Chapter 9
Influence of Copper Slag on the Mechanical Properties of Concrete: A Review

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Abstract The utilization and the safe disposal of the generated industrial wastes are one of the major concerns of environmentalists in order to reduce their harmful impacts on human health and the environment. Copper slag is also a waste product formed during the production of copper while smelting and refining processes. Copper slag possesses higher concentrations of heavy metals and minute particle size which may cause several environmental and health problems such as air and water pollution. Apart from various recovery facilities, its application in the construction field has been successfully done by many researchers as a substitution of cement and fine aggregate. Besides improving the performance of structural members, its utilization is also reported to cause a major reduction in the overall cost of construction. Thus, this chapter reviews the use of copper slag as a sustainable constructional material in the field of civil engineering.

Keywords Copper slag · Hazardous waste · Heavy metals · Waste management

9.1 Introduction

In the present scenario, due to increasing urbanization and rapid growth in industrialization, the amount and variety of waste generation have grown extensively. Different types of waste materials have been generated through various activities in domestic, industrial, and agricultural fields [1]. Considering the current scenario, the production of waste across the globe is around two billion tons, which is estimated to be increased by 70% by the year 2050 [2]. With continuous growth in the amount of waste generation, difficulties in obtaining approval for waste disposal also increase [3]. Thus, it is the responsibility of researchers and engineers from

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different fields to find an alternative way to use such wastes in order to ensure proper development in all aspects. Through numerous types of recycling and disposal techniques, the impact of such wastes on the environment and human health can be reduced. The utilization of such waste materials not only reduces the overall cost of construction but also helps to decrease the significant amount of CO_2 emissions [4, 5].

Copper slag (CS) is one of the industrial by-products that are generated while refining and smelting processes of the copper [6]. As per the report of the International Copper Study Group (ICSG) in the year 2017–2018, the production of copper reaches around 20.3 million tons [7]. Around 7.26, 5.90, and 5.56 million tons of copper slag have been reported to be produced in Asia, North America, and Europe, respectively [8]. Approximately, 2.2–3 tons of CS are generated as a by-product during the one-ton production of copper [8]. The composition of generated slag majorly depends on the type of furnace used for the production, whereas the recovery facility of the metals from the slag depends on the type of slag. The amount of energy required for the grinding process of the metallurgical slags is very low when compared to the processing of Portland cement, as it requires only 10% of the total energy needed to produce the cement. The direct dumping of the CS in the landfills is not a suitable idea to get rid of it as it may lead to various health- and environmental-related problems. In developing countries like India, building materials cost about 70% of the entire cost of construction; the usage of CS could result in showing a positive impact on the overall cost of construction activities and imparted strength to the structural members [9]. Many researchers have conducted studies on utilizing the CS as a partial and full replacement material of fine aggregate for the production of concrete. It has been reported that CS caused a positive impact on the performance of concrete when added up to certain limits [10, 11].

This chapter reviews the available literature on the application of CS as an alternative material to fine aggregate. The physical and chemical characteristics of CS are analyzed in detail. Special emphasis has been given to the problems caused by the production and disposal of CS. The impact of its utilization on the durability and mechanical properties of concrete is also discussed with the appropriate reasoning.

9.2 Physical and Chemical Properties of Copper Slag

9.2.1 Physical Properties

The detail of the physical properties of copper slag used by various researchers is given in this section with appropriate discussion. The different properties of CS are illustrated in Table 9.1.

Table 9.1 Physical properties of CS used in previous studies

Author(s)	Specific gravity	Water absorption (%)	Particle size (mm)	Bulk density (g/cm^3)	Specific surface area(cm^2/g)	Fineness modulus
Lori et al. [9]	3.85	0.48	–	2.164	–	–
Patil [3]	3.3	0.65	0.15–4.75	–	–	4.55
Janakiramaiah [12]	3.91	0.16	–	2.08	1250	3.476
Mary [13]	3.47	0.17	–	2.08	–	–
Patnaik et al. [14]	3.47	0.24	–	1.89–2.02	–	3.3
Rajasekar et al. [30]	3.572	0.35	–	1.885	–	–

