slump of concrete containing 100% copper slag and ferrous slag as fine aggregates remain comparable compared to the control mix. This study concluded that copper and ferrous slag could be used in mild exposure conditions up to 100% substitution of fine natural aggregates. Dhir et al. [13] carried out a meta-analysis of past literature on the utilization of copper slag as a substitution of fine natural aggregate in concrete. It was seen that substitution of fine natural aggregate up to 50% copper slag indicated a superior performance in terms of strength, modulus of elasticity, creep and shrinkage. It was reported that the addition of copper slag did not affect the durability performance of concrete except its acid resistance.

Patra and Mukharjee [14] carried out investigations to study the effects of partial replacement of 20%, 40% and 60% natural fine aggregate in concrete using GBFS on the mechanical and durability properties. Compressive strength, modulus of elasticity and chloride penetration resistance were found to increase with the enhancement in the percentage of GBFS. Devi and Gnanavel [15] investigated the effect of partially substituting conventional aggregates with steel slag on mechanical and durability properties of M20 grade concrete and recommended that the optimum percentage for replacing fine natural aggregate with steel slag can be 40%. The strength and durability characteristics were comparable to the control mix at 40% replacement of fine aggregate with steel slag. Noufal et al. [16] studied the influence of utilization of copper slag as a replacement of fine natural aggregates on mechanical properties of concrete. Results indicated that the optimum replacement levels for replacing conventional aggregates with copper slag could be 40%.

Given the studies mentioned above, it becomes imperative to conduct studies and evaluate the performance of concrete mixes containing copper slag, GBFS and ACBFS aggregates as replacement of natural sand beyond the presently proper proportions as per Indian standards and compare their performance with control concrete mix made with 100% natural sand. If the performance of mixes incorporating slag aggregates is comparable or better than control mix, this study may prove to help revise the existing limits in Indian Standards on the utilization of copper and blast furnace slag as aggregates in plain and reinforced concrete.

2. Experimental plan

Both ACBFS and GBFS samples were taken from JSW Plant in Bellary, Karnataka. The copper slag sample was taken from Sterlite Industries located in Tuticorin, Tamilnadu. ACBFS sample was crushed in the laboratory to meet the requirements of grading as mentioned in IS 383: 2016 [2]. After crushing, sieve analysis was carried out, and grading of sample conforms to Zone II as per IS: 383-2016. The slag sampled were tested and evaluated for their physical and chemical characteristics. Apart from slag samples, natural coarse aggregate (maximum nominal size of 20mm) and natural sand (conforming to Zone III as per IS-383-2016) were used to prepare control and experimental concrete mixes. OPC 43 conforming to IS 269: 2015 [17] and Naphthalene-based superplasticizer conforming to IS 9103: 2013 [18] were used in the study. Concrete was prepared at a water to cement ratio of 0.65. The mix design parameters of the control mix containing 100% conventional coarse and fine aggregates are given in Table 1. Natural sand was replaced by slag aggregates (both ACBFS and GBFS sand) in different proportions to prepare concrete mixes. 0, 30, 60 and 100% (by volume) of fine natural aggregate was replaced by GBFS and ACBFS. At the same time, substitution levels in the case of copper slag were kept as 0, 25, 50 and 75% (by volume) for the preparation of experimental mixes. A similar level of workability was maintained for experimental mixes by varying the admixture dosage. Samples were cast to study the various mechanical (compressive and flexural strength) and durability properties (such as rapid chloride penetration test, accelerated carbonation test, water permeability test) of concrete, along with leaching studies for heavy metals.

