Corrosion and Leaching Studies in Blended Copper Slag Mortar

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ABSTRACT

The effect of copper slag leaching was evaluated using Atomic Absorption Spectroscopy (AAS) immersed in three aqueous media such as tap water, sea water, and synthetic/artificial rain water. The mechanical and corrosion resistance properties of copper slag admixed concrete was evaluated using compression test and various electrochemical tests, respectively. Sand was totally replaced with copper slag in making the concrete specimens. From the investigations it is observed that the copper slag leaching was found to be very less even after 180 days of exposure in aqueous media. Compressive strength revealed that the addition of copper slag increased the compressive strength of the concrete. Rapid Chloride Penetration Test (RCPT) and other electrochemical tests indicated that copper slag admixed mortar performed equal to the sand mortar in sea water environments.

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I. INTRODUCTION

Large quantities of industrial by-products are produced every year by various industries. The main goals of environmental protection agencies are the dual problems of disposal and health hazards of these by-products. For many years, by-products such as fly ash, silica fume, and slag were considered as waste materials. They have been successfully used in the construction industry as a Portland cement substitute. Their role in enhancing concrete durability is well recognized in comparison with using Portland cement alone [1-5]. Moreover, new by-products are being generated by various industries, which could have a promising future for partial replacement of Portland cement. Copper slag is a by-product material produced from the process of manufacturing copper.

It has been estimated that for every ton of copper production, about 2.2 tons of slag is generated and in each year, approximately 24.6 million tons of slag is generated from world copper production. Slag containing <0.8% copper are either discarded as waste or sold as products with properties similar to those of natural basalt (crystalline) or obsidian (amorphous). Utilization and recovery of metal depend on the type of slag. Current options of management of this slag are recycling, recovering of metal, production of value-added products, and disposal in slag dumps or stockpiles. Processed air-cooled and granulated copper slags have number of favorable mechanical properties for aggregate use, including excellent soundness characteristics, good abrasion resistance, and good stability. Since copper slag has a low content of calcium oxide (CaO), granulated copper slag exhibits pozzolanic properties [6,7]. As CaO content increases or under the activation of sodium hydroxide (NaOH), it can exhibit cementitious properties and can be used as partial or full replacement for Portland cement.

Copper slag usually has a low content of CaO; granulated copper slag exhibits pozzolanic properties as CaO content in copper slag increases, it can exhibit cementitious properties. Studies [8-12] indicated that a copper slag, which contains approximately 19% CaO, show a good cementitious property under the activation of NaOH.

The effect of copper slag on the hydration of cement-based materials was investigated by Mobasher *et al*. [13] and Tixier *et al*. [14]. Results indicated a significant increase in the compressive strength for up to 90 days with 1.5% of hydrated lime as an activator to pozzolanic reactions. Also, a decrease in capillary porosity and an increase in gel porosity were observed. Moura *et al*. [15] reported that copper slag could be a potential alternative to admixtures used in concrete and mortars. The use of slag from copper smelting as a fine aggregate in concrete was also investigated by Akihiko and Takashi [16]. From mortar strength tests with a cement/slag/water ratio of 1/2/0.55, the ball milled slag gave a higher strength. The effects of using several types of slag on mortar and concrete reaction; reinforcing steel corrosion; abrasion; workability and slump; shrinkage; and freezing and thawing characteristics were examined. Copper slag was also used by Toshiki *et al*. [17] as a fine aggregate in concrete.

Al-Jabri *et al*. [18-20] reported that copper slag can be used as a sand replacement material for up to 40% and they have also tried the effect of copper slag along with silica fume for making high performance with good strength and durability properties. Shi *et al*. [21] studied the utilization of copper slag in cement and concrete. This paper reviews the characteristics of copper slag and its effects on the engineering properties of cement, mortars, and concrete.

Khanzadi and Behnood [22] studied the effect of copper slag as coarse aggregate and concluded that the use of copper slag aggregate compared with limestone aggregate resulted in a 28-day compressive strength increase of about 10-15%, and a splitting tensile strength increase of 10-18% and hence it can be used for making high strength concrete.

In the present investigation leaching of copper was evaluated using Atomic Absorption Spectroscopy (AAS) immersed in three aqueous media such as tap water, sea water, and synthetic acid rain water. The mechanical and corrosion resistance properties of copper slag admixed concrete was evaluated using compression and electrochemical tests like impedance and macro cell corrosion technique.

