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Review Article

Mechanical Strength and Microstructure Properties of Concrete Incorporating Copper Slag as Fine Aggregate: A State-of-the-Art Review

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Incorporation solid waste generated in industry into concrete production is considered an environmentally sustainable approach as it reduces pollution, lowers energy consumption, and mitigates the depletion of natural resources. Copper slag (CS) is a residual material produced through the copper smelting process. The slag materials are kept in expansive landfills and consume substantial land space. The typical approaches for managing CS involve recycling, metal recovery, and the creation of additional value through the manufacturing of items, including but not limited to railroad ballast, abrasive tools, cutting tools, roofing granules, abrasive tiles, glass, asphalt surfaces, and foundations for road construction. This study aimed to evaluate the mechanical strength and microstructural properties of concrete, focusing on using CS as a substitute for fine aggregate. This review systematically analyzes its use in concrete production over the last two decades. For the review, data were collected from various publishers, which are peer-reviewed articles, and validated using databases like Scopus, Scimago journal and country rank (SJR), Web of Science, etc. This review concluded that the potential of utilizing CS as a workable alternative for fine aggregate is highly attractive, given its superior performance in mortar and concrete mixes when compared to mixes without CS.

1. Introduction

In many countries, the construction sector is experiencing rapid growth where natural resources are used for infrastructural development [1]. In the construction industry, resource scarcity and growing waste generation pose a significant challenge, while sustainable development requires unconventional materials and waste recycling to avoid resource scarcity and preserve the environment [2]. Sustainable energy sources such as solar, wind, geothermal, biomass, and hydro are gaining significant attention as regards the advancement of the world toward becoming a carbon-neutral community. However, this transition to renewable energy is expected to lead to an important increase in the demand for metals, as lithium, nickel, manganese, and cobalt are required in traditional electric vehicle batteries, while iron, copper, and aluminum are needed in wind turbines. Most countries have set their own goals of becoming carbon neutral by 2050 or 2060 [3].

Concrete is generally considered as one of the major building materials that is used in construction projects worldwide due to its affordability and versatility [4, 5], with an average use of 1 m^3 per person on a global scale every year [6, 7]. The extensive use of concrete is due to its flexibility in molding it into various sizes and shapes, the ability to withstand environmental conditions, readily available raw materials, strong hardening properties, and cost-effective repair throughout its life span [8]. Normal-strength concrete (NSC) is manufactured through the mixing of primarily cement, aggregates, and water. It is the predominant choice for construction materials in a wide range of structures, including buildings, dams, port facilities, bridges, bunkers, tunnels, and the skeletal frameworks of factory buildings [9, 10], while high-strength concrete (HSC) is characterized as concrete having a

Table 1: Top five (5) worldwide importers of gravel, stone, and sand [22].

Trade price (2010–2014) ($)	Top importers
13,621,826,061	China
2,946,963,029	Netherlands
2,825,197,760	Singapore
2,755,605,436	Germany
2,695,719,208	India
35,127,603,231	Others
59,972,914,725	Total

Selected classification. SITC Rev. 1; selected commodities: 273 (stone, sand, and gravel); selected reporters: all; selected years: 2010, 2011, 2012, 2013, and 2014.

specified compressive strength equal to or exceeding 60 N/mm^2 according to ACI 363.2R and used for several practical applications, including nuclear waste containment structures, long-span bridges, high-rise buildings, and walkways [11].

Cement is considered a major constituent material in concrete production and consumes vast quantities of natural resources such as clay, limestone, and chalk, as well as a great amount of energy, resulting in a significant contribution to greenhouse gas emissions and global warming [12–14]. For each ton of cement production, the amount of CO_2 emission is equal [15]. Moreover, substantial amounts of natural resources including river sand and coarse aggregate are required to manufacture such an extensive volume of concrete [6, 16]. Based on the assessment, the construction demands worldwide are projected to necessitate 35 billion tons of sand and coarse aggregates [6, 17]. Indeed, aggregates comprise a significant portion, ranging from 70% to 80%, of the concrete mixture, serving as a fundamental component. In several countries, the availability of suitable natural aggregates for construction is not limited, whereas in other nations, their consumption is escalating due to a growing demand for construction [2, 18–20]. The aggregate types include coarse aggregates (particle sizes exceeding 4.75 mm) and fine aggregates (particle sizes below 4.75 mm) [21]. Table 1 summarizes the top five (5) worldwide importers of gravel, sand, and stone: Note the substantial influx of imports for these goods in Asia, especially in China, Singapore, and India. At present, nations experiencing heightened request and increased imports of natural resources are at greater risk of resource depletion; consequently, this is an issue that demands attention and cannot be ignored [22].

The three most essential metals on a global scale include steel, aluminum, and copper [23, 24]. Copper is currently a material frequently used in human daily existence and is also vital for global markets. It is typically used for a diversity of purposes, including those relating to building, electricity, transportation, and correlated industries [25]. CS is a substantial byproduct originating from the conversion of copper ore concentrates into metallic copper within smelting facilities, as illustrated in Figure 1 [26, 27]. The slag materials are stored in expansive landfills and consume substantial land space [28].

In 1900, the world produced less than 500,000 tons of copper. However, annual production of copper mining had increased by 3.2%, reaching a total of 20.6 million tons by 2018 [12, 29–31]. To be more specific, Oman generates 60,000 tons or more of CS annually. Additionally, the production of CS indicated for Iran, Brazil, Japan, and the United States is roughly 0.36, 0.244, 2.0, and 4.0 million tons annually, respectively [2, 32–35]. The statistics have been anticipated that a ton of copper yields roughly 2.2 tons of CS [25, 36–39]. Table 2 provides information on the primary regions responsible for CS production along with their respective quantities, while Figure 2(a)–2(c) shows the cooling process, appearance images, and grading of CS.