Table 1 – Mix Proportions for control and experimental concrete mixes

Sl.	Mix ID	Water kg/m^3	Cement kg/m^3	Fine Aggregate (kg/m^3)				Coarse Aggregate kg/m^3
				Crushed Sand	Copper Slag (CS)	Blast Furnace Slag		
						Granulated GBFS	Air-Cooled ACBFS	
1	M0	192	295	735	-	-	-	1223
2	M25CS	192	295	552	265	-	-	1223
3	M50CS	192	295	368	521	-	-	1223
4	M75CS	192	295	184	782	-	-	1223
5	M30GBFS	192	295	515	-	208	-	1223
6	M60GBFS	192	295	294	-	416	-	1223
7	M100GBFS	192	295	0.00	-	694	-	1223
8	M30ACBFS	192	295	515	-	-	239	1223
9	M60ACBFS	192	295	294	-	-	478	1223
10	M100ACBFS	192	295	0.00	-	-	797	1223

3. Test results and discussion

3.1 Characterization of fine aggregates

The specific gravity of ACBFS was higher than that of natural sand while the specific gravity of GBFS was lower than the natural sand. The specific gravity of copper slag aggregates was observed to be highest among all the aggregate samples. Sieve analysis results indicate that the ACBFS sample conforms to Zone II while GBFS and copper slag aggregate samples showed conformance to Zone I of IS 383:2016. Natural sand used in the study was conforming to Zone III as per IS: 383-2016. Specific gravity and water absorption of natural sand were 2.64 and 0.6%, respectively. Results of physical and chemical characterization of slag aggregates samples have been tabulated in Table 2(a) and Table 2(b), respectively.

Table 2 (a) – Physical properties of slag aggregates

Property		ACBFS	GBFS	Copper slag
Specific gravity		2.86	2.49	3.74
Water absorption (%)		0.69	1.10	0.60
Sieve Analysis Cumulative Percentage Passing (%)	20mm	100	100	100
	10 mm	100	100	100
	4.75 mm	99	100	99
	2.36 mm	85	95	97
	1.18 mm	58	63	73
	600 µ (microns)	39	24	25
	300 µ (microns)	26	6	6
	150 µ (microns)	15	2	1
Material finer than 75µ (microns), (%)		7.4	0.6	0.9
Zone		Zone II	Zone I	Zone I

Table 2 (b) – Chemical properties of Slag Aggregates

Property	ACBFS	GBFS	Copper slag
Silica (SiO_2), (%)	34.156	34.18	31.395
Reactive silica, (%)	28.545	27.286	30.387
Alkalis as Na_2O equivalent, (%)	0.561	00.486	1.045
Sulfate (SO_3), (%)	0.292	00.221	0.351

3.2 Studies on control and experimental concrete mixes

Control concrete mix with a water to cement ratio of 0.65 was prepared with 100% natural sand as fine aggregate. Experimental concrete mixes were prepared with different proportions of ACBFS, GBFS and copper slag sand to replace natural fine aggregate. All the mixes were studied for various fresh, hardened and durability parameters of concrete.

3.2.1 Fresh concrete properties

With the increase in percentage substitution of natural sand with slag aggregates, the water demand of experimental concrete mixes increased compared to the control mix. To compensate for the excess water demand and maintain a similar level of workability, a higher dosage of chemical admixture was used in mixes containing slag aggregates (as shown in Table-3).

Fresh concrete was observed to get segregated when natural sand was replaced beyond 50% using copper slag aggregates due to higher specific gravity and coarser nature of copper slag compared to natural sand. Copper slag particles settled to the bottom during the compaction of fresh concrete.

Admixture dosage in mixes containing GBFS sand increased from 0% to 1.7% to maintain similar workability (Table 4). Segregation was observed in fresh concrete, when natural sand was replaced beyond 60% replacement using GBFS sand, due to the coarser nature of slag. To maintain the similar workability in concrete mixes having ACBFS, the admixture dosage increased from 0 to 1.8% (Table 5). Cohesive mixes were obtained when ACBFS sand was used to replace 100% natural sand.

3.2.2 Mechanical properties of hardened concrete

Compressive strength (on 150 mm cubes) and flexural strength (on concrete beams of size 150×150×700 mm) were determined at the age of 28 days (as shown in Fig. 1 and 2, respectively). Samples were tested as per IS: 516. Results for various mixes are mentioned below in Table 6 to Table 8. A comparison of compressive and flexural strength for a different set of concrete mixes has been shown in Fig. s 3, 4 and 5.