2. EXPERIMENTAL

2.1 Methods and Material

2.1.1 Leaching studies in aqueous media

Copper slag was subjected to leaching studies in three aqueous media such as tap water, sea water, and synthetic acid rain water.

The composition of the supplied slag is given in Table 1:

The parameters of the leaching studies in solution media are as follows:

1. Slag used : Copper slag
2. Ratio taken with water : 0.5:1 and 1:1
3. Leaching time : 1-150 days
4. Aqueous media : Tap water, sea water, and acid rain water
5. Technique adopted : AAS

The parameters of the leaching studies in cement mortar are as follows:

1. Cement:Sand (Sand mortar denoted by SM) : 1:3 (control)
2. Cement:Copper slag (Copper slag mortar denoted by CM) : 1:3
3. W/C ratio : 0.44

The coarser slag was grained to a granule for all leaching studies.

3. RESULTS AND DISCUSSIONS

3.1 Leaching in Tap water

The tap water available in our laboratory was used for this study. The tap water was filtered before analysis. The water characteristics are as follows:

pH : 7.2
Free chloride : 120 parts per million (ppm)
Total hardness : 322 ppm
Permanent hardness : 230.4 ppm
Temporary hardness : 91.6 ppm

The powdered copper slag and tap water was mixed in the ratio of 0.5:1 and allowed to stand for various leaching periods from 24 hours (1 day) to 4320 hours (180 days) and shown in Table 2.

From Table 2, it could be observed that, the amount of leaching increases with the leaching period in both the ratios. At 24 hours, the amount of copper leaching was estimated to be 0.0368 ppm. At the end of 4320 hours (180 days) the value is 0.668 ppm only. The leached value of copper in tap water is well within the permissible limit as per toxicity characteristics leaching procedure (TCLP) test. As seen from Table 1a, the leached values for various elements other than copper are also within the permissible level as per TCLP test at the end of exposure period of 180 days.

3.2 Leaching in sea water

The sea water used for this study was collected from Thondi Marine station (Bay of Bengal). The water characteristics are given in Table 3

Table 4 gives the leaching of copper in sea water in ppm over a leaching period of 180 days.

From Table 4, it is observed that, 0.5:1 ratio showed more amount of copper leaching than 1:1 ratio. In general, in both the cases, the amount of copper leaching showed higher values in sea water. The amount of leaching in sea water is 10 times greater than tap water. For example, at 24 hours the amount of leaching in sea water and tap water was 0.3 and 0.03 ppm, respectively. At the end of exposure period of 180 days, the leaching was found to be 0.829 and 0.239 ppm, respectively, for 0.5:1 and 1:1 ratios. This may be due to the difference in the water characteristics (physico-chemical parameters) between sea water and tap water. Sea water contains higher amount of free chlorides, high pH, and the hardness is also high when compared with tap water. In 0.5:1 ratio, the amount of leaching increases with time, whereas in 1:1 ratio, the amount of leaching decreases with time.

Table 1: Composition of copper slag

Element	Percentage (%)
Copper	0.80
Iron	43.00
Silica	34.90
Sulfur	1.00
Lime	2.11
Magnetite	1.80
Alumina	3.11
Magnesium	0.22

Table 2: Leaching of Copper in tap water for different duration

Days	Leaching of copper in tap water		Permissible level (ppm)
	Slag water ratio		
	0.5:1	1:1	
	Amount of leaching (ppm)	Amount of leaching (ppm)	
1	0.0368	0.0275	1-2
25	0.1897	0.0905	
60	0.1836	0.0982	
120	0.0920	0.0450	
180	0.6680	0.1070	

3.3 Leaching in acid rain water

The composition of the artificial acid rain water used in the study is given below.

pH	:	2-4
Sulfuric acid	:	3.185 mg/l
Ammonium sulfate	:	4.62 mg/l
Sodium sulfate	:	3.195 mg/l
Nitric acid	:	3.15 mg/l
Sodium nitrate	:	2.125 mg/l
Sodium chloride	:	8.484 mg/l

Table 5 shows the leaching of copper in acid rain water in terms of parts per million (ppm) over a period of 180 days.

Here again, the amount of copper leached was increasing with the leaching period from 24 to 4320 hours (180 days). At the end of 180 days, the amount of leaching in acid rain water is more when compared with tap water and sea water. The amount of copper leached was found to be 0.03 and 0.911 ppm at 4320 hours (180 days). The same result was already observed in tap water. The amount of copper leached by the different media follows the order:

Acid rain water > Sea water > Tap water

Among all, tap water showed a least value when compared with acid rain and sea water.