Table 9.2 Chemical compounds present in the copper slag

Author(s)	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	CuO	SO_3	K_2O	TiO_2	ZnO	Na_2O	LOI
Fadaee et al. [15]	28.83	5.8	3.71	46.37	–	–	3.26	1.15	0.34	–	–	5.73
Sharma and Khan [16]	30.53	1.6	2.8	57.82	1.48	0.64	1.59	0.71	0.26	0.4	0.34	1.65
Bhoi et al. [17]	33.85	6.06	2.79	53.45	1.61	–	1.89	–	0	–	0.28	0
Effect of type of processing [18]												
QCS*	25.9	7.1	5.9	45.5	0.8	0.4	0.4	0.2	0.3	8.8	0.8	–
SCS*	29.3	5.2	3.2	50.7	0.5	–	0.2		0.1	5.4	2	–
Location [19]												
CS_PN*	39.14	13.41	7.76	30.48	2.09	–	0.46	1.5	–	–	1.05	−2.11
CS_PQ*	38.33	26.10	8.17	20.40	2.14	–	0.26	0.78	–	–	0.64	−1.5

Note – QCS (quickly cooled granulated CS)*, SCS (slowly cooled broken CS)*, CS_PN (from the Playa Negra landfill)*, and CS_PQ (from the puquios)*

9.2.2 Chemical Properties of Copper Slag

The chemical composition of copper slag used in the literature is given in Table 9.2.

It can be noticed that the combination of SiO_2, Fe_2O_3, and Al_2O_3 is greater than 70%, which makes CS a pozzolanic material, and increases the possibility of its usage in cement-based mixes [16]. It can also be observed from Table 9.2 that some of the authors have reported the negative LOI, which could be due to the oxidation of sulfur and iron oxide [19].

9.3 Problems Associated with Copper Slag

The presence of heavy metals in CS is a major concern due to its toxicity to human health and the environment. Generally, large-scale industries that deal with copper-based products have a proper facility to handle and dispose of the generated waste during the production of copper-based materials. On the other hand, small-scale industries do not have special equipment to take care of this waste. Therefore, the open dumping of copper slag in landfills is considered a common and easy practice for its disposal which may lead to the leaching of heavy metals to the groundwater during heavy rainfalls or contamination of air [20]. Heavy metals such as lead, mercury, and arsenic may cause several health problems related to the kidney, brain, and nervous system [21, 22]. Various authors have investigated the leachability of heavy metals present in the CS, and it was found that the concentration of heavy metals found with toxicity characteristic leaching procedure (TCLP) was less than the limits specified by United States Environmental Protection Agency (USEPA) [23]. The amount of leached heavy metals found in previous studies is given in Table 9.3.

9.4 Effect of Copper Slag on Concrete

In this section, a detailed discussion on the fresh and hardened properties of CS-based concrete made with the replacement of fine aggregate is presented.

Table 9.3 Concentrations of heavy metals present in CS found with TCLP are illustrated below

	Element concentration (mg/L)											
Author(s)	Ag	As	Ba	Cd	Cr	Cu	Hg	Mn	Ni	Pb	Se	Zn
Limits specified by USEPA [23]	5	5	100	1	5	–	0.2	–	–	5	1	–
Shanmuga nathan et al. [24]	–	0.04	–	0.01	0.15	2.2	–	–	0.08	0.1	–	0.08
Cheong et al. [25]	–	0.227	0.981	0.068	0.136	23.42	–	0.734	0.064	0.797	–	23.32
Lim and Chu [26]	0.01	0.08	1.2	0.03	0.081	33.6	0.02	–	0.37	0.51	0.05	18.5
Alter [27]	–	0.52	–	0.04	0.06	6.23	–	–	–	0.84	0.28	0.84
Brindha and Nagan [28]	–	0.923	0.258	0	0	11.64	–	0.048	0.097	0	0	0.991

9.4.1 Workability

The workability of copper slag-based concrete increases as the amount of CS is increased to replace the sand. It has been observed that the concrete was workable even when the 100% addition of CS is done in comparison to the control concrete. The results of the study conducted by Sharma and Khan [29] showed that the slump values were satisfying the limits suggested for the self-compacting concrete in the code (IS-9103-1999). Various tests like the J-ring, V-funnel, and L-box tests to check the workability of the SCC were performed and found that the flowability was enhanced by the incorporation of CS. The workability of the geopolymer concrete-based CS was checked and found that the concrete does not need any superplasticizer. There was no considerable change in the workability as the amount of the CS was increased to 100% [30]. The reason behind the increase in the workability of the concrete may be caused by the hydrophobic nature and glossy surface of the particles of CS which lowers the water absorption of water. Due to this, the amount of superplasticizer was also reduced as the content of CS was increased [17].

