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COMPREHENSIVE STUDY ON COPPER SLAG UTILIZATION: APPLICATIONS, CHEMICAL PROPERTIES, AND FUTURE DIRECTIONS

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ARTICLE INFO	***ABSTRACT***

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Copper slag produced in industry can be 2 to 3 times per ton of pure copper produced through smelting and conversion processes. Total waste generation from copper slag has reached 50 million tons per year. Typically, untreated slag is stockpiled, and if left dry, high-metal-content slag can generate airborne dust, posing serious environmental and health hazards. Addressing this challenge is therefore urgent. Over recent years, extensive research has explored strategies for copper slag utilization, yet the information remains scattered, making it difficult for researchers and practitioners to assimilate findings effectively. This review provides a comprehensive review of copper slag management with emphasis on its use as a construction material, including fine aggregate substitute in concrete, supplementary cementitious material for Portland cement, and sand substitute in road construction, and on chemical treatment and metal recovery strategies. By compiling and integrating these studies, this review helps in understanding, identifying trends and opportunities, and motivating academia to further the sustainable and full use of copper slag, thus contributing to resource efficiency and lower environmental impact.

1. INTRODUCTION

The mining industry is one of the sectors that has a significant role in economic development, population growth, and technological advancement. The natural resources generated from these activities, such as metals and minerals, are the basic materials for various other industries. This makes the mining industry responsible for the depletion of mineral resources. As a result, the waste generated is expected to increase in the next few decades. [2].

The copper production process involves the extraction of large amounts of raw ore, producing considerable by-products. For each ton of recovered copper, two to three tons of slag are produced. The world's annual production of copper, about 23 million tons, produces more than 50 million tons of slag. Traditionally, the copper content in slag is first reduced, and the remaining is left to accumulate, often with no further use. However, this industrial by-product contains hazardous elements that slowly leach into the environment, posing long-term ecological hazards. These challenges have generated a growing interest in the sustainable management and valorization of copper slag, such as the possible reuse in construction materials, metal recovery, and other industrial applications, opening the way to a circular economy and reduced environmental impact [1].

Currently, the overall utilization of copper slag (CS) is mainly focused on two things. One way to use it is to extract precious metals such as iron and copper through the process of secondary magnetic separation or flotation. In addition, Copper waste is used directly as an original material in the construction industry or other related sectors [2]. Therefore, when scientists tried to solve this problem, this study was conducted to help emphasize the development of copper slag utilization. This study aims to provide an understanding and get an idea of the urgency, and encourage readers to help and contribute in the long term in finding solutions.

2. RESEARCH METHOD

This study employs a comprehensive literature review approach to synthesize the research on copper slag utilization. The review is structured around three interconnected themes: (i) chemical and mineralogical properties of copper slag, (ii) construction applications including concrete, cementitious materials, pavement, and structural-fill systems, and (iii) resource-recovery technologies including leaching, high-temperature separation, magnetic separation, and related processes.

Relevant literature was identified from scholarly databases such as Scopus and Web of Science, supported by cross-checking references from selected articles. Search terms included “copper slag utilization,” “copper slag concrete,” “supplementary cementitious materials,” “copper slag pavement,” “copper slag leaching,” “copper slag metal recovery,” and “copper slag environmental impact.” Studies were prioritized when they reported chemical composition, mechanical performance, durability, leaching behavior, recovery efficiency or environmental implications.

The selected studies were analyzed thematically and comparatively rather than treated as independent experimental procedures of the present paper. Experimental details reported in the literature were retained only when they helped explain performance trends or technological feasibility. For construction applications, the review compared replacement level, compressive strength, durability, density, workability, and potential mechanisms. The review compared target products, recovery efficiency, operating conditions, reagent demand, energy intensity and environmental limitations for recovery processes. The synthesis also considered practical implementation factors such as availability of copper slag, consistency of slag composition, environmental safety, regulatory requirements and carbon emission reduction. This study approach allows the review to identify not only reported benefits but also inconsistencies, limitations, and research gaps that must be addressed before large-scale copper slag utilisation can be achieved.