Other than copper, the leached elements such as arsenic (As), antimony (Sb), bismuth (Bi), cadmium (Cd), lead (Pb) were estimated using atomic absorption spectroscopy and reported in Table 6.

From solution studies, it is concluded that, the tap water and sea water releases negligible amount of copper from copper slag even at a maximum period of 4320 hours (180 days).

4. LEACHING OF COPPER SLAG FROM COPPER SLAG ADMIXED MORTAR

Cylindrical mortar (1:3) specimens of size 5 cm diameter and 10 cm height were cast using copper slag as a sand replacement material. After 24 hours, the mortar specimens were demoulded and kept immersed in various aqueous media such as tap water, sea water, and rain water. The same quantity of water is taken for all the three systems studied. The surrounding solution near the mortar is taken and analyzed for leaching of copper periodically using AAS.

Rain water used in the study is natural rain water having the following characteristics:

pH	:	7.11
Free chloride	:	nil
Total hardness	:	69.12 ppm
Permanent hardness	:	55.29 ppm
Temporary hardness	:	13.83 ppm

Table 6 shows the data for leaching of copper in ppm for various systems under different exposure periods.

Triplicate studies were carried out for each exposure period and average value is reported in Table 7. It is observed from Table 7 that in all the three systems, the amount of copper leaching is found to be less up to 7 days of exposure period and reaches a maximum at 14 days and then gets reduced at 28 days except in the case of sea water. In the case of sea water, the amount of copper leaching increases with respect to time. But at the end of 150 days it gets reduced in sea water. When compared with solution studies, the amount of leaching is less in copper

Table 3: Physico-chemical parameters of thondi sea water

Properties	Volume
Salinity	29.45 ppm
Dissolved oxygen	4.11 ml/l
pH	8.68
Chloride	22000 ppm
Calcium	840 mg/l
Magnesium	1276 mg/l
Alkalinity	112 ppm
Alkalinity due to CO_3	16 ppm
Alkalinity due to HCO_3	107 ppm
Inorganic phosphate	6.48 μg PO_4/l
Organic phosphate	0.054 μg PO_4/l
Dissolved organic phosphate	3.302 μg PO_4/l
Total phosphorus	9.784 μg PO_4/l
Nitrite	0.394 ppm
Nitrate	0.670 ppm
Iron	0.002 ppm
Potassium	324.2 ppm
Sodium	1821.63 ppm

Table 4: Leaching of copper in sea water for 180 days

Days	Slag water ratio		Permissible level (ppm)
	0.5:1	1:1	
	Amount of copper leaching (ppm)	Amount of copper leaching (ppm)	
1	0.3328	0.4500	1-2
25	0.5430	0.3230	
60	0.5390	0.2650	
120	0.6020	0.2520	
180	0.8290	0.2390	

Table 5: Leaching of Copper in acid rain water 180 days

Days	Leaching of copper in acid rain water		Permissible level (ppm)
	0.5:1	1:1	
	Amount of copper leaching (ppm)	Amount of copper leaching (ppm)	
1	0.0325	0.0166	1-2
25	0.0330	0.1720	
60	0.1440	0.1420	
120	0.3600	0.1000	
180	0.9110	0.9310	

Table 6: Leachability study of copper slag for a period of 6 months with various leachants

Element	Limit as per TCLP* test (mg/l)	Tap water mg/l	Acid rain water mg/l	Sea water mg/l
As	5.0	0.389	0.334	0.745
Sb	1.0	NF	NF	NF
Pb	5.0	NF	NF	NF
Cd	1.0	0.029	0.003	0.007
Cr	5.0	NF	NF	NF
Bi	100	NF	NF	NF
Ag	5.0	NF	NF	NF
Hg	0.2	NF	NF	NF
Cu	2	0.1070	0.9310	0.2390

TCLP: Toxicity characteristics leaching procedure

Table 7: Leaching of Copper in various systems

		Leaching of copper in ppm		
Days	Hours	Tap water	Sea water	Rain water
1	24	0.0013	0.0638	0.0076
3	72	0.0150	0.0816	0.0150
7	96	0.0169	0.0842	0.0093
14	336	0.2370	0.1823	0.2234
28	672	0.0203	0.1940	0.0200
150	3600	0.0070	0.1310	0.0060

slag admixed mortar, this may be due to the complex formation with cement mortar. As already observed in solution studies, contrary behavior is observed in mortar specimens immersed in sea water. Among all, rain water and tap water yielded similar amount of copper from mortar specimens.