Table 3 – Fresh concrete properties of concrete mix having copper slag

Copper Slag			Observation
Fine Aggregate Replacement (%)	Workability (in terms of a slump), mm	Admixture Dose (%)	Concrete mixes were observed to get segregated when natural sand was replaced beyond 50% using copper slag. Slag particles appeared to settle down at the bottom during compaction
0	80	--	
25	75	0.6	
50	70	1.4	
75	70	1.7	

Table 4 – Fresh concrete properties of concrete mix having GBFS

GBFS			Observations
Fine Aggregate Replacement (%)	Workability (in terms of slump), mm	Admixture Dose (%)	Concrete mixes were observed to get segregated when natural sand was replaced beyond 60% using GBFS.
0	80	--	
30	90	0.6	
60	75	1.4	
100	70	1.7	

Table 5 – Fresh concrete properties of concrete mix having air-cooled blast furnace slag

ACBFS			Observations
Fine Aggregate Replacement (%)	Workability (in terms of slump), mm	Admixture Dose (%)	Cohesive concrete mixes were obtained in all the cases.
0	80	--	
30	70	0.9	
60	75	1.5	
100	70	1.8	

Fig. 1 – Compressive Strength Test set up

Fig. 2 – Sample undergoing Flexural Strength Test

Table 6 – Mechanical properties of experimental mixes containing different proportions of copper slag aggregate as a replacement of natural sand

Copper Slag				
Fine Aggregate Replacement (%)	Compressive Strength, MPa (at 28 days)	The standard deviation for compressive strength (MPa)	Flexure Strength, MPa (at 28 days)	The standard deviation for flexural strength (MPa)
0	25.93	1.40	2.72	0.23
25	28.35	1.70	3.13	0.34
50	31.43	1.55	3.36	0.30
75	33.43	1.60	3.68	0.37

Compressive and flexural strength of concrete mixes were observed to increase with the increase in percentage replacement of natural sand using copper slag as fine aggregate in concrete. Maximum improvement in compressive strength (28.92%) and flexural strength (35.29%) was observed at 75% replacement of natural sand using copper slag compared to the control sample made with 100% natural sand. This shows that copper slag aggregates have a positive influence on the mechanical properties of concrete, and their impact in terms of mechanical properties of concrete mix is similar to that of conventional natural fine aggregates. Compressive and flexural strength of experimental mixes containing different proportions of GBFS and ACBFS aggregate as a replacement of natural sand were found to be slightly better or comparable with control mixes made with 100% natural sand at all replacement levels. This shows that GBFS and ACBFS aggregates do not negatively influence the mechanical properties of concrete, and their behavior is similar to conventional natural fine aggregates.

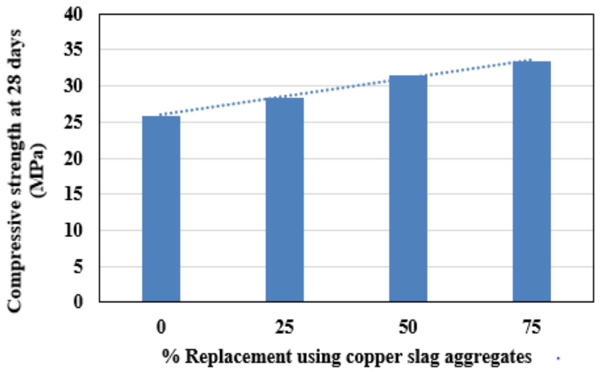

Fig. 3(a) –Compressive strength (28 days) of mixes with different replacement percentages of Copper Slag aggregate