9.4.2 Compressive Strength

The Change in the Compressive Strength by utilizing copper slag as an alternative material to replace the fine aggregate for the production of concrete is studied by many researchers [10, 11], and its positive influence was observed. The assessment of the impact on the properties of high-performance concrete manufactured with the partial substitution of fine aggregate with copper slag along with the addition of the different percentages of colloidal nano-silica was checked by Chithra et al. [10]. It has been noticed that the compressive strength gets increased when 2% addition of nano-silica replacement was done. The increase in the strength is connected to the liberation of $Ca(OH)_2$ during the hydration reaction of cement which is consumed through nano-silica, thus resulting in higher strength in the early days. The pores of the concrete specimens get filled up by the products that are formed during the hydration. In the early days, the consumption of $Ca(OH)_2$ is more due to the increase in hydration which was triggered by nano-silica. During the pozzolanic reaction, the compacted hydration products are generated, and the $Ca(OH)_2$ forms a coating on the unhydrated cement particles which decreases the rate of the hydration. The formed products during the hydration fill the voids between the particles of the cement which reduces the passage of water to the unhydrated particles of the cement and ultimately lowers the gain of strength after the addition of 2% of nano-silica.

A study conducted by Mithun and Narasimhan [30] showed that it is possible to manufacture geopolymer concrete through the application of copper slag in the concrete. In the study, fly ash and copper slag along with NaOH were used as an activator, whereas two different types of curing, that is, hot and ambient air curing, were provided to the concrete. Different blends of concrete were prepared having varying contents of copper slag in it. It was found that maximum compressive strength was 58.95 MPa obtained by hot air curing when 40% of copper slag is used to replace fine aggregate. Studies showed that all mixes possess a higher compressive strength at an early age when compared to normal concrete. The reason behind the increase in the strength could be the activator which helps to increase the solubility of the silica present in the mix, which causes a significant impact on the development of the strength and led to providing denser packaging of the materials in the concrete. The author suggested this type of concrete in the area of application where higher initial strength and cost-effective construction are required [30]. The production of self-compacting concrete was done with the addition of copper slag in different amounts to replace the sand and fixed amounts of metakaolin as a binder material. The compressive strength of all of the mixes increases, but the maximum strength is observed when 20% CS is added as a replacement for sand. The reason for the increase in the strength could be the production of identical and denser C-S-H compounds, which reduces the void content in the mix. Results suggested that when the 100% replacement of the sand is done with copper slag, the observed compressive strength was more than the control mix. This study suggests utilizing the combination of copper slag as a 100% replacement for sand and 10% metakaolin as a binding material [16].

The effect of ground and unground copper slag on the behavior of the ultrahigh-strength concrete was checked by Rajasekar et al. [31]. Normal, steam, and heat curing were provided to the specimens and tested after 28 days. It was found that when unground copper slag was added up to 40%, the maximum compressive strength was 212 MPa increased by 12%, 10%, and 4% when cured with heat, steam, and normal facilities. The reason for the increase in the strength is related to the better compressibility of the copper slag than the fine aggregate, which imparts better bonding with the ingredients of concrete. Figure 9.1 shows the results of specimens made with unground copper slag as given below.

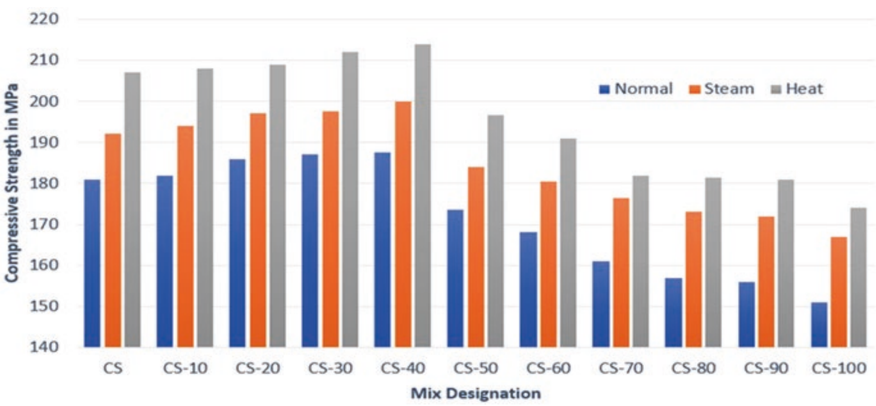

Fig. 9.1 The change in the compressive strength with the addition of unground copper slag [31]

