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A study on copper slag as fine aggregate in improving the electrical conductivity of cement mortar

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Abstract. Electrically conductive mortar (ECM) is a special type of mortar that can be used in applications such as deicing pavements, anti-static flooring, cathodic protection, self sensing etc. ECM can be prepared by incorporating electrically conductive particles in concrete. The carbon materials like graphite, carbon nano fibres, carbon nano tubes are generally used in the development of ECM. In order to make the ECM more sustainable and cost effective, industrial solid wastes having electrically conductive properties are attempted in this study. Carbon black and high carbon content bagasse ash obtained from petroleum and sugarcane processing industries respectively are used as cement replacement materials. Copper slag and steel slag are used as conductive fine aggregates in the development of ECM and tire waste, a coarser petroleum by-product is also used as fine aggregate substitute. Results indicated that the presence of high content of Fe_2O_3 in copper slag increased the conductive property of ECM. The 100% replacement of conventional fine aggregate by copper slag aggregate made the ECM more sustainable. The compressive strength of copper slag mortar is also found be higher than the steel slag or river sand mortar. The study demonstrates the usefulness of copper slag as fine aggregate in the development of special mortar.

Keywords. Copper slag; steel slag; river sand; electrical conductivity; steel fibre.

1. Introduction

Solid waste generation from the industry is increasing exponentially due to the increase in the number of industries. Industries are facing problem in disposing their generated waste safely. The means and methods adopted/proposed to use the waste generated from the industries would lead to sustainability. Nowadays, in the cement and aggregate making, many industrial by-products are used. Similarly, special concretes such as self compacting concrete, reactive powder concrete, ultra high performance concrete etc. are developed using one or more of the industrial by-products. In line with this, recently special concrete called electrically conductive concrete is developed using industrial by-products such as high carbon fly ash and copper slag [1]. It is concluded in the study that the electrical conductivity of concrete can be improved by using high carbon fly ash and copper slag. Greater than 50% replacement of copper slag improved the electrical conductivity of concrete [1].

Copper slag is a by-product obtained from the copper smelting industries [2]. The amount of slag produced during the production of copper is huge, in the range of three times that of the copper manufacturing [3]. Utilization of copper slag in any useful form would reduce the piling of slag at the industrial site. Research on copper slag as fine aggregate alternative in concrete reports the outstanding mechanical and durability properties [4–6]. Further, the use of copper slag reduces the drying shrinkage of concrete [7]. The improved strength and durability of copper slag incorporated concrete is reported to be due to the high toughness of copper slag [8]. Owing to the advantages reported in the literature, copper slag is considered as a sustainable and useful material for cement/concrete based composite applications [9]. A study recently reported the influence of copper slag on improving the electrical conductivity of self compacting concrete [10].

Electrical conductivity of cement mortar/concrete is influenced by the type and dosage of constituent materials present [11, 12]. It is reported that the presence of conductive aggregates like copper slag in mortar/concrete greatly improves the electrical conductivity [1, 13]. Further, it is stated that along with the conductive aggregates, the presence of carbon content in the cement paste enhances the electrical conductivity. Conductive aggregates used for improving electrical conductivity are either artificially made like fly ash aggregates, carbon black and carbon fibre incorporated aggregates or by using industrial by-products like copper slag [1, 14, 15].

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In view of this, in the present study, attempts are made to develop electrically conductive mortar using copper slag as fine aggregate. Application as fine aggregate in cement mortar/concrete helps in minimizing the piling of slag wastes, as the increasing number of industries increases the generation of industrial solid wastes posing severe environmental problems. It is reported that for every tonne of copper produced, about 2.2 tonne of copper slag is generated occupying the huge land space [16]. Though many literature reports the copper slag as fine aggregate replacement [8, 17] in conventional mortar/concrete, the special application like electrical conductivity identified for copper slag would increase its utilization in the concrete industry. In view of this, the present study proposes to use the copper slag as 100% replacement for fine aggregate in developing electrically conductive mortar. As mentioned earlier, conductive mortar can be used for many applications like deicing pavements, earthing, cathodic protection, anti static flooring, self sensing etc. The use of copper slag for developing electrically conductive mortar provides the potential use for the generated copper slag.

2. Experimental study

2.1 *Materials and methods*

Ordinary Portland cement (OPC) conforming to IS12269 [18] is used in this study. Elemental composition of OPC, steel slag and copper slag are presented in Table 1. The physical properties such as water absorption, specific gravity and fineness modulus of river sand, steel slag and copper slag aggregates are obtained and presented in Table 2. Cement mortar mixes are prepared with various combinations of materials with 1:3 (Cement:fine aggregate) ratio with the water to binder ratio of 0.45. Three types of fine aggregates are used in this study namely, river sand, steel slag and copper slag. Figure 1 shows the photograph of the selected fine aggregates used in this study. Further, three types of high carbon content material such as carbon black (CB), bagasse ash (BA) and tire waste (TW) are also used to increase the electrical conductivity. Hence, for each carbon material replacement in cement, four mortar mixes namely with river sand (RS), river sand and steel fibre (RSSF), steel slag (SS) and copper slag (CS) are prepared for electrical resistivity measurements. The mix proportion for each mortar and its designation are presented in Table 3. As the main focus of the study is to investigate the electrical conductivity of the mixes, all the 12 mixes are tested for its electrical resistivity and compared. Electrical conductivity is generally represented by its inverse i.e. electrical resistivity. The basic properties required for a cement mortar is the compressive strength to use the mortar for any applications. Hence, firstly, the suitability of replacing fine aggregate by steel and copper slag fine aggregates are found by conducting compressive strength test on 70 mm mortar cubes. The same 1:3 ratio of cement:fine aggregates is used for making cubes for compressive strength. Cement is replaced by 20% of bagasse ash in the mixes prepared for compressive strength testing.