The construction industry holds a bright outlook for CS; it exhibits characteristics of glassy, dark, and granular particles falling within a size range similar to that of sand due to its outstanding mechanical and physical characteristics. Its water absorption capacity is notably low; concrete requires less water when mixed with CS, compared to quartz sand. Therefore, an increase in content of CS is anticipated to reduce the quantity of water in the mixture [43, 44]. The current implementation of copper smelting slag treatment lacks a cost-effective and efficient approach. Consequently, the majority of copper smelting slags are directly deposited in open-air stacks, leading to both extensive land usage and significant environmental consequences such as polluting the surrounding water and soil [31, 45]. The primary constituents of CS consist of Fe_3O_4 (45–70 wt.%), SiO_2 (10–30 wt.%), Al_2O_3 (10 wt.%), and CaO (10 wt.%) [36, 41, 46]. These exhibit pozzolanic properties as a result of their low CaO content and the presence of various oxides substituting concrete components with slag in this manner can alleviate the environmental issues and concerns associated with disposing of slag in landfills. This leads to cost savings in managing slag to comply with sustainable development goals (SDGs) and environmental regulations, as well as decreased expenses in cement and aggregate production, given the low cost or potentially free nature of slag. This presents a favorable situation for both concrete manufacturers and metallurgical industries in various respects [47]. Alternatively, CS has found extensive application in the construction industry [7, 48], including its use as a substitute-grained copper for coarse aggregates [4] and fine aggregates [44] and utilizing fine CS powder to partially substitute for cement [49].

In summary, despite advances in the management of CS over the last couple of decades, the comprehensive recycling and thorough purification of CS are currently not extensively implemented. This review aims to investigate existing literature concerning the use of CS as a alternative material for fine aggregate. Data were collected from reputable publishers and validated with trustworthy websites. Considerable attention has been directed toward addressing the issues arising from the generation and proper disposal of CS. The physical, chemical, and microstructure properties of CS are examined in detail. The review delves into the influence of incorporating CS on concrete's mechanical and microstructure properties, accompanied by relevant explanations. In conclusion, the results are succinctly recapitulated to provide valuable and meaningful insights for the sustainable recycling of CS.

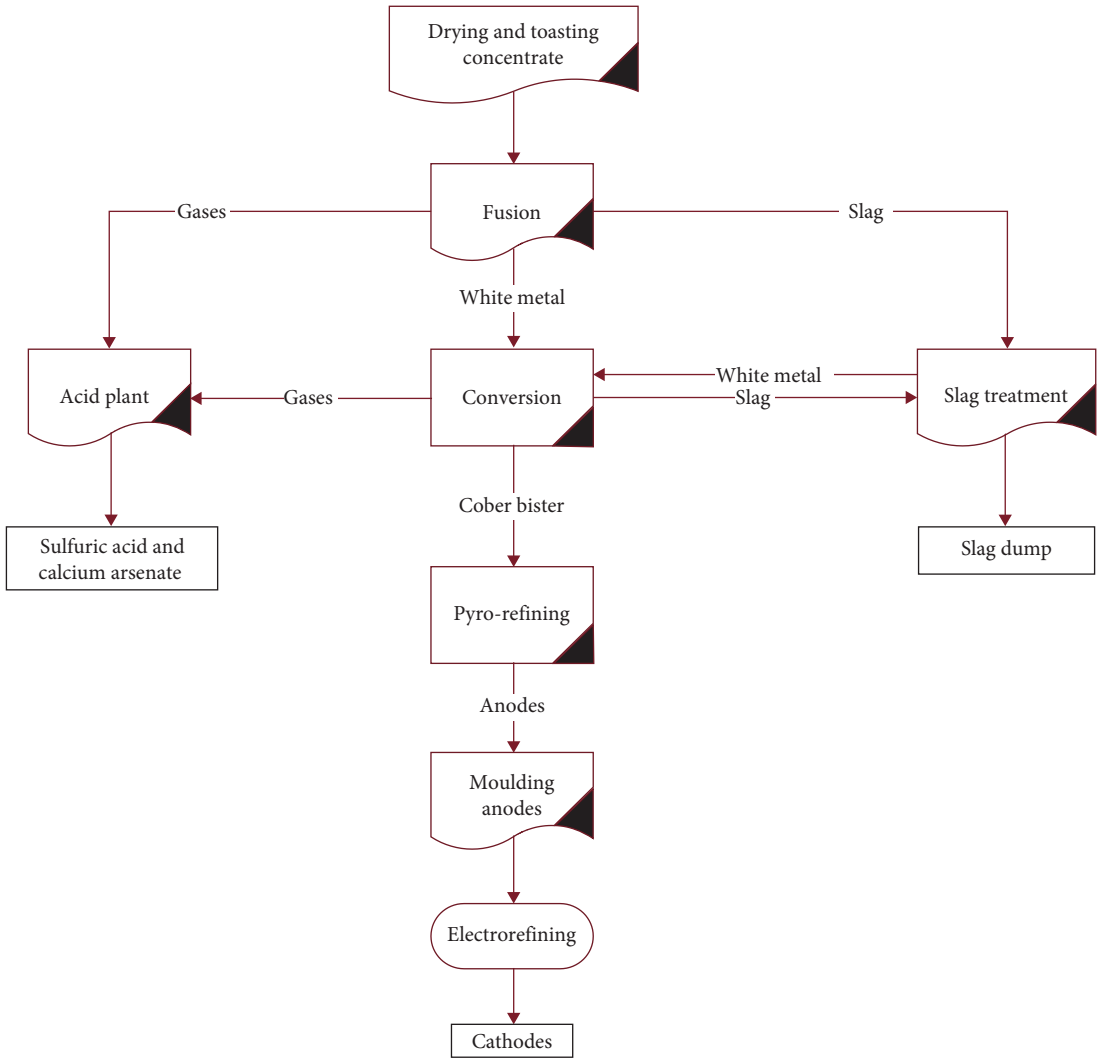


Figure 1: Production of copper cathodes through pyrometallurgical and electrometallurgical processes [28].

