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Experimental Investigation on Strength and Durability of Copper Slag Concrete

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Abstract: The increasing scarcity of natural resources and rapid urbanization has intensified the demand for sustainable alternatives in the construction industry. Copper slag, a by-product of the metal smelting and refining process, has emerged as a viable substitute for cement and aggregates in concrete production. With approximately 24.6 million tonnes of copper slag generated annually worldwide, its utilization presents a dual advantage of effective waste management and environmental sustainability. While extensive research has been conducted on the mechanical properties of copper slag concrete, limited studies have explored its durability, performance under elevated temperatures, and thermal cycling effects. This study investigates the strength and durability characteristics of copper slag concrete, with a specific focus on the inclusion of steel fibers to enhance mechanical properties. The research comprises four phases: determining the optimum replacement percentage of sand with copper slag, evaluating mechanical properties, assessing durability aspects, and analyzing the effects of elevated temperatures and thermal cycles. The incorporation of steel fibers addresses the inherent weaknesses of plain cement concrete, improving tensile strength and fracture resistance. The findings of this study provide valuable insights into the structural viability of copper slag concrete under extreme conditions, promoting its application as a sustainable and high-performance construction material.

Keywords: Cement; Copper slag; Optimum content; Mechanical properties; Durability characteristics; Elevated temperatures.

1. INTRODUCTION

The depletion of natural resources and rapid urbanization have significantly impacted the construction industry, creating an urgent need for sustainable alternatives. Among the primary concerns is the extensive mining of river sand, which has led to severe environmental degradation, increased costs, and resource depletion. Several Indian states, including Maharashtra, Kerala, and Gujarat, have already imposed bans on river sand mining due to its adverse ecological effects (Tiwari & Sinha, 2020). As a result, researchers and engineers have been investigating the potential of various industrial by-products, such as fly ash, silica fume, stone dust, carbonated sand, and slags, as substitutes for fine aggregates in concrete production (Patil et al., 2021).

Among these alternatives, copper slag has gained significant attention due to its physical and chemical properties, making it a viable substitute for river sand (Gorai, Jana, & Premchand, 2003). Copper slag is a by-product generated during the smelting process of copper production, wherein impurities are separated, and non-metallic residues are produced. It is estimated that for every tonne of copper extracted, 2.2 tonnes of copper slag are generated. Given the global copper production of nearly 15.9 million metric tonnes per year, approximately 34.98 million metric tonnes of copper slag are produced annually (US Geological Survey, 2010). This massive quantity of waste poses a significant environmental challenge, emphasizing the necessity of utilizing it in construction (Singh et al., 2022).

Research has demonstrated that copper slag can be effectively used as a partial or full replacement of sand in concrete without significantly compromising mechanical properties. However, while extensive studies have focused on the strength properties of copper slag concrete (CSC), limited research has been conducted on its durability, performance under elevated temperatures, and thermal cycling effects (Shanmugapriya et al., 2019).

Furthermore, plain cement concrete (PCC) has inherent weaknesses, such as low tensile strength and low fracture strain, primarily due to the presence of microcracks at the mortar-aggregate interface (Neville, 2011). The incorporation of steel fibers in concrete has been recognized as an effective method to enhance tensile strength, ductility, and resistance to cracking (Karihaloo, 2020). Therefore, this study investigates the combined effect of copper slag and steel fiber reinforcement on the strength, durability, and thermal performance of concrete.

1.2 Copper Slag as a Sustainable Construction Material

Copper, widely used in electrical, construction, and transportation industries, is extracted through a complex smelting process. This process generates large volumes of copper slag, which contains oxides of iron, silicon, and aluminum (Sikder et al., 2019). The refining process removes impurities through chemical reactions, producing copper slag as a non-metallic by-product.

In India, Sterlite Industries, Birla Copper, and Hindustan Copper are the primary producers of copper, generating approximately 25 million tonnes of copper slag annually (Bhattacharyya et al., 2020). Due to its favorable physical and chemical properties, copper slag has been proposed as a sustainable alternative to river sand. It has a glassy black appearance, granular texture, and specific gravity of 3.476, comparable to fine aggregates (Murari & Siddique, 2019). Additionally, the density of granulated copper slag ranges from 1898 to 2024 kg/m^3, making it suitable for concrete production. The hardness of copper slag falls between 6 and 7 on the Mohs scale, similar to that of gypsum (IS 11127, 1993). The silica content (approximately 34%) enhances its bonding capabilities within the concrete matrix (Patil et al., 2021).

Copper slag has found extensive applications in the construction industry due to its unique physical and chemical properties. One of its primary uses is in abrasive blasting, where it serves as an effective material for industrial cleaning, rust removal, and surface preparation before painting. Its hard and angular particles make it ideal for stripping coatings from metal surfaces, cleaning large industrial equipment, and maintaining structures such as bridges and ships (Sikder et al., 2019). Additionally, copper slag is widely used as a filling material in road construction and building foundations. Its high strength-to-weight ratio and excellent compaction properties make it a viable alternative to traditional backfilling materials, providing enhanced stability and durability to constructed surfaces (Murari & Siddique, 2019). Another significant application of copper slag is as a replacement for sand in concrete production. Due to its granular structure and high silica content, it improves the workability, compressive strength, and resistance to harsh environmental conditions when incorporated into concrete mixes. Studies have shown that replacing sand with copper slag in concrete enhances its mechanical properties while also contributing to sustainable waste management by reducing dependency on natural resources (Gorai et al., 2003). These diverse applications highlight the potential of copper slag as a sustainable and cost-effective material for modern construction projects.