3. RESULT AND DISCUSSION

3.1 Copper slag production

As seen in Figure 3.1, the copper production process starts with the feeding of copper-containing raw materials such as copper ore, concentrate, and matte through a series of pyrometallurgical operations, which include mining, crushing, flotation, smelting, conversion, flame refining, electrolytic refining, remelting, and casting. During the smelting, conversion, and flame refining processes, slag is formed as a by-product and then treated by air cooling or quenching. Slag is formed all along the smelting, conversion, and burning processes of fire, and contains relatively high levels of copper, which increases with higher matte purity. Slag containing likewise 1% copper is processed for copper readjustment over several means, namely: (i) melting smelted waste in a separate slag cleaning furnace, (ii) recycling molten slag back to the previous stage, or (iii) processing of hardened and air-cooled slag, using the same methods as ore treatment. Meanwhile, slag with a copper content of less than 1% is cooled first, then diverted for other uses or disposed of. The treated slag is then reused internally, used in external construction applications or disposed of in a landfill if not suitable, ensuring efficient resource utilization whilst minimizing environmental impact [3].

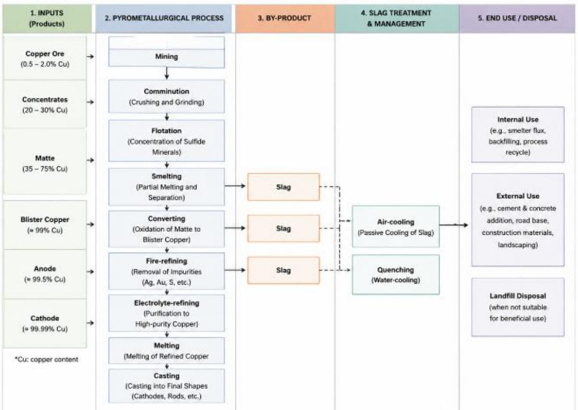

Figure 3.1 Copper Production and Copper Slag Using Pyrometallurgical Process [3]

3.2 Copper Slag Chemical Properties

Copper slag generally has high iron content and low calcium. Mine waste is mainly affected by the components of the base ore, sand, and, to a lesser extent, the refining processes used. Based on Table 3.1 on the copper slag chemical composition, the main component by weight is powdered crystalline silica (SiO2), which ranges from 40 to 75%. Secondary components, such as Al2O3 and CaO, account for about 10 to 20% of the total weight. The metal oxide content varies from 0 to 20%. Sulfates and alkali metals, such as lithium and sodium, are found in percentages of 0 to 5%. The main health concerns associated with these materials come from trace elements, such as arsenic, thorium, uranium, lead, and cadmium, which are often associated with copper. Although the amount is less than 1%, these harmful elements can be present in considerable quantities due to the scale of their waste. High levels of crystalline silica and heavy metals also increase the risk of cancer due to long-term exposure and inhalation of dust[4].

Table 3.1 Copper Slag Chemical (a)Components and (b) Implications [4]

(a)

Component	Relevance for Application	Limitations
SiO_2	Enhances pozzolanic activity in cement	High silica may form viscous gel in high-acid extraction
FeO/Fe_2O_3	Improves density and strength in concrete/pavements	Excess iron can hinder uniformity in composites
Al_2O_3	Supports cementitious behavior	Limited effect at low content
CaO	Influences setting time and durability	Excess may cause expansion
Trace metals (Pb, Zn, Cu, As)	Can be recovered for economic benefit	Environmental hazards, leaching risk

(b)

Component (wt %)	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]
Al_2O_3	5,92	2,79	3,01	3,5	5,9	14,89	3,78	3,53	-
CaO	7,09	6,06	2,76	4	7,1	25,29	5,24	20,06	10,2-10,6
FeO/Fe_2O_3	45,45	53,45	53,64	43,03	45,5	7,88	44,78	29,99	28,1-28,6
K_2O	0,19	0,61	1,21	-	0,2	3,08	2,03	0,43	-
MgO	0,81	1,56	0,53	1,39	0,8	7,9	1,16	0,5	14,6-16,6
MnO	0,74	0,06	-	-	0,7	-	-	0,04	-
Na_2O	0,8	0,28	1,43	-	0,8	0,87	0,3	0,15	0,9
SO_3	0,37	1,89	-	-	0,4	-	1,06	1,17	-
SiO_2	25,87	33,05	28,07	33,4	25,9	39,85	40,97	42,06	45-45,1
TiO_2	0,31	0	-	-	0,3	-	0,58	0,25	-
Cu/CuO	0,5-1,0	0,5-1,2	0,3-1,1	0,4-0,9	0,5-1,0	0,3-0,7	0,2-0,8	0,3-1,0	0,4-0,9
Location	Gent, Belgium	Muscat, Oman	Cape Coast, Ghana	Beijing, China	Gent, Belgium	Warsaw, Poland	Tehran, Iran	Belgrade, Serbia	Seoul, South Korea