Table 2: Production of CS in various regions [37].

Production of CS/year in million ton	Region
7.26	Asia
5.90	North America
5.56	Europe
4.18	South Africa
1.23	Africa
0.45	Oceania

2. Methodology of the Review

In this section, a comprehensive methodology is employed to review the use of CS as an alternative to fine aggregates in the production of concrete. The review article is based on an extensive analysis of peer-reviewed articles published within the last two decades in the fields of engineering, building materials, and material sciences. Information was gathered from different publishers, such as Elsevier, Springer, MDPI, Taylor & Francis, ASCE, Wiley, and Hindawi. In order to validate the data collection, the references were restricted to databases such as Scopus, Scimago Journal, country rank (Sjr), and Web of Science websites to ensure the inclusion of only peer-reviewed references. The review mainly focuses on the production and characterization of CS. In addition, it examines the influence of CS on various concrete properties, including workability, mechanical strength, and microstructures. Finally, conclusions and future insights have been drawn. The methodology of the review is shown in Figure 3.

3. Results and Discussions

3.1. Copper Slag Properties

3.1.1. Physical and Mechanical Properties. In this section, an in-depth examination of the physical and mechanical properties of CS as investigated by various scholars along with pertinent discussions is presented. Table 3 describes the distinct properties of CS. Data indicate that the usual color of CS is predominantly black or dark brown, with a glassy appearance. Its specific gravity falls within the range of 3.37–3.91, primarily contingent on the iron (Fe) content

Figure 2: (a) Cooling of CS in the air [40]. (b) Pictorial view of CS [41]. (c) Images of CS: (c1) before grinding and (c2) after grinding [42].

[25]. Moreover, CS exhibits irregular particle size, a fineness modulus in the range of 2.8–3.47, and too-low water absorption in the range of 0.15%–0.46%. Thus, whether CS undergoes metallurgical recycling processes or is employed in civil material applications, its mechanical and physical qualities should be fully analyzed. Figure 4 contrasts the gradation curves of CS and sand.

3.1.2. Chemical Compositions. The chemical constituents of a specific slag are formed by various factors, including the approach used to classify copper metal, the furnace type in use, the metallurgical procedures applied, and the constituents of the ore from which copper is derived [30, 32]. In numerous conventional construction building materials like silica fume, sand, fly ash, and clay, SiO_2 constitutes a significant component [30], but the CS contains high amounts of iron oxide (Fe_2O_3), followed by silica dioxide (SiO_2), and small amounts of several other oxides, including Al_2O_3, SiO_2, CaO, MgO…, and so on [56]. Given its chemical and physical characteristics, this substance could be employed as a cement substitute as well as an aggregate in concrete production [57]. Table 4 summarizes the CS chemical compositions from various research. The primary element present is iron (Fe), which indicates that the increased iron (Fe) content is responsible for the greater density and hardness of CS when compared with other industrial waste materials [43], followed by silica, alumina, and calcium oxide. As a result, the existence of silica and alumina in CS makes it a viable choice for use as a starting material in alkali-activated substances. It can be observed that, in most cases, the total of Fe_2O_3, SiO_2, and Al_2O_3 exceeds 70%, which is evident to indicate that CS possesses pozzolanic characteristics, thus enhancing the potential for incorporating CS into cement-based mixtures.

3.1.3. Microstructure Properties. Previous studies have employed various characterization techniques to study the microstructure, chemical composition, and elemental makeup of CS. Some of these methods are X-ray diffraction (XRD), scanning electron microscopy (SEM), thermogravimetric/differential thermal analysis (TG/DTA), energy dispersive spectroscopy (EDS), EDX, and fourier transmission infrared (FTIR) analysis. For example, Gu et al. [43] stated that the surface texture of CS was laminar, densely structured, and had high compression qualities based on the SEM images of the material displayed in Figure 5(a). In a study by Sheikh et al. [63] based on SEM images, it was observed that the smooth surface and rough texture of CS, as shown in Figure 5(b), in contrast, Najimi et al. [33] carried out XRD analysis on CS, and the findings indicated that the primary components are recognized as fayalite (SiO_4Fe_2), pyroxene ($CaZnSi_2O_6$), magnetite (Fe_3O_4), anorthite ($CaAl_2Si_2O_8$), and quartz (SiO_2). Similarly, Najimi and Pourkhorshidi [34] reported that mineralogical components of CS are fayalite (SiO_4Fe_2), pyroxene ($CaMgSi_2O_6$), quartz (SiO_2), anorthite ($CaAl_2Si_2O_8$), and magnetite (Fe_3O_4). While the other research showed the presence of only fayalite and magnetite, as shown in Figure 6 [3, 23, 51, 64].

3.2. Workability of the Copper Slag Concrete. Concrete workability refers to its capacity for easy placement, compaction, and finishing without facing issues such as separation or bleeding. Factors such as the water-to-cement ratio, the quantity and nature of the aggregate, and the incorporation