The amount of copper leaching in ppm for various systems follows the order:
Sea water > Tap water = Rain water

4.1 Leaching of copper from copper slag admixed concrete

Concrete cubes of size 10 × 10 × 10 cm were cast with water cement ratio 0.44 using copper slag. After 24 hours of casting the specimens were demoulded and kept immersed in tap water, rain water, and seawater. Periodically the copper leaching is estimated using AAS. The table shows the copper leaching in different media in ppm level.

It is seen from Table 7 that, the same trend is observed that of the mortar. But initially the leaching is observed to be very less (not deductible) indicated by the negative sign. Tap water and rain water showed no leaching of copper up to 3 days of exposure. But sea water showed leaching of copper in all the exposure periods.

Here again, the trend in leaching of copper from slag admixed concrete follows the order:
Seawater > Tap water > Rainwater

5. ELECTROCHEMICAL EVALUATION OF COPPER SLAG ADMIXED STEEL/ CONCRETE INTERFACE

5.1 Electrochemical Impedance Spectroscopy

The electrochemical characteristics of the embedded steel in copper slag admixed mortar and sand mortar was analyzed by electrochemical impedance spectroscopy (EIS) technique. Three electrode cell assembly was used for impedance measurements. Mild steel embedded in mortar specimen was used as a working electrode and the platinum foil was used as the counter electrode. Saturated Calomel electrode (SCE) served as a reference electrode. The mortar and 0.04 N NaOH solution was used as an electrolyte.

Figure 1 shows an EIS response of the steel/copper slag used cement mortar interface and steel/sand used cement mortar interface immersed in tap water. The response is shown as a Bode plot. It can be seen that steel specimen in conventional sand mortar has shown higher impedance than the specimen in copper slag-based mortar after 100 days of exposure. The increase in impedance value with respect to immersion time clearly states that, this is due to cement hydration. In the case of copper slag mortar the continuous increase of impedance correlates the posthydration reaction. The impedance values were found to be greater than 5 Ω for sand mortar and it is found to be lesser than 5 Ω for the copper slag mortar which indicates that copper slag mortar is found to perform better than the sand mortar even after 100 days of exposure [Figure 1].

Figure 2 shows the behavior in seawater immersion. Higher impedance has been observed in sand-based cement mortar. In the case of copper slag mortar lesser magnitude of impedance was observed than the conventional mortar. In seawater the leached $Ca(OH)_2$ may be consumed, which reduces further reaction. The only difference is that the higher order of impedance is seen for the tap water exposed system than the seawater exposed system [Figure 2].

Figure 3 shows the EIS response in rainwater exposure. The trend is same in tap water exposure but higher magnitude of impedance response has been realized. From the EIS studies it is observed that, all the copper slag admixed mortar has shown lesser impedance values than sand mortar after 100 days of exposure in tap water, rain water, and sea water. This may be due to the presence of iron present in the in the copper slag which favored the corrosion of steel in mortar, which decreased the impedance values of the mortar [Figure 3].

5.2 Potentiodynamic polarization

The observations made through EIS measurements have further been supported by potentiodynamic polarization study of all the test solution both in the copper slag and sand-based cement mortar. These data were generated for the systems at the maximum exposure of time to different environment such as in tap water, seawater, and rainwater. Figure 4 relates the corrosion potential (E_{corr}) with different exposure period recorded for bare mild steel specimen in all the three solutions. The copper slag admixed cement mortar performed as like conventional mortar in tap water and rainwater exposure. In the case of seawater exposure the values were shifted to more negative side, which implies passive film disruption has taken place due to the chloride attack. Chloride present in the seawater reacts with mild steel and iron present in the copper slag, which breaks down the passive layer formation in mild steel and shifter the potential to the more negative direction.

5.3 Compressive strength measurements

Concrete cubes of size 100 × 100 × 100 mm were cast using 1:1.56:3.08 mix with a W/C ratio of 0.44 with and without copper slag. During casting, the cubes were mechanically vibrated using a table vibrator. After 24 hours the specimens were demoulded and subjected to curing for 28 and 90 days in distilled water. After curing, the specimens were tested for compressive strength using AIMIL compression testing machine of 100 T capacity. The maximum load at failure reading was taken and the average compressive strength is calculated using the equation.

$$\text{Compressive strength (N/mm}^2) = \frac{\text{Maximum failure load (N)}}{\text{Area of cross section (mm}^2)}$$

The tests were carried out on a set of triplicate specimens and the average compressive strength values are given in Table 9:

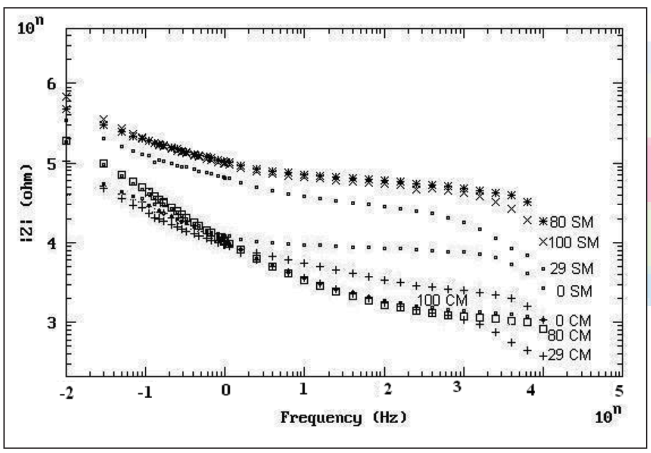

Figure 1: Bode plot for mild steel in Copper slag and Sand mortar exposed in tap water at 29, 80, and 100 days of exposure period

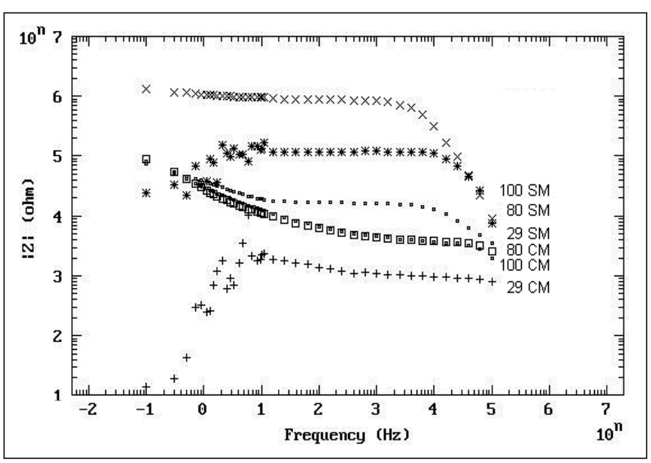

Figure 3: Bode plot for mild steel rebar in Copper slag and Sand mortar exposed in Rain water at 29, 80, and 100 days of exposure period

It is found from Table 9 that, for control concrete (i.e., concrete without slag) the compressive strength is found to be 31.69 N/mm². In contrast, slag admixed concrete has the compressive strength of 36.35 N/mm² after 28 days of curing. After 90 days of curing also, the compressive strength of the copper slag admixed concrete is found to be more than the compressive strength of the ordinary Portland cement (OPC) concrete. The slag admixed concrete showed higher strength values than corresponding control concrete. The percentage increase in strength is found to be 14.70% and 17.80% at 28 and 90 days, respectively. The important observation is that the addition of slag did not affect the compressive strength of concrete but actually increased the compressive strength of admixed concrete.

5.4 Chloride permeability test

Mortar disk specimens of size 83 mm diameter and 50 mm thickness were cast using with and without copper slag. After 24 hours, the disk specimens were removed from the mould and subjected to curing for 28 and 90 days in chloride free distilled water. After curing, the specimens were tested for chloride permeability. All the specimens were dried free of moisture before testing.

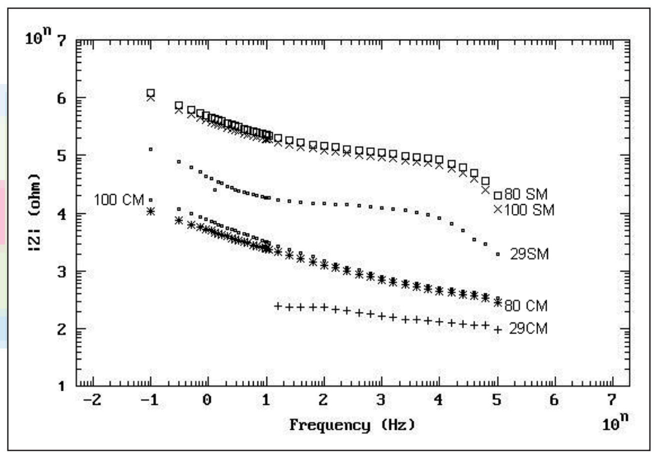

Figure 2: Bode plot for mild steel in Copper slag and Sand mortar exposed in sea water at 29, 80, and 100 days of exposure period