The mineralogy of copper slag is important not only to define the chemical composition of the slag, but also controls the physical behavior and reactivity of the slag for a wide range of applications. The mineralogy of copper slag includes crystalline phases such as fayalite ($Fe_2 SiO_4$), magnetite (Fe_3O_4), and less frequently, wüstite (FeO), as well as minor mineral phases such as enstatite ($MgSiO_3$) and spinel with trace metals. The mineralogical composition can influence the hardness, density, and mechanical strength of the slag. For example, fayalite can contribute to structural stability, and magnetite can influence the magnetic properties of the slag that is used in the beneficiation or recovery process. The mineralogical composition also impacts the pozzolanic reactivity of the slag in cement applications and the leaching behavior of the slag, as certain crystalline phases can encapsulate harmful elements, and thereby influence their mobility in the environment. As a result, the chemistry and mineralogy are both important for optimizing the reuse of copper slag in construction, roadbeds, or metal recovery.

3.3 Utilization of copper slag as a construction material

Sustainability concerns, green issues, and advancements in technology are the focus drivers in the construction sector to switch to smart materials that are designed to be more eco-friendly and more cost-effective than old-time construction materials. The use of these materials can significantly extend the life of a building while drastically reducing maintenance needs and costs [14]. Copper slag constitutes a form of metallurgical byproduct that is abundant and has the potential to be used as the main material in the manufacture of construction materials. There are a variety of ways to utilize copper slag in the construction industry, such as mixing it with concrete, making it an additive in regular cement production, or using it as a supplement to increase the strength of pavement.

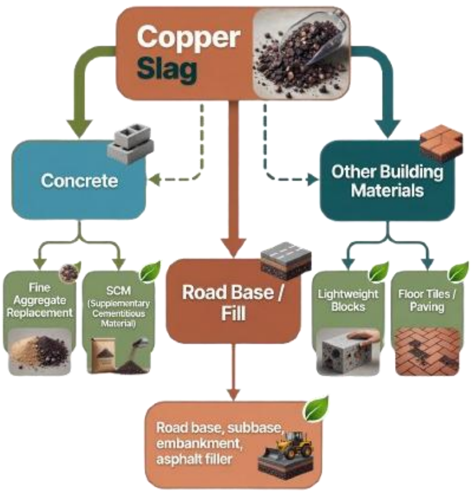

Figure 3.2 Applications of Copper Slag in Construction

3.3.1 Copper Slag As an Admixture For Concrete

In modern developments, many additives have been transformed to improve the performance of concrete. For instance, superplasticizers are utilized to augment the mechanical strength, workability, void content, and transport properties of concrete. In addition to the benefits provided by superplasticizers, supplementary mineral admixtures are also incorporated to further improve workability and confer substantial strength to concrete. Due to its high silica and metallic composition, copper slag is regarded as a valuable addition to boost the quality of cement-based composites.[15]. Certain research findings have demonstrated that the consistency and density of concrete are enhanced by a higher proportion of copper slag in concrete formulations. Higher copper slag percentages resulted in enhanced compressive strength up to a 50% substitution, after which a decline was noted with further increments in copper slag relative to the control mix. Among the various proportions evaluated, the 50% copper slag substitution showcased superior compressive and split tensile strengths, along with commendable elasticity and resistance to chloride, acid, and sulphate aggression.[16].

In 2023, M. Velumani, with the team. Conducted a study resulting in these findings. This research employed materials such as 53-grade standard cement, fine aggregates, coarse aggregates, and water, adhering to the standards set forth by IS 12269:1997, IS 9377-1979, IS: 383–1970, and IS 456-2000 for the formulation of concrete[17]. The guidelines outlined in IS10262-2009 were followed to create an M30 rank of concrete with a combination of 1:1.87:3.37. A total of eleven different blends were created by swapping sand with Copper Slag at substitution levels ranging from 0% to 100% by weight, in increments of 10%. The water-to-binder ratio was set at 0.4 for all mixes. Superplasticizer was added in three amounts: 1.2% for 0–30% Copper Slag, 1.15% for 40–60% Copper Slag, and 1.1% for 70–100% Copper Slag replacement. Each mixture used 144.78 kg of water and 381 kg/m³ of cement. Table 3.2 lists the different amounts of fly ash and coarse aggregate used in each mix.