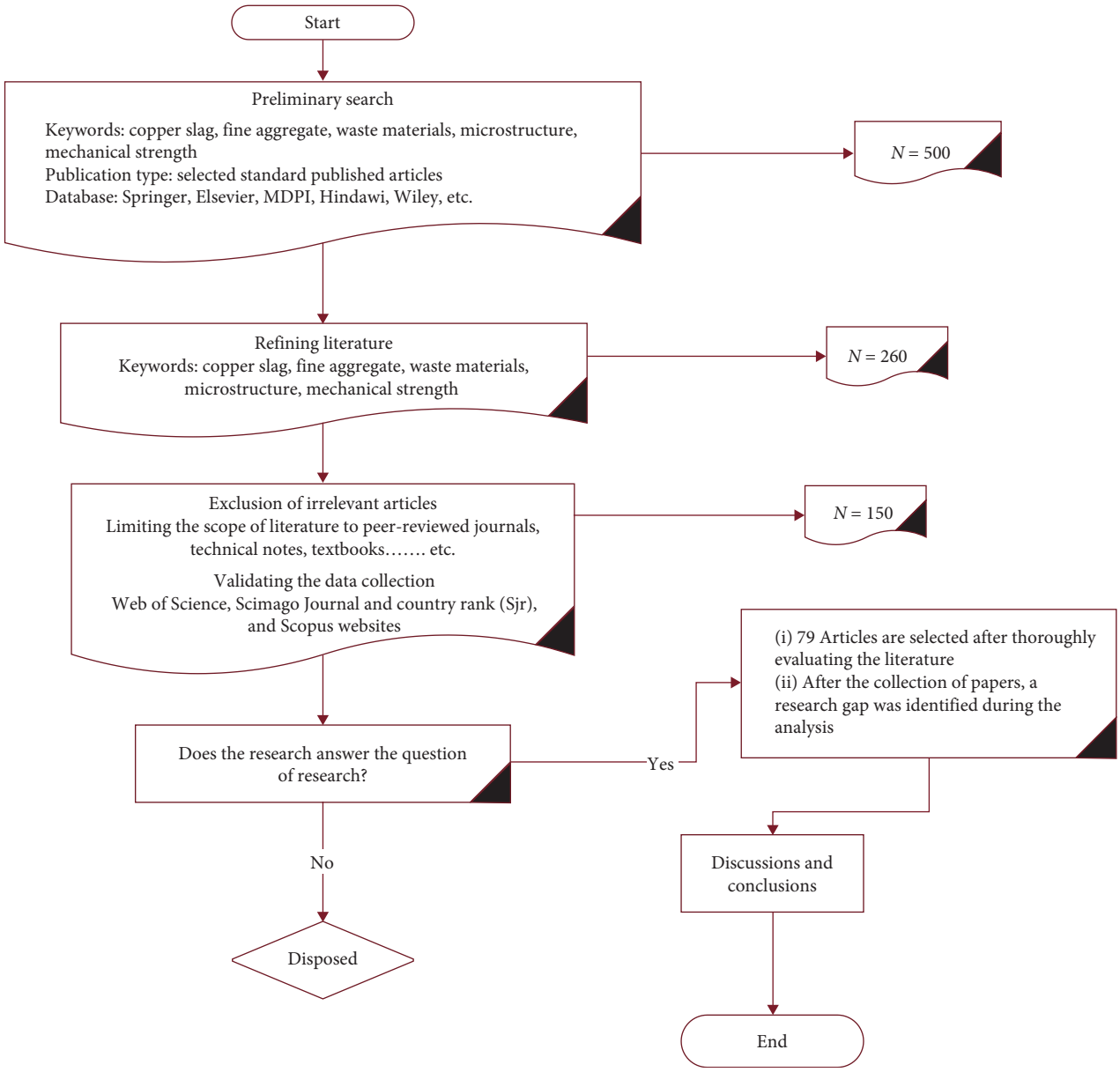


Figure 3: Research methodology process flowchart.

Table 3: Mechanical and physical characteristics of CS.

Property	References							
	[50]	[51]	[52]	[44]	[53]	[6]	[54]	[5]
Particle shape	Irregular	Angular, multifaced	Irregular	Irregular	—	—	—	—
Appearance	Black and glassy	—	Black and glassy	Black and glassy	—	—	Black and glassy	—
Type	Air-cooled	—	Air-cooled	—	—	—	—	—
Specific gravity	3.91	3.5	3.37	3.86	3.57	3.51	3.572	3.83
Percentage of the voids (%)	43	—	43.2	—	—	—	40	—
Bulk density	2.08	1.87	2.08	—	1.85	—	1.885	2.120
Fineness modulus	3.47	—	3.43	4.437	2.8	3.11	—	2.206
Water absorption (%)	0.15–0.2	—	0.3–0.4	0.13	0.46	0.36	0.35	0.5
Moisture content (%)	<0.1	—	0.1	0.1	<0.5	—	—	—
Particle size	—	—	—	0.3–0.4	—	—	—	—
Hardness	—	—	—	6–7	6–7	—	—	—

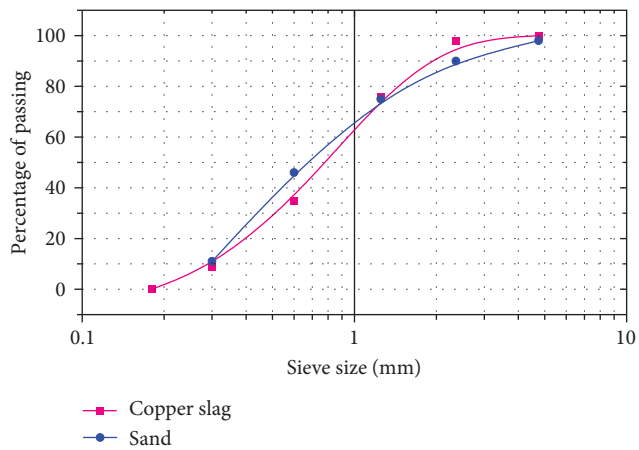
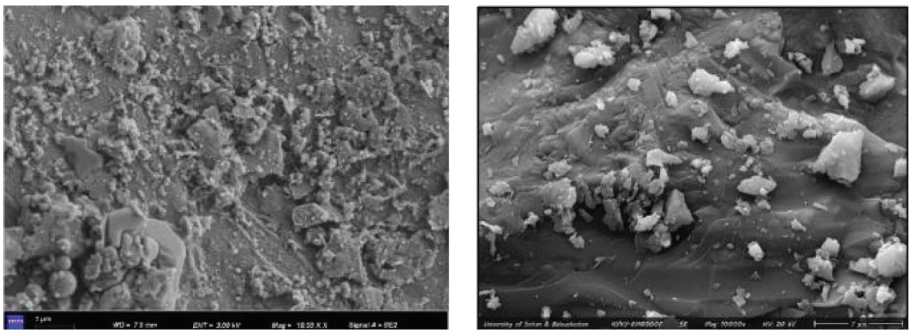


Figure 4: Gradation curve comparison between CS and sand [55].