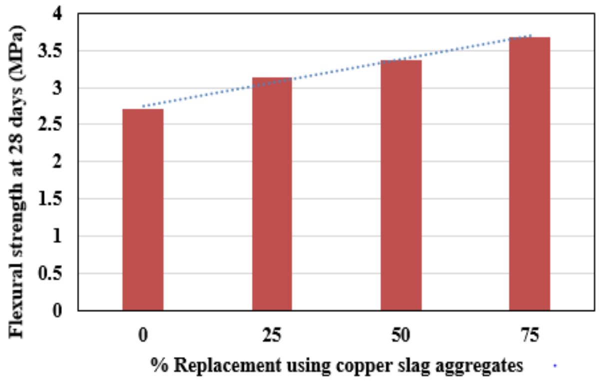

Fig. 3(b) –Flexural strength (28 days) of mixes with different Replacement Percentages of Copper Slag aggregate

Table 7 – Mechanical properties of experimental mixes containing different proportions of GBFS aggregate as a replacement of natural sand

GBFS				
Fine Aggregate Replacement (%)	Compressive Strength, MPa (at 28 days)	The standard deviation for compressive strength (MPa)	Flexure Strength, MPa (at 28 days)	The standard deviation for flexural strength (MPa)
0	25.93	1.55	2.72	0.22
30	27.54	1.60	2.71	0.34
60	28.76	1.65	2.83	0.26
100	28.16	1.50	2.61	0.24

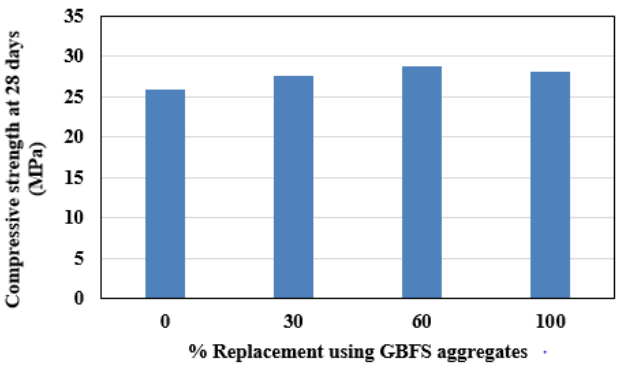

Fig. 4(a) –Compressive strength (28 days) of mixes with different replacement percentages of GBFS aggregate

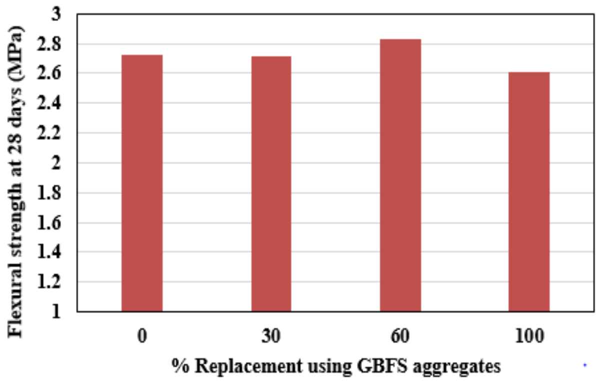

Fig. 4(b) –Flexural strength(28 days) of mixes with different Replacement Percentages of GBFS aggregate

Table 8 – Mechanical properties of experimental mixes containing different proportions of ACBFS aggregate as a replacement of natural sand

ACBFS				
Fine Aggregate Replacement (%)	Compressive Strength, MPa (at 28 days)	The standard deviation for compressive strength (MPa)	Flexure Strength, MPa (at 28 days)	The standard deviation for flexural strength (MPa)
0	25.93	1.24	2.72	0.25
30	28.65	1.35	2.89	0.27
60	30.87	1.50	2.95	0.28
100	28.50	1.65	2.80	0.30