Table 3.2 M30 grade concrete of Mix proportions

. Specimen identification	CC	Copper Slag									
		1	2	3	4	5	6	7	8	9	10
Copper Slag (%)	0	10	20	30	40	50	60	70	80	90	100
Water to Binder Ratio	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Super Plasticizer (%)	1.2	1.2	1.2	1.2	1.15	1.15	1.15	1.1	1.1	1.1	1.1
Water (kg/m3)	144.8	144.8	144.8	144.8	144.8	144.8	144.8	144.8	144.8	144.8	144.8
Cement (kg/m3)	381	381	381	381	381	381	381	381	381	381	381
Copper Slag (kg/m3)	0	71.1	142.2	213.3	284.4	355.5	426.6	497.7	568.8	639.9	711
Fly Ash (kg/m3)	711	639.9	568.8	497.7	426.6	355.5	284.4	213.3	142.2	71.1	0
Coarse Aggregate 10 mm	513.2	514.2	515.2	516.2	517.2	518.2	519.2	520.2	521.2	522.2	523.2
Coarse Aggregate 20 mm	769.8	769.8	769.8	769.8	769.8	769.8	769.8	769.8	769.8	769.8	769.8

In accordance with IS 10086-1982, the casting and curing process involved the preparation of specimens, including cubes measuring 150 x 150 x 150 mm, cylinders measuring 150 x 300 mm, and prisms measuring 100 x 100 x 500 mm. These specimens were used to assess mechanical strength, with curing carried out over 28 days at ambient temperature. The 150x150x150 mm cubes were specifically employed to test resistance to acid, chloride, and sulphate attacks. The acid resistance test followed ASTM C 642 standards. The specimens were submerged in a 5% Magnesium Sulphate ($MgSO_4$) solution, with their initial weights recorded before immersion. After a set period, the specimens were removed from the solution, and their weights were measured again. The specimens were then tested for compressive strength. To evaluate acid resistance, the measured weight loss and the decrease in compressive strength. Also, the specimens were placed in a 3.5% sodium chloride (NaCl) solution for 30, 60, and 90 days, and changes in their weight and compressive strength were tracked. The acid resistance test adhered to ASTM C 642 standards, and the chloride resistance evaluation followed the same procedure. For sulphate attack resistance, the ASTM C1012 standard was used, which involved immersing the specimens in a high-concentration sulphate solution and measuring changes in weight and compressive strength after the test. As mentioned earlier, it was observed that the strength increased with copper slag up to a 50% replacement level, after which the strength declined as more copper slag was added compared to the control mixture. Among all tested proportions, the 50% copper slag replacement exhibited the best compressive and split tensile strength, enhanced elasticity, and significant resistance to chloride, acid, and sulphate attacks. [16].

Table 3.3 Performance of Concrete with Copper Slag as Fine Aggregate

Study	Replacement Level (%)	Key Findings	Advantages	Limitations
Velumani et al., 2023 [17]	0–100	Peak compressive strength at 50% replacement	Improved strength and consistency	Reduced workability at replacement levels above 60%
Al-Jabri et al., 2009 [6]	20–40	Better density and durability	Higher resistance to chemical attack	Requires superplasticizer adjustments
Filipović et al., 2021 [12]	30–50	Maintains flexural strength	Supports sustainable waste utilization	Limited long-term durability data