Table 1. Elemental composition of ordinary Portland cement (OPC), steel slag and copper slag.

Element oxides OPC	OPC Percentage	Steel slag	Copper slag
CaO	64.1	3.14	3.400
SiO_2	21.0	65.8	10.80
Al_2O_3	5.10	8.40	0.860
Fe_2O_3	3.10	14.8	59.90
MgO	2.5	0.72	0.002
K_2O	0.70	0.32	0.300
Na_2O	0.30	1.25	0.020
SO_3	2.20	0.35	1.190
MnO	–	12.2	–
TiO_2	1.50	0.34	
Loss on Ignition (LOI)	0.60	2.50	10.70

Table 2. Physical properties of fine aggregate.

Properties	River sand	Steel slag	Copper slag
Specific gravity	2.6	2.4	3.3
Fineness modulus	2.48	2.34	3.2
Water absorption (%)	1.8	4.4	6.1

2.2 *Specimen preparation*

Six numbers of 70 mm cubes are cast for each mix to carry out 7 and 28 days compressive strength respectively. Cubes are cured under water till 7 and 28 days and tested on the respective days. For carrying out electrical resistivity measurements, prisms of size 50mm x 50mm x 250mm are cast for each mix. Steel meshes are embedded in the specimens as shown in Figure 2 which act as electrodes for the measurement using four probe method.

2.3 *Electrical resistivity (ER) measurements*

Electrical conductivity is generally expressed by the measurement of electrical resistivity. Higher electrical resistivity indicates the lower conductivity. Electrical resistivity measurements are carried out by using the functional generator, power amplifier, multimeter and oscilloscope as shown in Figure 2. The parameters for measuring the resistivity of cement mortar have been determined based on the reported literature [19]. 10 kHz frequency and 20V peak to peak amplitude is applied and voltage is measured using the four probe method as shown in Figure 2. The specimens

Figure 1. Different types of fine aggregate a) River sand b) Copper slag c) Steel slag.

Table 3. Designation and batch quantities for 6 cubes and 2 prisms for cement mortars.

Mix	Cement	Carbon black	Steel fibre	Fine aggregate
		kg		
RSCB	1.98	0.22	–	6.6
RSSFCB	1.98	0.22	0.0011	6.6
SSCB	1.98	0.22	–	6.6
CSCB	1.98	0.22	–	6.6
Mix	Cement	Bagasse ash	Steel fibre	Fine aggregate
RSBA	1.56	0.44	–	6.6
RSSFBA	1.56	0.44	0.0011	6.6
SSBA	1.56	0.44	–	6.6
CSBA	1.56	0.44	–	6.6
Mix	Cement	Tyre waste	Steel fibre	Fine aggregate
RSTW	2.2	0.33	–	6.27
RSSFTW	2.2	0.33	0.0011	6.27
SSTW	2.2	0.33	–	6.27
CSTW	2.2	0.33	–	6.27

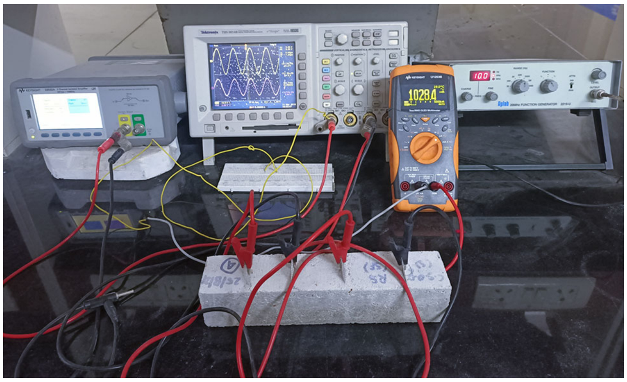

Figure 2. Experimental set up for the electrical resistivity measurements.

cast for electrical resistivity measurements are kept under water curing for 28 days to allow for complete hydration. After 28 days, the specimens are taken out of the water and kept under ambient condition. During the curing period, i.e. till 28 days, for testing at 1, 7, 14 and 28 days, the specimens are taken out of the water, surface is wiped off before taking the measurements. At 56, 90, 120 and 180 days the electrical resistivity measurements are carried out on specimens that are kept under ambient condition.