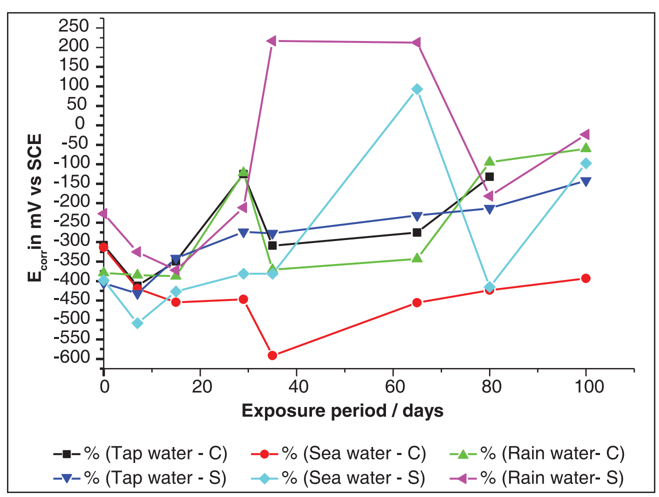

Figure 4: Corrosion potential of Copper slag and Sand mortar in various environments

The test set up is called rapid chloride penetration test (RCPT) assembly. This is the two compartment cell assembly. Disk specimen is assembled between the two compartments cell assembly and checked for air and water tight. The cathode compartment is filled with 3% NaCl solution and the anode compartment is filled with 0.3 N NaOH solutions. Then the mortar specimens were subjected to RCPT by impressing a 60 V from a direct current (DC) power source between the anode and cathode. Current is monitored up to 6 hours at an interval of 30 minutes. Table 10 shows the current recorded over a period of 6 hours at an interval of every 30 minutes. From the current values, the chloride permeability is calculated in terms of coulombs at the end of 6 hours by using the formula:

$$Q = 900\,[I_0 + 2\,I_{30} + 2\,I_{60} \text{ - - - - } 2\,I_{300} + 2\,I_{360}]$$

where Q = Charge passed in coulombs

I_0 = Current (Amp.) immediately after voltage is applied and

It = Current (Amp.) at "t" minutes after voltage is applied.

For control mortar, the average charge passed is found to be 3175 coulombs and for slag admixed mortar the charge passed is found to be 3119 coulombs after 28 days of curing. The charge passed for copper slag admixed mortars have showed less values than control mortar. It indicates the lesser permeability of slag admixed mortar than sand mortar. The important observations are that the addition of slag definitely reduced the pores of concrete and make the concrete impermeable. At 90 days curing period, the values obtained for sand and slag mortars are 302 and 295 coulombs, respectively. As per ASTM C-1202, both the values are graded under the category "very low".

Table 8: Leaching of Copper from Copper slag admixed Concrete

Days	Hours	Leaching of copper in ppm		
		Tap water	Sea water	Rain water
1	24	−0.0157	0.0214	−0.0128
3	72	−0.0143	0.0251	−0.0215
7	96	0.0015	0.0032	0.0153
14	336	0.2414	0.2657	0.2504
28	672	0.0630	0.2950	0.0170

Table 9: Compressive strength

System	Compressive strength (N/mm²	
	@ 28 days	@ 90 days
Control	31.69	33.70
Slag concrete	36.35	39.70

Table 10: Chloride permeability test

Curing period	Charge passed in coulombs		As per ASTM C1202
	Sand mortar	Copper slag mortar	
28 days	3175	3119	Moderate
90 days	302	295	Very low

5.5 Open circuit potential measurements

Cylindrical reinforced mortar (1:3, w/c 0.45) specimens of size 50 mm diameter and 100 mm height were cast in triplicate with and without copper slag. All the triplicate specimens were cured in distilled water for 28 days. After 28 days the specimens were taken out and dried. The potential of the embedded rebar was monitored against SCE using a high impedance voltmeter before keeping the specimens in 3% NaCl solutions. Then the specimens were subjected to alternate wetting (5 days) and drying (5 days) in 3% NaCl solutions in order to induce accelerated corrosion. The potential readings were measured periodically. The experiment was continued for a period of 150 days. The measurements were carried out as per the procedure given in ASTM C 876-1999. The solution was changed once in a week in order to induce accelerated corrosion. Potential measurements were carried out for both sand mortar and copper slag admixed systems at an ambient temperature of 32 + 1°C. Figure 5 depicts the relationship between potential time behavior of sand mortar and copper slag admixed mortar.