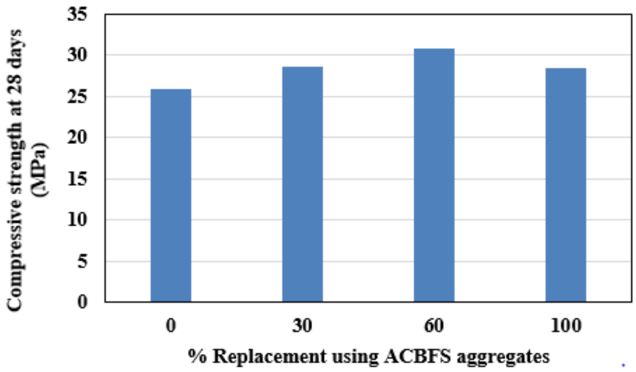

Fig. 5(a) –Compressive strength (28 days) of mixes with different replacement percentages of ACBFS aggregate

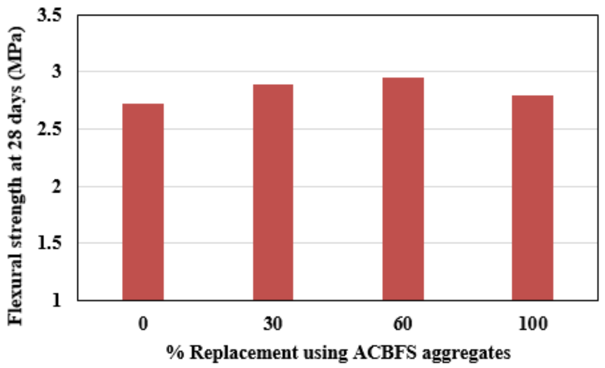

Fig. 5(b) –Flexural strength (28 days) of mixes with different Replacement Percentages of ACBFS aggregate

3.2.3 Durability studies on hardened concrete

As mentioned above, concrete mixes were prepared with different proportions of natural sand, GBFS, ACBFS and copper slag as fine aggregate. Along with fresh and hardened properties, samples were cast to conduct several durability studies for all concrete mixes, such as the rapid chloride penetration test, carbonation depth, water permeability and abrasion test. The results are given in Table 9 to Table 11. RCPT test (as shown in Fig. s 6(a) and 6(b)) was conducted as per ASTM C120 on concrete cylindrical samples (100 mm diameter and 50 mm thickness). The test setup consists of cathode and anode with a central hole of 100 mm size. The sample was placed in between cathode and anode. The cathodic section contains a NaCl solution of 3% concentration. Whereas the anodic section is made up of NaOH solution having a concentration of 3M. Through a DC supply, the potential difference of 60 volts was kept across the cells. The test was conducted for 6 hours, and readings of currents were taken at a gap of 30 minutes. The total charge that flowed through the sample was calculated from the current readings, representing the resistance of concrete against the penetration of chlorides.

Accelerated Carbonation test (ACT) was conducted on beam samples of 100 ×100×500 mm as per ISO 1920 Part 12. After 28 days of water curing, beams were transferred to an ambient environment (temperature = 27 ± 2 oC and relative humidity = 65 ± 5 %) for 14 days. After that, the top and bottom longitudinal surfaces and end faces of the sample were sealed with paraffin wax so that carbonation can occur through two unsealed longitudinal faces only. Further, beams were kept in a carbonation chamber (as shown in Fig. 7) having 4±0.5 % CO_2, temperature = 27±2 ºC and relative humidity of 65±5%. Depth of carbonation that occurred in beams was measured after 70 days of exposure in the chamber by cutting a slice with a thickness of 50 mm and spraying 1% phenolphthalein solution on the sliced section.

A water permeability test was carried out on cube specimens of size 150 mm in accordance with DIN 1048, part 5, to get an idea about resistance against penetration of water inside concrete. Water pressure of 0.5 N/mm^2 was applied on the concrete sample for 72 ±2 hours (as shown in Fig. 8). Then, the sample was split, and a maximum depth of penetration of water was measured.

Resistance of horizontal concrete surfaces against abrasive action was evaluated on concrete slabs at 28 days using the revolving disc method as per ASTM C 779. Sliding and scuffing action on concrete was achieved by rotating steel disks with abrasive grit. Silicon carbide was fed on disks as abrasive at a rate of 4 to 6 grams per minute. In the present study, the testing period was kept at 60 minutes. The revolving disc abrasion test machine has been shown in Fig. 9.