3.3.2 Utilizing copper slag as supplementary cementitious material in cement

Building materials are a significant contributor to carbon emissions and the depletion of natural resources in the construction industry. One way to tackle this issue is by changing the segment of the ordinary Portland cement (OPC) with supplementary cementitious materials (SCMs), a method believed to boost the durability and performance of concrete. Detailed research comparing different SCMs, especially in terms of environmental impact, cost, durability, and strength, is still quite rare [18]. Inclined to the large amount of copper slag waste produced globally, and its affinity to SCMs, researchers have started to explore its potential. One such study by Mahajan et al. in 2024 looked into using copper slag (CS) as an SCM to replace part of the OPC in concrete for more sustainable construction. In its raw form, the slag was granular, black, and had a smooth presence. To improve its fineness, the slag was milled in a laboratory, and the finely ground material was sieved to 90 µm before being used in the experiments. The researchers mixed the Copper Slag with OPC in different proportions, labeling the samples as Copper Slag 1, Copper Slag 2, and Copper Slag 3 based on different grinding times. Comparing fly ash and quartz powder was also prepared. To assess the pozzolanic activity of the samples, the researchers conducted suspension and paste studies. They used derivative thermogravimetry (DTG) to monitor the decomposition of calcium hydroxide (CH). Disintegration of the process increases dissolution and nucleation, which boosts pozzolanic reactivity. The outcome showed that the pozzolanic activity of Copper Slag 1 was higher than that of Copper Slag 2. While copper slag does exhibit pozzolanic characteristics, the study concluded that its reactivity is lower than that of fly ash.[19].

3.3.3 Copper slag utilization in pavement road

Along with the quick development of pavement construction, the demand for road basic materials continues to increase. However, the basic materials of traditional roads, such as cement and pebbles, are ever more difficult to obtain. Thus, important to look for alternative raw ingredients that have abundant resources and better economic benefits to replace those resources.[20]. Copper slag is an industrial waste product that has the property of being able to be used as a raw material for road construction. In a study conducted by Sony, Jaykumar, and colleagues in 2022, fine copper slag was mixed with different types of soil, while sand was combined with different types of soil. The geotechnical characteristics of the mixture are then evaluated. This study compared the advantages of fine copper slag with sand in road construction and found that this material has good structural potential for use in road construction and structural embankment applications[21].

This study utilizes fine copper slag for uses in road infrastructure, specifically in landfill and street construction. The research process begins with mixing fine copper slag and sand with soil in varying amounts, Subsequently, its geotechnical properties are assessed. Comparisons were made to observe the properties of fine copper slag and sand. To assess its application in structural heap applications, CBR tests were performed on a mixture of fine copper slag and granular copper slag. This test is used to determine the density of the material and is carried out in accordance with the IS:2720 standard (Part 3, Part I).

Sand has a density of 2.69, while Fine Copper Slag (FCS) has a density of 3.49, which is quite high due to its abundant iron oxide content. The high density value of copper slag indicates that roads built using copper slag will be denser, making them more durable and stronger. As a waste product, copper slag has great potential in the road construction sector as a substitute for traditional materials. Copper slag has been shown to improve soil characteristics, making it more beneficial in road construction.

Table 3.4 Copper Slag in Pavement and Structural Fill

Study	Application	Key Findings	Advantages	Limitations
Soni et al., 2022 [21]	Fine copper slag in embankment fill	Enhanced soil strength	Reduced natural resource use	Requires grading control
Gu et al., 2023 [20]	Road base	Higher density than traditional aggregates	Improved durability	May increase material handling costs

3.4 Metal and Resource Recovery

Copper slag contains recoverable metals (Cu, Fe, Zn) and silica. Extraction techniques include acid leaching, high-temperature chlorination, and magnetic separation [22][23] [24]. Integrating metal recovery with construction applications allows full resource utilization while mitigating environmental risks. Copper slag has different phases inside. As for the main phase that commonly exists is fayalite, pyroxene, magnetite, and metal sulfide [22]. Then the element inside copper slag is rich in silicon and iron elements, and some non-ferrous metal elements [4]. Extracting the silicon and the non-ferrous in copper slag is beneficial in both the economic aspect as for the environmental aspects. That is the reason scientists are finding solutions to create an effective treatment for copper slag [23].

Extracting silica and metal elements by utilizing copper slag can help reduce solid waste, in addition to providing economic benefits. Thus, efficient copper slag processing is now a critical issue in solid waste management [24]. One of the scientists conducting research in this area is Qikai Wang. The copper waste chemical composition in Table 3.5 for most elements and Table 3.6 for the remaining elements.

Table 3.5 Most Elements of Chemical composition of copper slag [24]

Content	**w_B%**
Silica Dioxide	31.3
Titanium Dioxide	0.08
Aluminum Oxide	3.95
Iron (III) Oxide	9.13
Iron (II) Oxide	41.9
Manganese (II) Oxide	0.08
Magnesium Oxide	1.55
Calcium Oxide	2.25
Sodium Oxide	0.79
Dipotassium Oxide	0.72
Phosphorus Pentoxide	0.08
Sulfur Trioxide	0.76
LOI	<0.20

Table 3.6 Less Elements of Chemical composition of copper slag [24]

Content	Cobalt	Nickel	Copper	Zinc	Molybdenum	Plumbum
µg/g	349	158	2892	18,330	1493	5243

The entire process is broken down into three stages: dissolving copper slag with sulfuric acid, preparing hematite, and processing the acid solvent residue. The process in Figure 3.3.