From Figure 5 it is found that all the systems are showing more negative potentials than −270 mV versus SCE indicating the active condition of the rebar. Both sand mortar and copper slag mortar in sea water showed a very high negative potential of more than −500mV versus SCE indicating the active condition of rebars. Both the mortars system in tap water and rain water showed a negative potential of −300mV versus SCE at the end of 150 days indicating the slight passive condition of rebars. The trend in reduction in the passivity of the various systems follows the order:
Sea water > Tap water = Rain water

5.6 Gravimetric weight loss measurements

The weighed mild steel specimens were embedded in mortar cylinder of size 50 mm diameter and 100 mm height. The mortar samples were subjected to alternate wetting and drying exposure in 3% NaCl solution. At the end of the exposure period (150 days), the mortar specimens were broken open and the rebar specimens were cleaned in the pickling solution as per ASTM G1-90. After cleaning, the specimens were washed with water and dried. The specimens were reweighed and the loss in weight was calculated. From the weight loss values, the corrosion rates were obtained from the relationship:

$$\text{Corrosion rate (mmpy)} = \frac{87.6 \times \text{Loss in weight (mg)}}{\text{Density (g/cm}^2) \times \text{Area (cm}^2) \times \text{Time (hours)}}$$

From Table 11, it is observed that the slag admixed mortar showed slightly lesser corrosion rates than control mortars in all the three systems studied. The corrosion rate of slag admixed mortar in tap water is found to be 11 times lesser than control mortar. The corrosion rates for control and slag mortars in seawater were found to be 0.0040 and 0.0020 mmpy, respectively, that is, the corrosion rate for control system in sea water is almost doubled when compared with slag admixed mortar.

The corrosion rate in rainwater is slightly lower than the sea water. Here also, the corrosion rate for admixed mortar is lower than the control mortar.

Among all, both the mortar systems in sea water showed a higher corrosion rate, when compared with systems in tap water and rain water. Negligible corrosion rates were observed for slag mortars in tap water and rain water.

The trend in reduction of corrosion rate for copper slag admixed mortars in various media follows the order:

Tap water > Rain water > Sea water

5.7 Macro cell corrosion technique

A rectangular concrete specimen of size 279 × 152 × 114 mm was designed as per ASTM G 109 - 92 for macro cell corrosion studies. Cold Twisted Deformed (CTD) rebar of size 12 mm diameter, 300 mm length was used as cathodes, 220 mm length was used as anode and exposed in the same concrete and taking electrical connection by screwing the 6 mm diameter rod on the anode and the edges were properly insulated from the aggressive environments. Initially the CTD rods were cleaned in hydrochloric acid, degreased with acetone and washed with double distilled water and dried. The initial weight of the anode was taken before casting using Mettler balance for gravimetric measurements. The top mat of rebar acts as anode and the bottom mat of rebars act as cathodes. The anode to cathode area ratio was maintained as 1:2 in order to induce accelerated corrosion.

Table 11: Corrosion rate of mild steel in sand mortar/ slag mortar

System	Average corrosion rate (mmpy)	
	Sand mortar	Slag mortar
Tap water	0.0022	0.0002
Sea water	0.0040	0.0020
Rain water	0.0025	0.0014

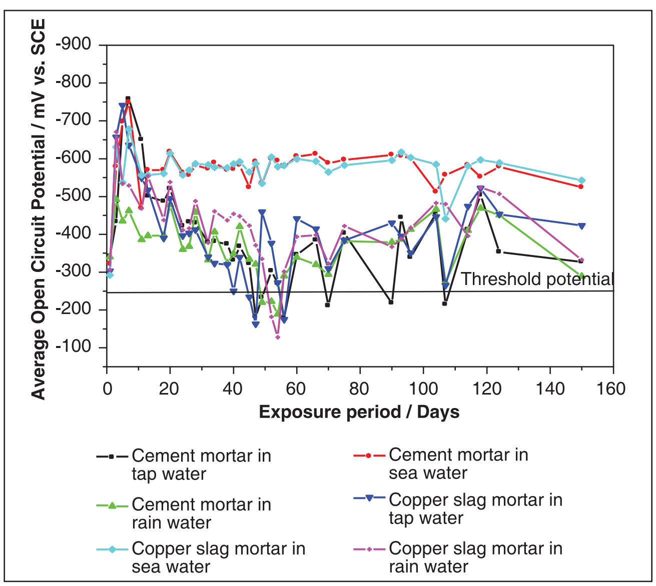

Figure 5: Average Open Circuit Potential for cement mortar and copper slag mortar in different mediums

Concrete specimens were cast with and without copper slag using 1:1.71:3.1 mix with a w/c ratio of 0.50. The specimens were cast with mechanical vibration. After 24 hours, the specimens were demoulded and cured in distilled water for 28 days. After curing, then all the concrete specimens were ponded with 3% NaCl wetting cycle immediately. One alternate wetting and drying cycle consists of 5 days wetting with 3% NaCl solution and 5 days drying. Measurements were carried out during wetting cycles as macro cell current showed maximum magnitude due to the low resistivity of concrete. The triplicate concrete specimens were subjected to 120 days test period. Tests were conducted on a minimum of three replicate specimens and the average values were recorded.