3. Results and discussion

The average compressive strength of three numbers of cubes have been obtained and the results with error bar (standard deviation) at 7 and 28 days are shown in Figure 3. Compressive strength obtained for the copper slag mortar mixes shown the highest value at both 7 and 28 days. As reported in many literature [8, 17], the strength of the mix with copper slag is high compared to river sand and steel slag mixes. It is further noticed that the compressive strength is very high in the mix with 100% replacement of river sand by copper slag than 50% replacement. This shows that the compressive strength of the mix is unaffected by the replacement of copper slag and even improved the strength significantly.

During the electrical resistivity (ER) measurements, there are many factors influencing the measurements. The presence of moisture content, dosage of carbon materials and its dispersion, period of measurement etc. With the presence of moisture content, the electrical resistivity is less and it increases when the moisture content reduces. Hence, the electrical resistivity is measured for the samples till the values are almost stabilized.

Considering the cement replacement materials used in this study, carbon black (CB) mostly composed of carbon (about 89%) and bagasse ash (BA) having high carbon content (about 10%) are used in this study. As the carbon black is composed of about 89% of unburnt carbon, it is replaced for only 1% by weight of cement. Bagasse ash having pozzolanic nature is replaced for cement by 20%. Another material tyre waste, having carbon content of about 92% is also used for improving the electrical conductivity. However, owing to the coarser nature of the tire

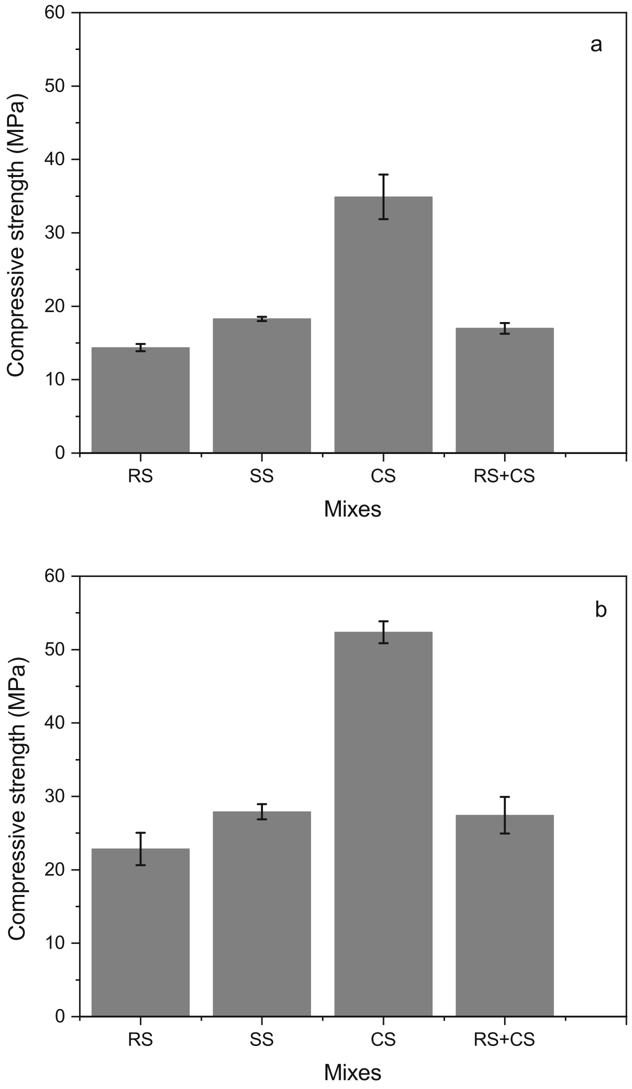

Figure 3. Compressive strength of river sand, steel slag sand and copper slag mortar mixes a) 7 days b) 28 days.