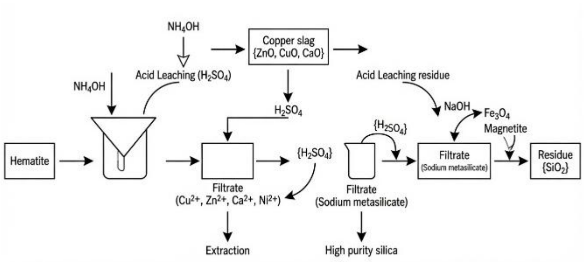

Figure 3.3 Copper Slag Schematic Diagram of resource utilization [24]

The advantages and limitations of each method were compared from the author's review. The acid leaching method can recover valuable metals like Cu, Fe, and Zn with an efficiency of 70–90% but requires careful acid handling and has a risk of forming silica gels. The high-temperature chlorination method can effectively extract some metals like Cu, Pb, and Zn with an efficiency of 60–85%, but it needs high energy. The magnetic separation method has the highest efficiency for Fe recovery (80–95%) and is more environmentally friendly, but only suitable for the magnetite phase.

Table 3.7 Resource Recovery From Copper Slag

Method	**Metals Recovered**	**Recovery Efficiency (%)**	**Advantages**	**Limitations**
Acid leaching	Cu, Fe, Zn	70–90	Recovers high-value metals	Requires acid handling and may cause silica gel formation
High-temperature chlorination	Cu, Pb, Zn	60–85	Efficient for recovering multiple metals	High energy demand
Magnetic separation	Fe	80–95	Low environmental impact	Only suitable for magnetite phases

Summarizes the main studies on different applications of copper slag in construction and metal recovery in Table 3.8. The table presents the composition and properties of copper slag used in each study, the experimental methods, and the key findings. It shows the use of copper slag as a replacement for fine aggregate in concrete, as a cementitious addition, as an addition in road base or structural fill, and as a material for chemical or high-temperature processing to extract metals and silica. This structured presentation allows the reader to easily compare the effectiveness of copper slag in the different applications. This highlights the flexible character of copper slag as a sustainable material and its capability to enhance construction quality and resource recovery efficiency.

In the summarize table shows some future trends and challenges in the field. The use of copper slag in concrete and road construction has clear advantages in terms of strength, durability and sustainability but the variability in slag composition poses a problem for standardisation and consistent performance. Similarly, chemical and high-temperature treatments for metal recovery are highly efficient, but the energy demands and environmental management are still key concerns. Further research is required to improve the processing techniques, reduce environmental risks and develop guidelines for large scale, standardised applications in the construction and metallurgical industries.

Table 3.8 Summary of Copper Slag Applications in Construction and Metal Recovery

Application	Study	Copper Slag Composition / Characteristics	Experimental Method	Main Results
Concrete fine aggregate	Velumani et al., 2023 [17]	Copper slag as sand replacement, rich in silica and iron oxides	Sand replaced by copper slag at 0–100% in M30 concrete	Best performance was found at 50% replacement, with improved compressive strength and durability
High-performance concrete	Al-Jabri et al., 2009 [6]	Copper slag used as partial fine aggregate replacement	Fine aggregate replaced at 20–40%	Improved density, durability, and resistance to chemical attack
Concrete aggregate	Filipović et al., 2021 [12]	Copper slag with pyroxene composition	Natural aggregate replaced at 30–50%	Flexural strength was maintained, but long-term durability data remain limited
Supplementary cementitious material	Mahajan et al., 2024 [19]	Ground copper slag sieved to 90 µm	Pozzolanic activity tested using paste and suspension studies	Copper slag showed pozzolanic activity, but lower reactivity than fly ash
Road and structural fill	Soni et al., 2022 [21]	Fine copper slag with higher density than sand	Mixed with soil and tested using geotechnical and CBR tests	Improved soil strength and showed potential for embankment and road applications
Road base material	Gu et al., 2023 [20]	Copper slag used with industrial solid wastes	Review of road base materials from solid wastes	Copper slag can improve density and durability of road base materials
Metal and silica recovery	Wang et al., 2022 [24]	SiO_2 31.3%, FeO 41.9%, Fe_2O_3 9.13%, and trace metals	Sulfuric acid leaching, hematite preparation, and residue treatment	More than 85% of non-ferrous metals remained in solution, and silica purity reached 99.9%
High-temperature recovery	Wu et al., 2023 [1]	Copper slag containing Cu, Zn, and Pb	High-temperature treatment using $CaCl_2$	Cu, Zn, and Pb removal reached 90.3% under optimum conditions