Macro cell current flow between anode and cathode was measured using a high input impedance voltmeter. The top mat and bottom mat rebars were connected by a 100 Ω resistor and macro cell current was obtained from the relation I = V/100. Current was monitored once in every cycles until, the average macro cell current of the control specimens is 10 μA or greater. From the experiment the total integrated current for each system was calculated as per ASTM G 109-92.

$$TCj = TCj\text{-}1 + [(tj - tj\text{-}1)^* (ij + ij\text{-}1)/2]$$

TC = total corrosion (coulombs)

tj = time (seconds) at which measurement of the macro cell current is carried out and

ij = macro cell current (amps) at time tj

Figure 6 depicts the relation between anode potential versus exposure period for OPC concrete and copper slag admixed concrete. From the figure it is observed that, both the systems are showing the less negative potential indicating the passive condition of the rebar. Another important observation is that after 120 days of exposure also copper slag admixed concrete is showing the potential lesser than the ordinary Portland cement concrete. From the macro cell corrosion studies it is concluded that copper slag admixed concrete is found to perform better than the OPC.

The macro cell current versus exposure period and the total integrated current versus exposure period studies for the copper slag admixed concrete shows that there is a negligible

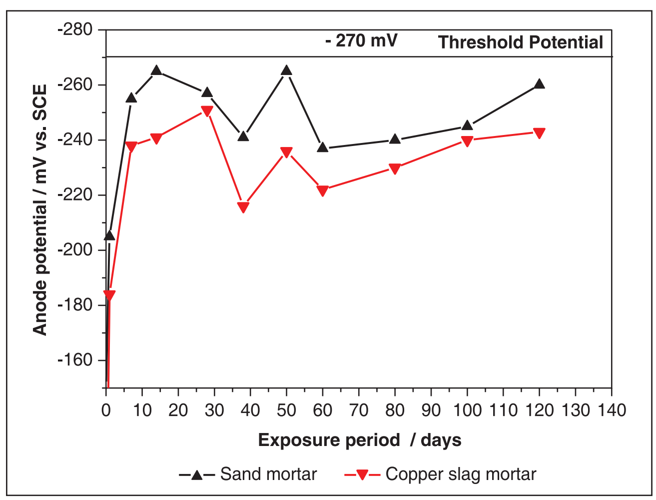

Figure 6: Anode Potential versus exposure period for OPC concrete and copper slag admixed concrete under macro cell condition

current flow between anode and cathode were observed. At the end of 60 days exposure period under severe alternate wetting and drying conditions with 3% NaCl, the copper slag admixed concrete perform better than corresponding control concrete.

6. CONCLUSIONS

Following conclusions can be drawn from the investigations:

- From our investigations it is concluded that copper leaching is very less even after 150 days of exposure in all aqueous media.
- Compressive strength measurements revealed that the addition of copper slag did not affect the compressive strength of the blended copper slag concrete. In fact it increased the compressive strength of the copper slag concrete.
- RCPT test revealed that after 90 days curing period the total charge passed was found to be very less when compared with the sand mortar.
- Gravimetric weight loss measurements indicated that negligible corrosion was observed after 150 days of exposure in sea water.
- OCP and impedance measurements revealed that the potentials were found to be less than -275 mV versus SCE indicating the passivity of the rebars.
- It can be seen that steel specimen in conventional mortar has shown higher impedance values than the specimen in copper slag-based mortar. The increase in impedance for a test period clearly states that, this is due to cement hydration. In the case of copper slag mortar the continuous increase of impedance correlates the posthydration reaction.
- Copper slag can be used as an alternative material for coarse and fine aggregate, since it gives better performance in all the corrosion tests conducted and permeability is less when compared with control concrete. Hence Copper slag can be utilized as sand replacement material without affecting the durability properties of concrete. Copper slag can be used as a potential alternative to coarse aggregate/fine aggregate used in concrete and mortars.

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