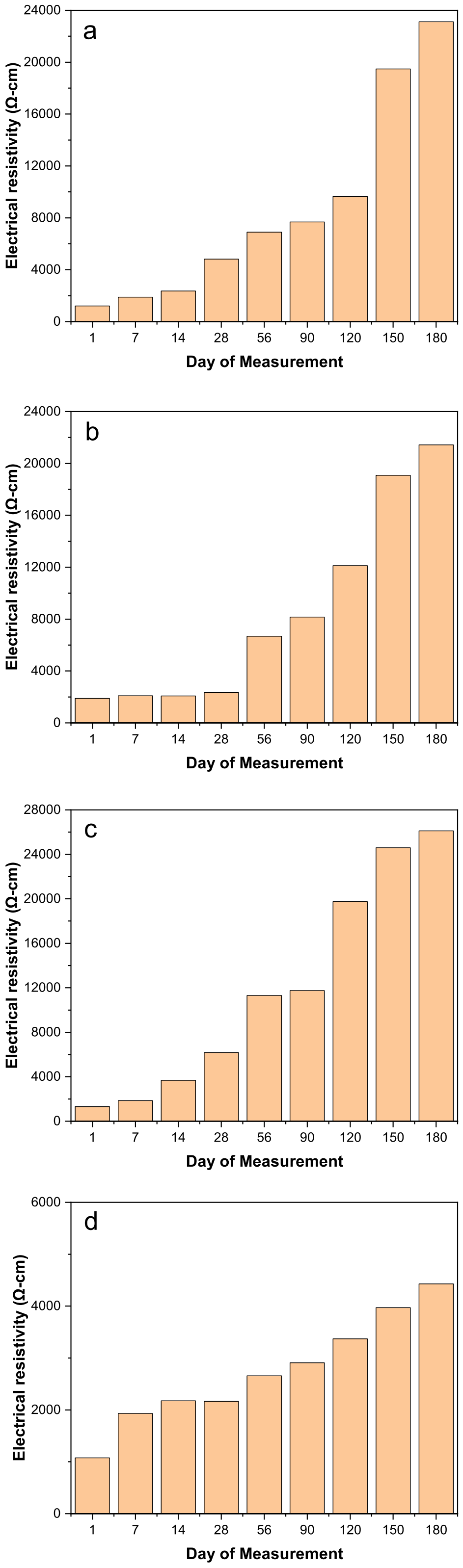

Figure 4. Electrical resistivity of carbon black mortars a) RSCB b) RSSFCB c) SSCB d) CSCB.

waste, it is replaced for fine aggregate by 5%. Based on the chemical composition of various materials used in this study, it is realized that carbon black and tire waste may not participate in the hydration reactions, however, helpful in improving the electrical conductivity. Bagasse ash on the other hand would contributes for the pozzolanic reaction to a greater extent but contribution to the electrical conductivity would be lesser. With the background of the reactivity of the various materials used in this study, electrical conductivity of the mortar prepared with these materials are measured and presented in Figures 4 to 6.

Figure 4 shows the electrical resistivity measurements of carbon black incorporated cement with river sand (RSCB), river sand and steel fibres (RSSFCB), steel slag (SSCB) and copper slag fine aggregates (CSCB). It is noticed that

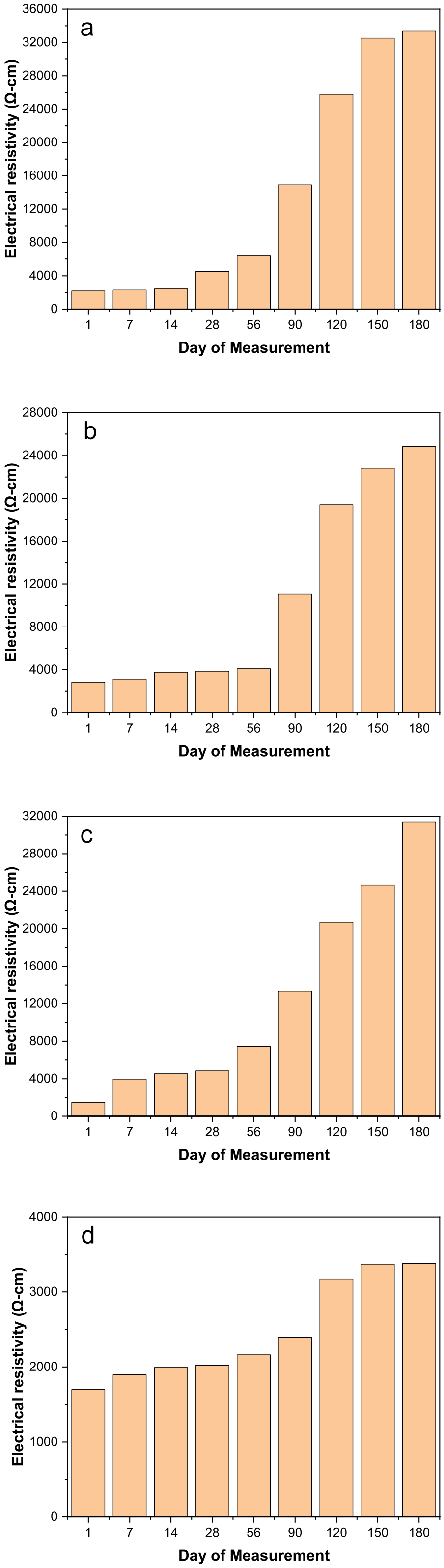

Figure 5. Electrical resistivity of Bagasse ash mortars a) RSBA b) RSSFBA c) SSBA d) CSBA.