3.2.3.1 Observations on experimental concrete mixes made with Copper slag (Table 9)

Replacement of natural sand with different proportions of copper slag sand does not seem to have an impact on the RCPT results as RCPT values of all the mixes were observed to be comparable and fall in the 'moderate' class (ranges from 2000-4000 Coulombs) of penetrability as per ASTM C1202. The carbonation depth and water permeability of experimental mixes containing copper slag as a replacement of natural sand are lower than the control mix and decrease with an increase in the proportion of copper slag in concrete. Improvement in abrasion resistance of concrete was observed with an increase in the proportion of copper slag in the concrete mix. This may be attributed to the higher specific gravity and abrasion resistance of copper slag aggregate compared to natural sand.

Fig. 6(a) – Vacuum box

Fig. 6(a) – DC voltage system for RCPT tests

Fig. 7 – Carbonation Chamber for ACT

Fig. 8 – Test Setup for Water permeability test

3.2.3.2 Observations on experimental concrete mixes made with ACBFS (Table 10)

Replacement of natural sand with different proportions of ACBFS sand does not seem to have an impact on the on RCPT results till natural sand is replaced up to 60% using ACBFS, as RCPT values of all the mixes were observed to be comparable and fall in the 'moderate' class (ranges from 2000-4000 Coulombs) of penetrability as per ASTM C1202. However, when 100% of the natural sand is replaced with ACBFS sand slightly higher value of RCPT was observed and it comes in the 'high' class of penetrability. Carbonation depths, water permeability and abrasion resistance of experimental mixes containing different proportions of ACBFS as replacement of natural sand were observed to comparable control mix.

Table 9 – Durability Test results of experimental mixes containing different proportions of copper slag aggregate as a replacement of natural sand

% Replacement of Fine Aggregate with slag aggregate	RCPT as per ASTM C1202 (Coulombs)	Carbonation Depth as per ISO-1920-12 (mm)	Water Permeability as per DIN- 1048 (5) (mm)	Abrasion (mm)
	28 Days	70 days Exposure	28 Days	28 Days
0	3723	14.90	26	0.481
25	3520	11.73	22	0.410
50	3271	10.62	20	0.416
75	2894	9.65	17	0.396

Table 10 – Durability test results of experimental mixes containing different proportions of ACBFS aggregate as a replacement of natural sand

% Replacement of Fine Aggregate with slag aggregate	RCPT as per ASTM C1202 (Coulombs)	Carbonation Depth (mm) as per ISO-1920-12	Water Permeability as per DIN-1048 (5) (mm)	Abrasion (mm)
	28 Days	70 days Exposure	28 Days	28 Days
0	3723	14.9	26	0.481
30	3472	8.90	28	0.458
60	3671	8.71	25	0.462
100	4228	9.65	22	0.496

Table 11 – Durability test results of experimental mixes containing different proportions of GBFS aggregate as a replacement of natural sand

% Replacement of Fine Aggregate with slag aggregate	RCPT as per ASTM C1202 (Coulombs)	Carbonation Depth (mm) as Per ISO-1920-12	Water Permeability as per DIN-1048 (5) (mm)	Abrasion (mm)
	28 Days	70 days Exposure	28 Days	28 Days
0	3723	14.90	26	0.481
30	3321	8.82	24	0.468
60	3587	9.80	26	0.465
100	4194	14.2	27	0.458

Fig. 9 – Revolving-disk abrasion test machine

3.2.3.3 Observations on experimental concrete mixes made with GBFS (Table 11)

Replacement of natural sand with different proportions of GBFS sand does not seem to have an impact on the RCPT results till natural sand is replaced up to 60% using GBFS, as RCPT values of all the mixes were observed to be comparable and fall in the 'moderate' class (ranges from 2000-4000 Coulombs) of penetrability as per ASTM C1202. However, when 100% of the natural sand is replaced with GBFS sand slightly higher value of RCPT was observed, and it comes in the 'high' class of penetrability. Carbonation depths, water permeability and abrasion resistance of experimental mixes containing different proportions of GBFS as replacement of natural sand were observed to comparable control mix.