Table 4: The chemical compounds of CS carried out by different authors.

Reference	Oxide										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	Na_2O	Mn_2O_3	SO_3	CI	CuO
[58]	33.93	4.68	37.89	12.65	1.06	0.83	—	—	1.83	—	—
[59]	29.5	9.85	45.5	2.6	0.19	1.05	3.66	0.65	0.85	—	—
[3]	13.3	3.26	38.7	0.17	0.72	1.96	0.63	—	0.65	—	—
[18]	31.92	2.5	59.11	1.25	0.81	1.65	1.40	—	1.34	—	—
[33]	9.57	4.43	57.42	22.25	—	1.56	1.47	—	—	—	—
[26]	27.89	2.91	41.45	2.10	—	0.88	—	—	—	0.12	—
[60]	34.5	4.1	51.1	3.4	1.2	—	—	—	—	—	—
[61]	28.83	3.71	46.37	5.80	1.15	—	—	—	3.23	—	0.54
[23]	26.0	3.3	55.0	2.0	0.6	2.7	1.1	—	—	—	1.4
[3]	13.3	3.26	38.7	1.98	0.72	1.96	0.63	—	0.64	—	0.36
[62]	26.72	0.25	69.33	0.16	—	0.25	0.6	—	—	—	—



(a) (b)

Figure 5: (a) SEM image depicting morphology of CS [43] and (b) SEM image depicting morphology of CS [63].

of chemical admixtures influence this attribute. The slump test (also known as the "slump cone test") is a commonly employed method for evaluating the workability of freshly mixed concrete. It can be conducted either on-site during construction or in a laboratory environment [65]. As the percentage of CS in place of sand rises, the workability of the resulting concrete is enhanced. Notably, the concrete retains its ease of handling even with a complete replacement of sand with 100% CS, in contrast to the control concrete [29]. In Figure 7, the statistical data related to concrete incorporating CS as a fine aggregate compile findings from various studies that have evaluated workability. It is noticeable that the increase in the proportion of CS leads to a substantial improvement in workability. This enhancement can be

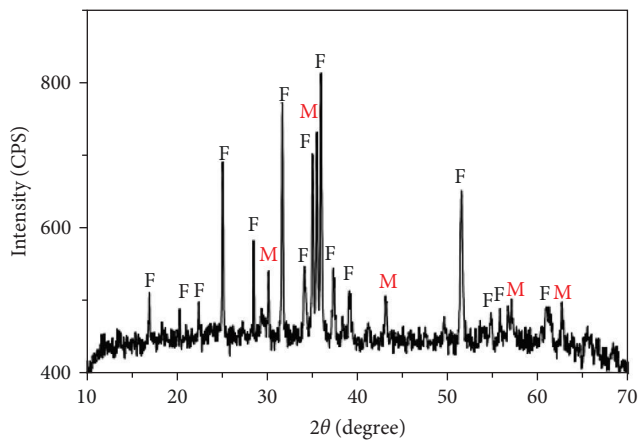


Figure 6: X-ray diffraction patterns of CS (M—magnetite; F—fayalite) [64].

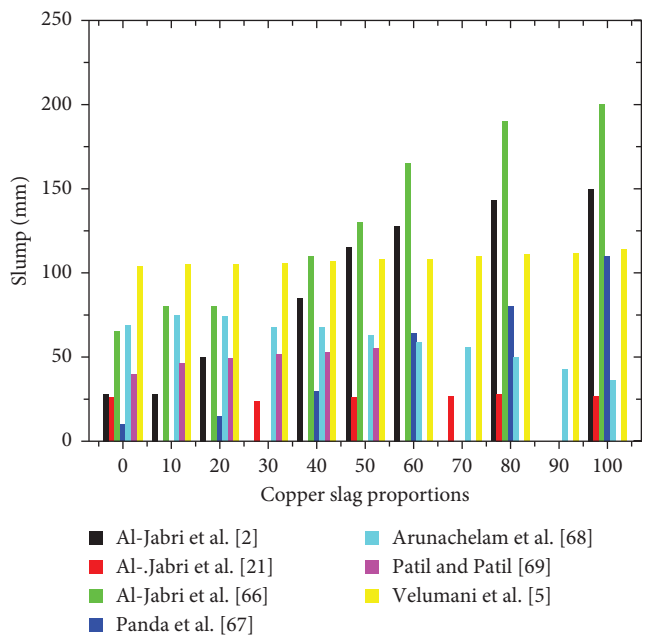


Figure 7: Slump of concrete including CS as fine aggregrates.

attributed to the limited water absorption capacity of CS, which facilitates the retention of free water within the concrete matrix during the entire hydration process.