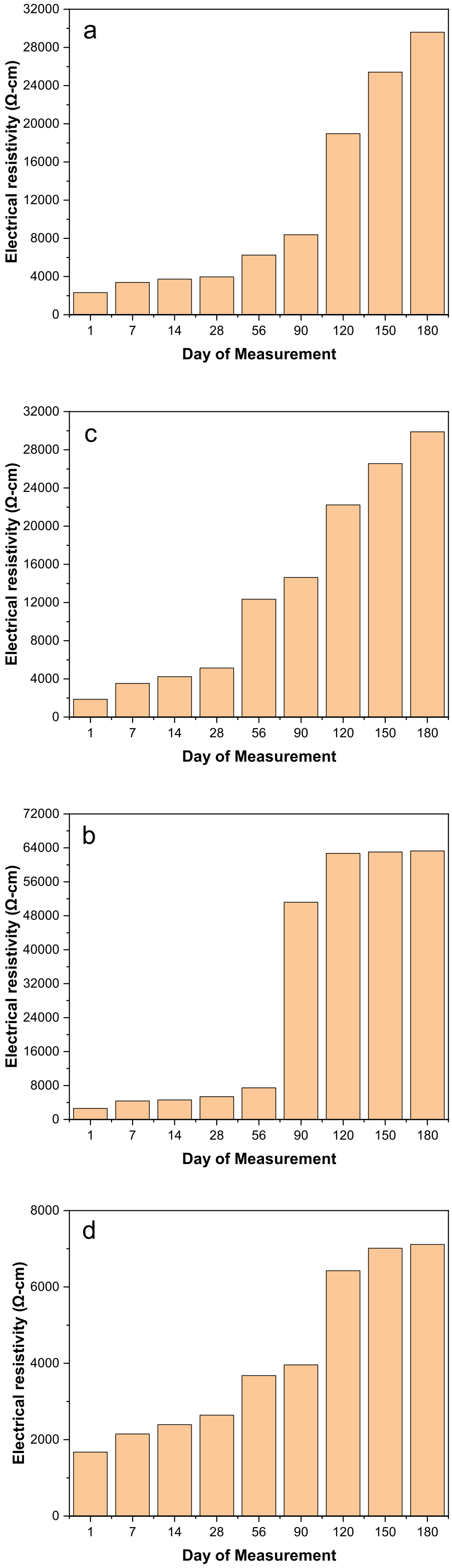

Figure 6. Electrical resistivity of tyre waste mortars a) RSTW b) RSSFTW c) SSTW d) CSTW.

among the four mortar mixes, the electrical resistivity of copper slag mix (CSCB) is very less i.e. more conductive indicating the copper slag as a potential candidate for making electrically conductive mortar. The other observations are, upto 180 days, the electrical resistivity values are not stabilized and is increasing with period of time in all the four mixes. However, the rate of increase in electrical resistivity is slow in the CS mix. This indicates that in the mix with copper slag, the increase in resistivity is slow and steady. Comparing the four CB mixes, 180 days electrical resistivity is higher in steel slag mix indicating the low conductivity.

Similarly, Figures 5 and 6 shows the similar trend that the mix with copper slag had the lowest electrical resistivity indicating the good electrical conductivity for the CS based mixes. This shows that irrespective of the type of carbon materials in cement, the fine aggregate used greatly influenced the electrical resistivity measurements. The four mixes shown in Figures 4 to 6 indicate that the rate of increase in electrical resistivity with time varies based on the mixture proportion. In all the mixes, it is noticed that upto 180 days the electrical resistivity increases steeply. This rate of increase depends upon the type of aggregates used and also the cement replacement materials. It is found that the electrical resistivity of copper slag mortar is in the order of 10^3, that is, one order less than the other mixes. Further, it is noticed that the rate of increase in the electrical resistivity is steady in copper slag mortar mixes compared to other three mixes and stabilized relatively beyond 120 days.

Among the three materials, carbon black, bagasse ash and tire waste, the electrical resistivity of the mortar in the mix with tire waste is higher. Especially, in the mix with steel slag as fine aggregate, it is very high compared to all the other mixes. Considering the composition of tire waste and carbon black, both are having loss on Ignition (LOI) of about 89% and 92% respectively. However, the particle size of the tire waste is coarser than the carbon black, hence, owing to the coarser nature of the tire waste, it is replaced for fine aggregate in cement mortar. Further, comparing the electrical resistivity of river sand mortar mixes (Figures 4(a), 5(a) and 6(a)), the electrical resistivity of mortar with tire waste is found to be higher. The results presented in Figures 4 to 6 show that the conductivity of mix at mortar scale is not only *affected* by the carbon content present in the cementitious material and type of aggregates (conductive and non conductive) but also influenced by the other parameter such as the interfacial transition zone (ITZ) between aggregate, conductive cement paste etc. The conductive property of aggregate, the size of fine aggregates and the electrolytic conductance due to changes in the pore solution etc. are also influencing the electrical conductivity of the mortar [20].

According to Jian *et al* [21], conductive mechanisms in cement composites are explained by theories like conductive passage, tunnel *effect* and field emission theory. As per the conductive passage theory, the formation of conductive network depends upon the contact between the conductive particles present. Conductive passage theory explains that when the spacing between the particles are small, the conductivity is high. In the present study, as the copper slag is used as conductive aggregate with the ratio of 3 parts (1:3=cement:fine aggregate) in mortar ensuring the good contact between the adjacent particles forming a conductive network. On the other hand, tunnel theory states that for forming a conductive network, it is not necessary to have a direct contact between the particles but conductive particles closer to each other at certain distance forms a tunnel for the conductive process to take place [22]. Field emission theory states that when the voltage increases to a certain value, electric field is formed between the conductive particles to generate a *effect* of the current. From the various theories reported on electrical conductivity, it is understood that in the present study, the electrical conductivity may be improved in the mortar mixes either by the formation of conductive chains by the overlap of copper slag particles or through the contact between carbon particles and copper slag. Further, there is a possibility due to the combined *effect* of slag-slag as well as carbon-slag contact.