3.5 Environmental and Health Impacts

The environmental and health impacts of use of copper slag need to be assessed together with technical performance . Copper slag may contain crystalline silica and trace metals such as arsenic, lead, cadmium and other potentially harmful elements. When copper slag is stored, crushed, transported or used in dry conditions, dust formation may increase inhalation risks . In unbound applications such as road base or structural fill, leaching under rainfall, groundwater, acidic conditions or carbonation should also be considered . For construction applications, cementitious matrices may help immobilize some metal-bearing phases, but this should be verified through leaching tests and long-term durability assessment. Safe utilization therefore requires source-specific characterization, dust suppression, worker protection, environmental monitoring, and compliance with relevant local regulations.

These precautions are especially important because copper slag composition depends on ore source, flux, smelting practice, and cooling method.

3.6 Future Direction

Future research should first standardize the characterization of copper slag. In addition to major oxides, studies should report origin or source location, Cu or CuO content, trace elements, particle size distribution, cooling history, and mineralogical phases. This information is necessary because chemical composition alone cannot fully explain concrete performance, pozzolanic behavior, leaching risk, or metal recovery efficiency. Second, construction studies should move beyond strength testing and include microstructural and durability analysis. The repeated observation that about 50% copper slag replacement can improve concrete properties should be explained through mechanisms such as particle packing, density, water demand, paste-aggregate bonding, and pore structure. Long-term field trials and leaching tests are required to confirm performance in real environmental exposure for pavement and road applications. Third, extraction studies should be performed with minimized energy demand, chemical consumption and secondary emissions. Metal recovery combined with subsequent construction use of treated residues can provide a more complete circular utilization pathway. Large-scale pilot studies, life-cycle assessment, techno-economic analysis and clear regulatory guidelines are needed to apply copper slag safely and economically.

4. Conclusion

It turns out that even though currently copper slag is still waste, its potential to be used and become valuable is not empty. With this study, we have learned what approaches researchers have taken to resolve this problem. Some researchers are trying to provide a solution by using copper slag for material of construction. Copper slag is used as an admixture in concrete so that the durability of the concrete is increased by 50 % with copper slag as a substitute for fine aggregate. Other researchers use copper slag as supplementary cementitious materials (SCM) for ordinary Portland cement (OPC) combinations, although the results for the pozzolanic slightly slower than using fly ash. This can be a lesson for readers, even though scientist have done their best, the results will perhaps not come out as desired. But the struggle must not stop. Then, there are also researchers who are conducting studies to use copper slag as a original material to replace sand to making paving roads. The finding indicate that roads made of copper slag will be denser so that they can easily withstand heavier loads with a density of 3.49 that huge difference from sand with only 2.69 for their density. Apart from that, in our study this time, we have seen researchers who carry out extraction processes to use all the component in the waste separately that can be used more widely. Researchers who carried out three leaching processes, namely: sulphuric acid dissolution of copper slag, preparing of hematite powder, and handling of acid dissolvable waste, succeeded in utilizing the copper slag with wonderful results. As the iron ion in the copper slag is dissolved completely, the silica gel was established the acid dissolvable, and more than 85% of the other non-ferrous elements remain in the liquid. And with the sub-extraction process of the liquid, the silica content can achieve 99,9 % purity. Some studies carry out high temperature separation to separate Cu, Zn, and Pb in the copper slag. The results state that in ideal form of 13 % $CaCl_2$ add, 1373 K temperature, and 0.5 h duration, the removal percentages of Cu, Zn, and Pb can be achieved in 90.3 %. With this, the author ends this study, however research to utilize copper slag as a whole without any economic burden and provide a good impact for a better world has not been completed and will continue. Hopefully, with this study, readers can become part of this journey.

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