3.3. Mechanical Strength Properties of the Copper Slag Concrete. In particular, the compressive strength of the concrete stands as a vital engineering parameter that enables the indirect assessment of many mechanical and durability characteristics. Evaluating compressive strength offers valuable insights into other important mechanical and durability properties of concrete, enabling meaningful conclusions to be made [70, 71]. Numerous authors have conducted investigations on the impact of slag of copper on concrete's mechanical strength. For instance, Najimi and Pourkhorshidi [34] stated that the utilization of CS waste at high dosages as a supplementary cementitious material diminishes the structural performance of concrete. In research by Rojas et al. [4], their investigation led to conclude that CS is a feasible substitute for serving as the primary coarse aggregate material in concrete production. Another research by Mavroulidou [57] stated that CS, which underwent water cooling, can be regarded as a viable option for use as a fine aggregate in the production of concrete. A study by Wu et al. [18] proposed that substituting a part of CS with the sand with up to 40%, when assessing high-strength concrete, yields mechanical properties that are on part with or superior to those of the reference concrete. Nevertheless, the performances of concrete are considerably reduced when the substitute exceeds 40%. Similarly, Al-Jabri et al. [2] explored the impact of replacing sand with CS (up to 50%), resulting in strength levels comparable to the control mixture. However, as larger quantities of CS were incorporated, the strength diminished due to a rise in the volume of unbound water in the mixture. Another research carried out by Moura et al. [23] examined the application of CS as an additional pozzolanic cementitious material in concrete, the authors observed that the inclusion of CS results in improved splitting tensile and axial compressive strengths. Furthermore, research conducted by Gupta and Siddique [72] replaced natural sand with CS in different ratios ranging from 0% to 60%, with intervals of 10%. Additionally, 20% of the cement component was exchanged for fly ash to produce self-compacting concrete (SCC). While the long-term durability and compressive strength results were observed to be a remarkable enhancement in SCC mixtures when up to 30% CS was incorporated, beyond this ratio, the consequences closely resembled those seen in the conventional concrete mix. In addition, a study by Rohini and Padmapriya [44] observed that the substitution of 50%–75% of the sand with CS resulted in enhanced mechanical characteristics and increased density of concrete.

Table 5 displays several studies that have reported the mechanical strength of concrete with CS as fine aggregate as carried out by various researchers. In accordance with the statistical data in Table 5, it can be seen that some of the authors have reported that the control mixtures had better performance; similarly, some researchers also noted that the maximum improvement in mechanical strength was observed at a 20% substitution of CS; exceeding this percentage led to a significant decrease in mechanical strength. Many factors affect the increase or decrease of the strength, which include, replacement proportion, water-binder (w/b) ratio, type of the concrete, activators, age of the curing, etc. The decrease in mechanical strength of the specimens can be attributed to the relatively low absorption rate of CS, resulting in an increased presence of free water within the mixture. Consequently, this promotes the creation of pores/voids in the hardened concrete, ultimately leading to ultimately reduction in its overall strength [2, 43, 54]. The inclusion of heavy metals within CS, which has the potential to hinder the hydration process in concrete mixtures, may provide insights into the observed reduction, as reported by Sharma and Khan [56].

3.4. Microstructure Analyses of the CS Concrete. To assess the bonding characteristics of mixtures, an analysis of the microstructure can be conducted on different samples using

Table 5: A summary of mechanical strength in concrete when containing CS as a replacement for fine aggregate.

Mechanical strength pattern	CS replacement ratio	*w/b*	Type of the concrete	Age	Activator/ dosage	Change range of control compared to optimum (MPa)	The optimum dosages (%)	Remarks	Ref.
Compressive strength	0,10, 20, 40, 50, 60, 80, and 100 by weight	0.35	HSC	7 days 28 days	7.9 L/m^3	76.6–79.6 93.9–99.8	10	—	[2]
	0,10, 20, 30, 40, 50, 60, 80, 90, and 100 by weight	0.35	HSC	7 days 28 days 90 days	7.9 L/m	75.7* 89.0* 93.5*	control	—	[21]
	0, 20, 40, 60, 80, and 100 by weight	0.3	HSC	7 days 28 days 90 days	4 kg/m^3	81* 99* 103*	Control	—	[18]
	0,10, 20, 40, 50, 60, 80, and 100 by weight	0.5	NSC	7 days 28 days	—	36.2–40.2 45.0–47.1	20 40	—	[69]
	0,10, 20, 30, 40, 50, and 60 by weight	0.4	SCC	7 days 28 days 90 days 365 days	1.2%	20.54–24.0 35.63–38.55 43.57–46.8 45.56–48.01	20	—	[68]
	0,10, 20, 30, 40, 50, 60, 80, 90, and 100 by weight	—	HSGPC	3 days 7 days 28 days 3 days 7 days 28 days	—	6.30–11.83 18.79–26.14 30.08–40.17 30.23–57.8 35.38–63.21 39.08–63.40	90	Ambient-cured Steam-cured	[70]
	0, 20, 40, 60, 80, and, 100 by weight	—	AAM	28 days	—	31.0–34.5	20	—	[71]
	0, 20, 40, 50, 60, 80, and 100 by weight	0.4	CM	28 days 56 days 90 days	—	24.6–42.7 25.3–44.5 27.0–50.3	50	—	[69]
Tensile strength	0,10, 20, 40, 50, 60, 80, and 100 by weight	0.35	HSC	28 days	7.9 L/m^3	5.4–6.2	20	—	[2]
	0,10, 20, 30, 40, 50, 60, 80, 90 and 100 by weight	0.35	HSC	28 days	7.9 L/m	5.2*	Control	—	[21]
	0, 20, 40, 60, 80, and 100 by weight	0.3	HSC	28 days	4 kg/m^3	5.6*	Control	—	[18]
	0,10, 20, 40, 50, 60, 80, and 100 by weight	0.5	NSC	28 days	—	3.0–4.1	50	—	[69]
Flexural strength	0,10, 20, 40, 50, 60, 80, and 100 by weight	0.35	HSC	28 days	7.9 L/m^3	14.6*	Control	—	[2]
	0,10, 20, 30, 40, 50, 60, 80, 90 and 100 by weight	0.35	HSC	28 days	7.9 L/m	11.7*	Control	—	[21]
	0, 20, 40, 60, 80, and 100 by weight	0.3	HSC	28 days	4 kg/m^3	9.3–9.6	40	—	[18]
	0,10, 20, 40, 50, 60, 80, and 100 by weight	0.5	NSC	28 days	—	7.7*	Control	—	[69]
	0, 20, 40, 60, 80, and, 100 by weight	—	AAM	28 days	—	5.6–5.08	20	—	[71]

Note. HSC: high-strength concrete; NSC: normal strength concrete; CM: cement mortar; SCC: self-compacting concrete; HSGPC: high-strength geopolymer concrete; AAM: alkali-activated material; *control strength is better than CS replacements.