It is further analyzed the reason for the lower resistivity in the three copper slag mixes with carbon black (CSCB), bagasse ash (CSBA) and tire waste (CSTW). From the physical properties of the copper slag (table 2), it can be observed that copper slag has high water absorption. The high water absorption of copper slag would have been the reason for the improved electrical conductivity. Further, from the fineness modulus as well as from the particle size distribution as shown in Figure 7, copper slag is found to be coarser. The coarser copper slag as the fine aggregate may provide an easier conductive path in the mortar. Furthermore, it is observed that the presence of iron oxide content in copper slag is also the reason for the improvement of electrical conductivity in the mortar. Though both the steel

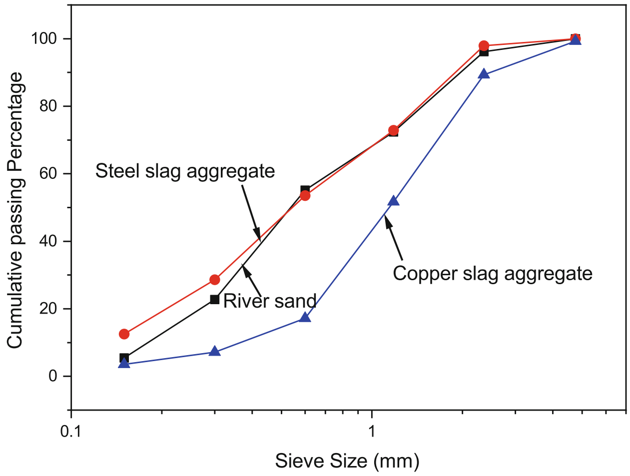

Figure 7. Particle size distribution of river sand, steel slag aggregate and copper slag aggregate.

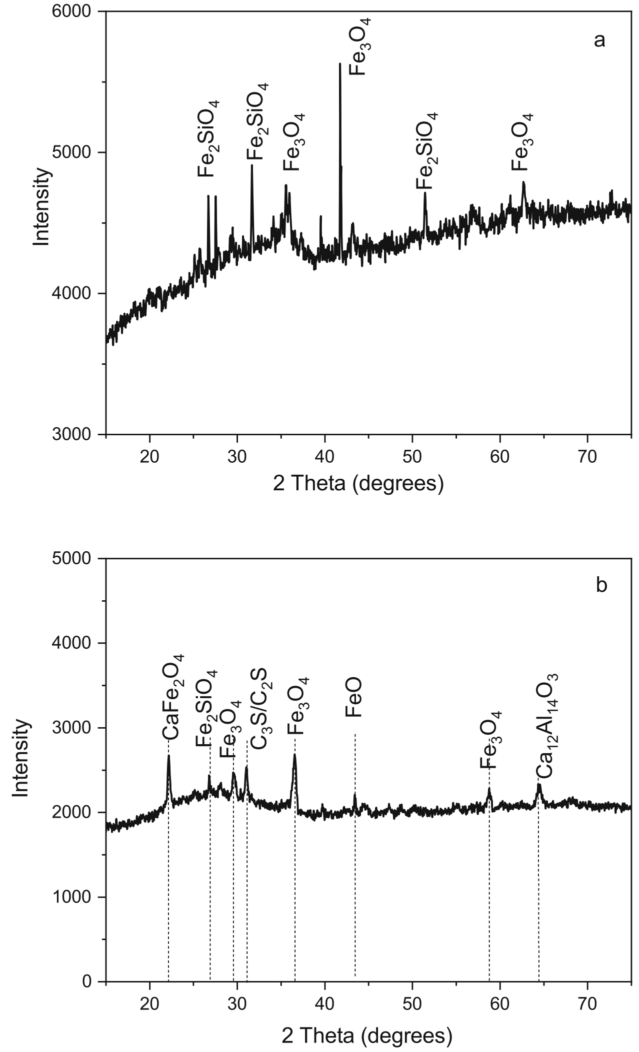

Figure 8. X-ray diffraction pattern of a) Copper slag b) Steel slag.

and copper slag have Fe_2O_3 content, the amount of iron oxide present in copper slag is more. Further, the form of iron oxide as Fe_2O_3 and Fe_2SiO_4 present in the slag also influence the electrical conductivity. To investigate the form of iron oxide present, X-ray *diffraction* (XRD) patterns of copper slag and steel slag are obtained and are shown in Figure 8. Figure 8 indicate that fayalite (Fe_2SiO_4) and magnetite (Fe_3O_4) are the two major phases found in copper and steel slag. In steel slag, besides the fayalite (Fe_2SiO_4) and magnetite (Fe_3O_4) calcium compounds are also found. As observed from the chemical composition (Table 1), silica content is more than 50% in steel slag whereas in copper slag, iron oxide is more than 50%. The presence of magnetite in copper slag may be the reason for the low electrical resistivity or the high electrical conductivity. Further, it is stated that the presence of oxides of Fe, Ca and Mg contribute majorly for the electrical conductivity of the slag. As the chemical composition of copper slag has higher concentration of FeO, the higher electrical conductivities are obtained for the copper slag mixes.