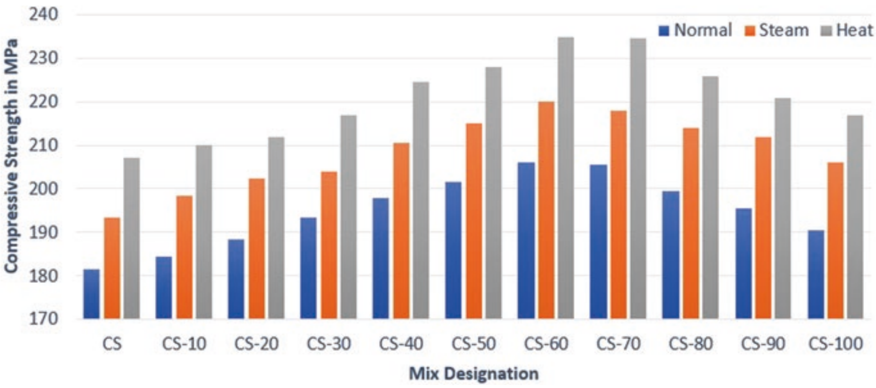

Fig. 9.2 Change in the compressive strength with ground copper slag [31]

On the other hand, when grounded CS was used in the concrete, the gain in the strength was even higher than the strength obtained by the ungrounded copper slag. As per the results, the maximum compressive strength of 234 MPa was obtained at 60% replacement of CS as shown in Fig. 9.2. The increase in the strength could be due to the smaller particle size and higher curing temperature, which results in the development of longer chains of the C-S-H compound. The increase in temperature also results in the fast hydration of the cement. The author suggested that the ultrahigh-strength concrete can be formed with the unground CS as the minimum strength of the specimens was 150 MPa [31].

It has also been observed when CS was used in addition to any other pozzolanic material used as an alternative material to cement. The compressive strength of the specimens was reported to be increased [32]. The combined effect of the granulated blast furnace slag (GBFS) and CS when used as partial replacement of cement and fine aggregate in concrete, respectively, was checked by Divya et al. [33]. The compressive strength was increased due to the pozzolanic actions of both materials. It was found that at 30% of replacement of CS and GBFS with fine aggregate and cement in concrete, the maximum compressive strength was observed. However, Tiwary [34] suggested that better results were obtained when a mix containing 20% fly ash and 30% CS was used to manufacture concrete. For the production of high-strength CS concrete, the utilization of glass powder, silica fume, rice husk ash, and fly ash was taken into account for the replacement of cement along with copper slag which was added as a replacement of fine aggregate. The better results were obtained when the maximum amount of glass powder, fly ash, and copper slag was used [35].

Other researchers have also assessed the impact of using CS in concrete and noticed that the replacement of copper slag up to 40% does not cause any harm to the failure load of columns [13, 36]. The cause of the reduction in the compressive strength of the specimens may be because of the increase in the amount of the surplus water which remained in the mix due to the less absorption capacity of CS, which leads to the growth of the voids in the matrix and ultimately reduces the compressive strength [13, 36]. Some of the authors have also reported that at 20%

replacement of copper slag, maximum increase in the compressive strength was observed and beyond that percentage, substantial reduction in the compressive strength was noticed [3, 37].

9.4.3 Split Tensile Strength

The assessment of copper slag on the split tensile strength was done by many researchers, and better results were obtained when used as a partial replacement of fine aggregate. The increasing pattern of the tensile strength was observed when specimens were tested after 7, 14, and 28 days of curing. Best results were obtained when the combination of copper slag and GBFS was added at 30% in the concrete. The GBFS helps in increasing the binding property, whereas the copper slag increases the compressibility of the mix which provides more enhancement in the split tensile strength of the specimens [33]. Another study assessed the impact of the integration of nano-silica with different dosages along with the copper slag for high-performance concrete that has resulted in achieving the highest split tensile strength (5.1 MPa) when 2% of nano-silica was added in the mix. The product formed during the hydration reaction helps to fill the voids which impart to an increase in the strength of the specimens even after 90 days of curing [10]. The positive effect of CS on the properties of self-compacting concrete and geopolymer concrete was observed, even when 100% replacement of fine aggregate with copper slag has been ensured [29, 30]. Although the highest split tensile strength was found when copper slag is added up to 60%. The reason behind the increase in strength could be due to the cohesion, pozzolanic and packaging behavior, higher surface area, and shape of the particles of copper slag, which ultimately led to the enhancement in the split tensile strength of concrete [38]. A similar positive influence of the addition of the copper slag and metakaolin on split tensile strength was observed by Sharma and Khan [16]. Rajasekar et al. [31] found that significantly higher split tensile strength of ultrahigh-strength concrete was observed when the ground CS was used as a replacement material for fine aggregate rather than the unground CS when different types of curing facilities were provided. With the addition of 40% of unground CS, the split tensile strength was 10%, 1.7%, and 5.7% higher than the control mix treated with heat, steam, and normal curing, respectively. Whereas the strength of concrete made with ground CS showed 25% and 11% higher strength in comparison to the control mix of steam and heat curing.