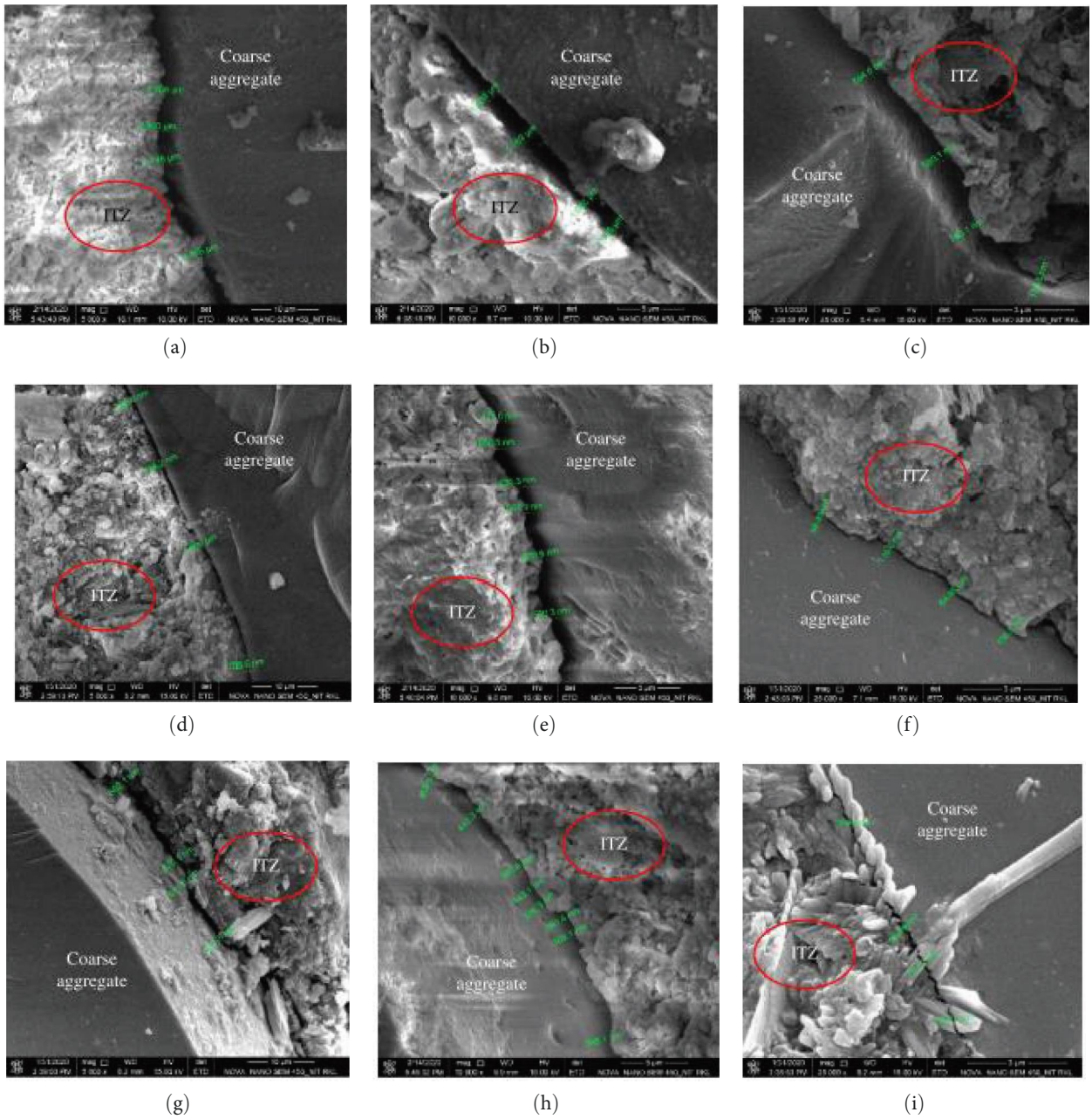
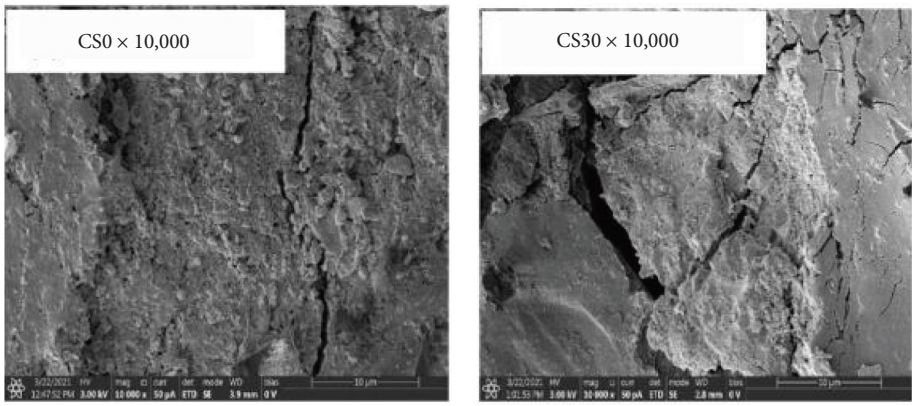


Figure 8: Microcrack analysis in the ITZ of specimens concrete: MCS0 at (a) 28 days, (b) 56 days, and (c) 91 days; MCS40 at (d) 28 days, (e) 56 days, and (f) 91 days; MCS80 at (g) 28 days, (h) 56 days, and (i) 91 days [67].