Based on the electrical resistivity measurements carried out, it is inferred that when the carbon content in the cement paste is low, then the resistivity is mainly governed by the electrical continuity of the aggregates in the cement mortar. The variation in the electrical resistivity of the three *different* mortar mixes (CB, BA and TW) in this study are due to the variation in the electrical continuity of the cement paste containing carbon particles. The presence of carbon particles as well as non conductive or less conductive aggregate in mortar *affects* the electrical continuity of the cement mortar. Due to this reason though the cement paste conductivity is higher, the conductive aggregates are required to create a conductive path for the increased conductivity. Further, the variation in the electrical resistivity of the mortar mixes with same aggregate (Figures 4(d), 5(d), 6(d)) demonstrates that the carbon content present in the cement paste has influence on the electrical resistivity although the copper slag aggregates play a significant role in developing the conductive path.

In order to investigate the influence of carbon materials on the conductivity of mortar mixes, typically, bagasse ash and carbon black mixes with two *different* replacement levels are made. Cement is replaced with 10% and 20% bagasse ash (10BA and 20BA) in one set of mix and 1% and 2% carbon black (1CB and 2CB) is replaced for cement in another set of mix. The electrical resistivity measured for these mixes are shown in Figures 9(a) and 9(b). It is observed that the electrical resistivity is not *affected* by the percentage replacement of bagasse ash or carbon black considered in this study. This indicates that when highly conductive aggregates with a good volume (about 60% to 70% of aggregates in mortar) is used in the mortar, the conductive aggregates are majorly responsible for the formation of conductive network rather than the presence of carbon particles.

Electrical conductivity of the mortar mix depends upon the electronic conductance that depends mainly upon the conductivity of the materials used and conductive network formed. Whereas the electrolytic conductance depends upon the electrical conductivity of the pore solution. The scope of the study is to analyze the potential of the slag obtained from steel and copper manufacturing industries for special applications. However, the mechanism behind the electrical conductivity of the mortar mix can be well explained by considering both the electronic and electrolytic conductance. As the bagasse ash is pozzolanic in nature and participates in hydration, the microstructural development and pore solution in bagasse ash mortar mixes are *different* from that in carbon black and tire waste mixes. The conductive network is *affected* by the pore structure of the mixes, hence, the microstructural development in the mixes with the period of time is also considered to be important. As the carbon black and tire waste are composed majorly of carbon content, the microstructural development

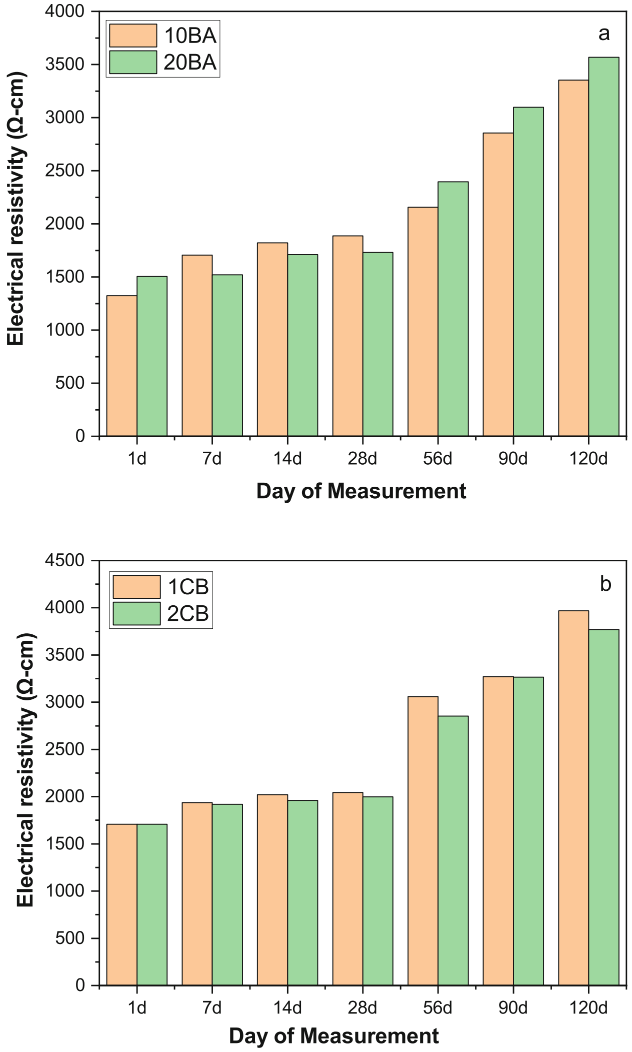

Figure 9. Electrical resistivity of mortar mix with a) Bagasse ash and b) Carbon black.

in these mixes are only due to cement hydration. Further studies are needed to understand the combined mechanism of electronic and electrolytic conductance in improving the overall electrical conductivity of the mortar.

4. Conclusions

This study demonstrates the potential use of copper slag as fine aggregate for the development of electrically conductive cement mortar. Among the three fine aggregates such as river sand, steel slag and copper slag, copper slag as fine aggregate improved the electrical conductivity of the cement mortar. Further, it is found that the high carbon content materials like carbon black, bagasse ash, tire waste have less influence on the electrical conductivity of cement mortar when compared to fine aggregates. The amount of iron oxide content especially in the form of Fe_2O_3 in copper slag is found to be responsible for the improvement of the electrical conductivity in copper slag mixes.