3.2.4 Leaching study on experimental concrete mixes incorporating different proportions of copper slag, ACBFS and GBFS aggregates.

Leaching studies were carried out on concrete made with copper slag, ACBFS and GBFS aggregates (after 28-day exposure in different solutions). The concrete cubes made with 75% copper slag were exposed to different solutions such as distilled water, 5% HCl solution, 5% NaCl solution and 5% $MgSO_4$ solution for 28 days. Similarly, concrete cubes made with 60% replacement by ACBFS and GBFS were exposed to these solutions for 28 days. After the exposure period, solutions of immersed cubes were tested for the presence of various heavy metals using Inductively Coupled Plasma Spectroscopy. The results are mentioned in Table 12. Results showed that concentrations of different heavy metals are considerably lower than the values prescribed in IS: 383-2016 for leaching study on concrete made with slag aggregates.

Table 12 –Test results of leaching study on slag aggregate

Constituents, mg/l	Materials	Distilled water	HCl Solution	NaCl Solution	MgSO4
Cadmium (Cd)	Concrete made with 75% copper slag	0.001	0.090	<0.001	<0.001
Lead (Pb)		0.048	2.225	0.051	0.034
Hexavalent Chromium (Cr)		<0.001	0.078	0.011	0.006
Selenium (Se)		<0.001	<0.001	<0.001	<0.001
Cadmium (Cd)	Concrete made with 60% GBFS	0.017	0.058	2.501	0.072
Lead (Pb)		0.088	4.225	2.251	0.090
Hexavalent Chromium (Cr)		0.021	1.078	2.311	0.116
Selenium (Se)		0.015	0.084	2.821	0.605
Cadmium (Cd)	Concrete made with 60% ACBFS	0.007	0.098	1.001	0.007
Lead (Pb)		0.078	3.225	1.051	0.078
Hexavalent Chromium (Cr)		0.011	0.078	1.011	0.011
Selenium (Se)		0.005	0.034	1.021	0.005

4. Conclusion

Based on the observations of different tests conducted in this study, the following conclusions were drawn:

- Characterization results indicated that water absorption of copper slag, ACBFS and GBFS aggregates is slightly higher than conventional fine aggregates. Therefore, an increase in percentage replacement levels of natural sand with slag aggregates leads to an increase in the water demand of concrete mix for similar workability. Concrete mixes were observed to get segregated when natural sand was replaced beyond 50% using copper slag. Segregation was observed in fresh concrete, when natural sand was replaced beyond 60% replacement using GBFS sand, due to the coarser nature of slag. Cohesive mixes were obtained when air-cooled blast furnace slag sand was used to replace 100% natural sand.
- Compressive and flexural strength of concrete mixes were observed to increase with the increase in percentage replacement of natural sand using copper slag as fine aggregate in concrete. At the same time, the compressive and flexural strength of experimental mixes containing different proportions of GBFS and ACBFS aggregate as a replacement of natural sand were slightly better or comparable with control mixes made with 100% natural sand at all replacement levels.
- Replacement of natural sand with different proportions of slag aggregates sand does not seem to have any significant impact on the RCPT values, carbonation depths, water permeability and abrasion resistance of experimental mixes till natural sand is replaced up to 75% using copper slag aggregates and 100% using ACBFS and 60% using GBFS aggregates. A study on the concentration of heavy metals in concrete made with different proportions of slag aggregates shows that concentrations of different heavy metals are considerably lower than the values prescribed in IS:383-2016 for the leaching study.
- Considering the effect of usage of different proportions of slag aggregates as a replacement of fine natural aggregate on fresh, hardened and durability properties of concrete, natural fine aggregate can be replaced up to 50% using copper slag, up to 100% using ACBFS and up to 60 % using GBFS aggregates.

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