scanning electron microscopy (SEM) [74]. The thickness of the interfacial transition zone (ITZ) is characterized as the space between coarse aggregate and the cement paste [75]. Most structural flaws are located within the ITZ which is the weakest point in concrete structures [76, 77], and usually, the ITZ thickness is between 10 and 50 μm [78]. To understand the microstructure of CS concrete, several researchers have examined it through SEM analysis. For example, a research by Panda et al. [67] examined the ITZ of concrete using CS instead of sand and concluded that CS has greater pozzolanic reactivity than natural sand and improves the ITZ properties of hardened concrete as shown in Figure 8. Another research by Zheng et al. [36] investigated how replacing 30% of metakaolin with CS influences the microstructure of concrete. The results indicated that, in the CS0 sample (Figure 9(a)), an amorphous gel phase was evident. Equally, the CS30 sample displayed more sheet-like and crystalline materials, accompanied by a decrease in the quantity of amorphous gel compared to CS0, as depicted in Figure 9(b). This phenomenon could be attributed to the fact that some of the CS sheets did not actively participate in the reaction and instead served as microaggregates. Moreover, the study by Rathanasalam et al. [79] investigated an innovative method entailing utilizing fly ash as a substitute for ultrafine ground granulated blast furnace slag (UFGGBFS), alongside the use of CS as an alternative to fine aggregate, in the production of geopolymer



(a) (b)

Figure 9: Microstructure of concrete without CS and with 30% CS (a and b) [36].

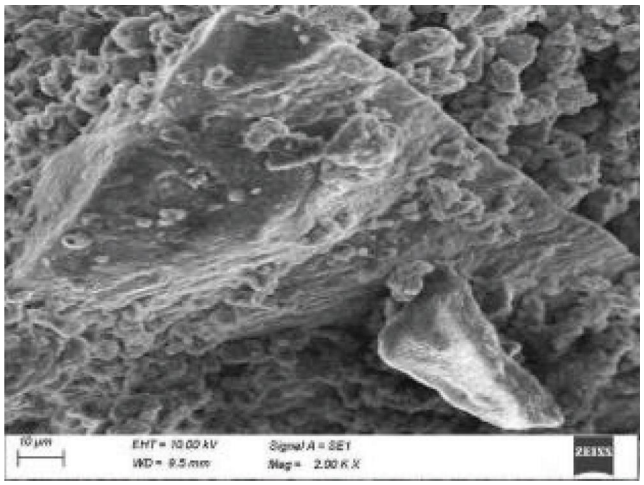
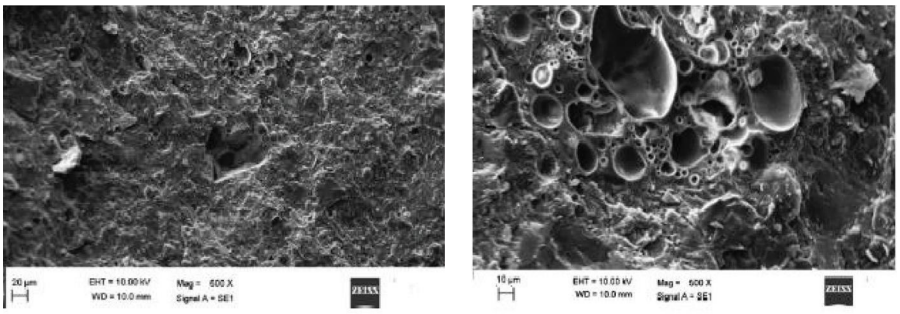


Figure 10: Microstructure of geopolymer concrete using CS [79].



(a) (b)

Figure 11: SEM image of 100% CS mix at 10 μm (a and b) [55].

concrete; subsequently, SEM was employed to examine this blend. Results of SEM analysis demonstrated that the incorporation of CS markedly improves the microstructure of geopolymer concrete. It promotes the formation of geopolymeric gel, diminishes voids and cracks, and efficiently fills the spaces between aggregates, as depicted in Figure 10. In the research carried out by Mahesh Babu and Ravitheja [55], it has been noted that when fine aggregate is completely replaced with CS, an excess of water tends to accumulate within the concrete, leading to an increased presence of capillary channels and voids. The formation of these capillary channels and voids has adverse effects on the bond between

aggregates and cement, resulting in a reduction in strength. Thus, the concrete durability characteristics are directly affected by this occurrence, as depicted in Figures 11(a) and 11(b).

4. Conclusions

This review examined numerous copper slag (CS) publications, predominantly focusing on CS, concerning its environmental consequences. Although commonly viewed as waste, CS exhibits potential viability in concrete production. The primary objective of this review was to identify practical approaches for reducing environmental risks, either through the reuse or recycling of CS in the production of concrete. The following conclusions can be drawn:

(i) The chemical composition of CS reduces its suitability as a binding material due to its high content of heavy metals and oxides, which may limit its use in specific applications.

(ii) Compared with natural aggregates, most CS exhibits a higher specific gravity and a smoother surface. Typically, CS displays reduced water absorption and a greater tendency to bleed, primarily attributable to its glassy composition, irregular surface, and shape. These characteristics lead to improved workability.

(iii) Given the superior performance of CS in concrete and mortar mixes compared to the control mixes, it is reasonable to propose that this substance can serve as a viable alternative for fine aggregate. However, replacing fine aggregate with CS has increased waste volume and demonstrated more substantial property improvements than substituting CS for cement.

Data Availability

The article incorporates data that support the conclusions of this work.

Conflicts of Interest

The authors declare that they have no competing interests.

Authors' Contributions

Scientific information was collected, and the text was made with the help of both authors. Both authors contributed to the writing, editing, concept design, and study proposal and reached an agreement on the final version to be published.

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