References

[1] Lim S, Lee W, Choo H and Lee C 2017 Utilization of high carbon fly ash and copper slag in electrically conductive controlled low strength material. *Construction and Building Materials* 157: 42–50

[2] Najimi M, Sobhani J and Pourkhorshidi A R 2011 Durability of copper slag contained concrete exposed to sulfate attack.*Construction and Building Materials* 25(4): 1895–1905

[3] Behnood Ali, Gharehveran Mahsa Modiri, Asl Farhad Gozali and Ameri Mahmoud 2015 Effects of copper slag and recycled concrete aggregate on the properties of CIR mixes with bitumen emulsion, rice husk ash, Portland cement and fly ash. *Construction and Building Materials* 96: 172–180

[4] Wang X, Geysen D, Padilla Tinoco S V, D'Hoker N, Van Gerven T and Blanpain B 2015 Characterisation of copper slag in view of metal recovery. *Mineral Processing and Extractive Metallurgy* 124(2): 83–87

[5] Goñi S, Lorenzo Ma P and Sagrera J L 1994 Durability of hydrated Portland cement with copper slag addition in NaCl+ Na_2SO_4 medium. *Cement and concrete research* 24(8): 1403–1412

[6] Lye Chao-Qun, Koh Siew-Kiang, Mangabhai Raman and Dhir Ravindra K 2015 Use of copper slag and washed copper slag as sand in concrete: a state-of-the-art review. *Magazine of Concrete Research* 67(12): 665–679

[7] Gupta Nikita 2020 Strength and Durability Properties of Self-Compacting Concrete Incorporating Copper Slag. PhD thesis, Department of Civil Engineering,Thapar University, Punjab, India

[8] Al-Jabri Khalifa S, Al-Saidy Abdullah H and Taha Ramzi 2011 Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete. *Construction and Building Materials* 25(2): 933–938. Composite Materials and Adhesive Bonding Technology

[9] Ahmari Krishna Parameswaran Saeed and Zhang Lianyang 2015 Alkali activation of copper mine tailings and low-calcium flash-furnace copper smelter slag. *Journal of Materials in Civil Engineering* 27(6): 04014193, 2015

[10] Sharma Rahul and Khan Rizwan A 2018 Influence of copper slag and metakaolin on the durability of self compacting concrete. *Journal of Cleaner Production* 171: 1171–1186

[11] Wen Sihai and Chung D D L 2007 Double percolation in the electrical conduction in carbon fiber reinforced cement-based materials.*Carbon* 45(2): 263–267

[12] Wu Jianmin, Liu Jianguo and Yang Fei 2015 Three-phase composite conductive concrete for pavement deicing. *Construction and Building Materials* 75: 129–135

[13] He Yongjia, Lu Linnu, Jin Shun, and Hu Shuguang 2014 Conductive aggregate prepared using graphite and clay and its use in conductive mortar. *Construction and Building Materials* 53: 131–137

[14] Wang Ziyi, Wang Zhi-Jie, Tang Shengxuan and He Yunfei 2017 Preparation and properties of electrically conductive aggregate made using magnetically separated fly ash. *Construction and Building Materials* 150: 547–557

[15] Chen Binmeng, Li Bo, Gao Yan, Ling Tung-Chai, Lu Zeyu and Li Zongjin 2017 Investigation on electrically conductive aggregates produced by incorporating carbon fiber and carbon black. *Construction and Building Materials* 144: 106–114

[16] Gorai Bipra, Jana R K and Premchand 2003 Characteristics and utilisation of copper slag-a review. *Resources, Conservation and Recycling* 39(4): 299–313

[17] Dhir Ravindra K, de Brito Jorge, Mangabhai Raman, and Lye Chao Qun 2017 Use of copper slag as concrete sand. In: Ravindra K Dhir, Jorge de Brito, Raman Mangabhai, Chao Qun Lye, editors, *Sustainable Construction Materials: Copper Slag* pages 87–163. Woodhead Publishing

[18] IS:12269-1987 *Specification for 53 grade ordinary Portland cement*. Bureau of Indian Standard

[19] Dong Wenkui, Li Wengui, Shen Luming and Sheng Daichao 2019 Piezoresistive behaviours of carbon black cement-based sensors with layer-distributed conductive rubber fibres. *Materials and Design* 182: 108012

[20] Tumidajski Peter J 1996 Electrical conductivity of Portland cement mortars.*Cement and Concrete Research* 26(4): 529–534

[21] Sun Kateryna Krayushkina Jian, Bieliatynskyi Andrii and Akmaldinova Oleksandra 2020 Research of properties on graphite conductive slag in asphalt concrete. *E3S Web of Conferences* 175: 11015

[22] Chaki T K, Sau K P and Khastgir D 1998 Electrical conductivity of carbon black and carbon fibre filled silicone rubber composites journal = Die Angewandte Makromolekulare Chemie 258: 11–17