9.4.4 Flexural Strength

Better results were obtained when CS with any other pozzolanic material was used to manufacture the concrete [39]. The flexural strength of the specimens formed with the addition of CS and GBFS as a replacement of fine aggregate and cement,

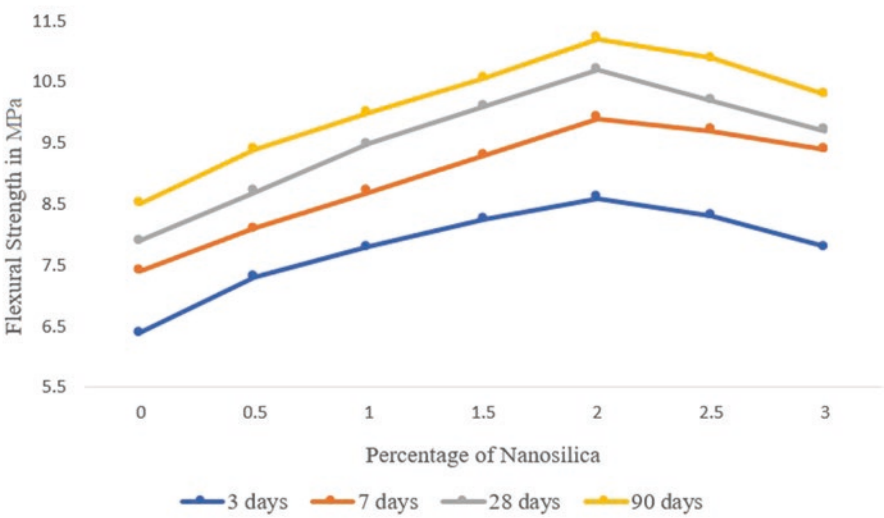

Fig. 9.3 Effect of addition of nano-silica along with copper slag on flexural strength of concrete [10]

respectively. The highest flexural strength was reported at the addition of 30% of copper slag and GBFS. The siliceous part of the mineral admixture and smaller size of copper slag support the densification of the specimens, which led to cause an increase in the strength [11, 33]. The mechanical properties of concrete were reported to be improved by the addition of copper slag along with nano-silica in comparison to the control mix of concrete at all curing periods [10]. The nano-silica causes major changes in the flexural strength when added up to 2% as shown in Fig. 9.3.

Another study suggested that 60% addition of copper slag in the place of fine aggregate led to provide the highest flexural strength to the reinforced concrete; at the same time, the strength of 100% copper slag incorporated concrete was even higher than the control mix [17]. The columns made with the higher dosages of CS showed more buckling at the initial stages of loading when compared to the lower dosages. The outcome of the ground and unground CS on the flexural strength of concrete was found by Rajasekar et al. [31], who observed that the ground CS has led to show much improvement in the performance when subjected to higher loading on the specimens than the unground CS.

9.5 Conclusions

This research article made an attempt to review the available relevant data on the incorporation of copper slag as an alternative material for cement and fine aggregate for the sustainable production of concrete. Various physical and chemical properties of copper slag used by many researchers were analyzed thoroughly, and numerous possibilities of using this waste as a sustainable constructional material in the field of civil engineering were also studied. The authors have tried to discuss the change in the properties of concrete due to the addition of copper slag in the mix in detail. The following conclusions drawn based on the studied literature are as follows:

- As the use of copper slag in the mortar and concrete mixes has shown better performance than the control mixes, thus, it can be suggested that this material can be used as an alternative to cement and fine aggregate. But the replacement of fine aggregate with CS has caused more addition of more amount of waste and improvement in the properties than the replacement of CS with cement.
- The majority of the available literature suggested that 40–50% of the addition of CS with fine aggregate can be done, without compromising much change in the fresh and hardened properties. The cost of overall construction can be saved by using this waste as its use allows the no use of superplasticizer in the mixes.
- Self-compacting, ultrahigh performance geopolymer and other types of concrete can be produced through the application of copper slag. To get even better performance of concrete, ground copper slag is recommended.
- Apart from the technical advantages, by integrating copper slag as a partially or fully replacement of materials in the mixes, the safe and proper stabilization of copper slag can be ensured to reduce its harmful effect on the environment.

Based on the carefully reviewed literature, it is suggested that the feasibility of the integration of CS with other available pozzolanic materials can be checked at various replacement levels. The possibility to use CS for the production of self-healing concrete can be recommended to the readers. The application of the combination of different parameters such as w/c ratio and curing facilities can also be evaluated in addition to the above-suggested scopes.

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