The utilization of copper slag in concrete offers multiple advantages, making it a sustainable and efficient alternative to conventional materials. One of the most significant benefits is waste management, as the large-scale production of copper results in substantial amounts of copper slag, which, if not utilized effectively, would require landfill disposal, contributing to environmental pollution. By incorporating copper slag into concrete, the need for waste disposal is reduced, leading to a more eco-friendly approach to industrial by-product management (Bhattacharyya et al., 2020). Additionally, the use of copper slag promotes sustainability by conserving natural resources such as river sand, which is becoming increasingly scarce due to excessive mining. By replacing sand with copper slag, the construction industry can ensure the long-term availability of essential materials while minimizing the negative environmental impact associated with riverbed depletion (Singh et al., 2022). Furthermore, copper slag utilization enhances the cost-effectiveness of concrete production. Since copper slag is an industrial by-product, repurposing it in construction lowers material costs, making it an economical alternative to natural sand without compromising the structural integrity of concrete. This cost reduction benefits both large-scale infrastructure projects and smaller construction applications, promoting widespread adoption (Shanmugapriya et al., 2019). Overall, the integration of copper slag into concrete production aligns with sustainable construction practices, addressing environmental, economic, and resource conservation concerns effectively.

Concrete, despite being the most widely used construction material, has inherent weaknesses in tension. The introduction of steel fiber reinforcement has proven to significantly improve tensile strength, ductility, and resistance to cracking (Neville, 2011).

Steel fiber reinforcement has been widely adopted to improve the mechanical properties of concrete, particularly in enhancing its tensile strength, ductility, and crack resistance. Various types of steel fibers have been developed for different structural applications, including straight fibers, which provide basic reinforcement by resisting microcrack formation, and hooked-end fibers, which offer superior anchorage, enhancing load transfer efficiency and post-crack performance. Additionally, crimped fibers are commonly used due to their wavy or deformed shape, which improves the bond between the fiber and the concrete matrix, thereby increasing toughness and crack-bridging capacity. Another widely used type is indented fibers, which have surface indentations that enhance mechanical interlocking, further improving concrete's resistance to cracking. Hybrid fibers, which combine different fiber types or materials, optimize performance by leveraging the strengths of each fiber type, improving both strength and energy absorption capacity (Karihaloo, 2020).

The aspect ratio (length-to-diameter ratio) and volume fraction of fibers play a crucial role in determining the workability, toughness, and load-bearing capacity of Steel Fiber Reinforced Concrete (SFRC). Higher aspect ratios generally improve crack resistance, but excessive fiber content may reduce workability. In this study, crimped steel fibers were selected due to their enhanced bonding and crack-bridging abilities, ensuring improved flexural and tensile strength, along with better stress distribution under loading conditions (Bhattacharyya et al., 2020). Their effectiveness in controlling microcracks and enhancing durability makes them an ideal choice for applications where impact resistance and long-term performance are critical.

2. SIGNIFICANCE OF THE RESEARCH

The primary objective of this study is to explore the suitability of copper slag as a partial replacement for sand in concrete production while enhancing its properties with steel fiber reinforcement. To achieve this, the research first determines the optimum percentage of copper slag replacement that maintains the required workability and strength characteristics of concrete. Since copper slag has different physical and chemical properties compared to natural sand, identifying an appropriate substitution level is essential for ensuring structural performance. Following this, the study evaluates the mechanical properties of copper slag concrete (CSC), including compressive strength, split tensile strength, and flexural strength, which are critical parameters for its application in construction. In addition to strength assessment, durability tests such as acid resistance, sulfate resistance, water absorption, and chloride permeability are conducted to analyze the long-term performance of CSC in different environmental conditions.

3. MATERIALS USED IN THE STUDY

53 Grade Ordinary Portland Cement (OPC) was used in this study. OPC was selected due to its superior compressive strength and durability in concrete applications. The cement was obtained from the same brand and batch to maintain consistency and stored in airtight containers to prevent moisture contamination. The physical properties of the cement were tested according to IS 4031:1988 standards.

Table 1: Properties of 53 Grade Ordinary Portland Cement (OPC)

Property	Test Result
Specific Gravity	3.09
Fineness (%)	4.62
Normal Consistency (%)	32
Initial Setting Time (min)	120
Final Setting Time (min)	320

Clean locally available river sand was used as fine aggregate, ensuring that it was free from salt, organic matter, and clay impurities. The fine aggregate conformed to Grading Zone II of IS 383:1970. The sand was tested as per IS 2386:1963 standards.

Table 2: Physical Properties of Fine Aggregate

Property	Test Result
Specific Gravity	2.601
Fineness Modulus	2.43
Bulk Density (Loose) (kg/m³)	1597
Bulk Density (Compacted) (kg/m³)	1700
Water Absorption (%)	0.012

Machine-crushed angular granite aggregates of a maximum size of 20 mm were used as coarse aggregate. It was ensured that the aggregate was free from dust, clay, and organic impurities. The properties of the coarse aggregate were tested as per IS 2386:1963.

Table 3: Physical Properties of Coarse Aggregate

Property	Test Result
Specific Gravity	2.637
Fineness Modulus	7.102
Bulk Density (Loose) (kg/m³)	1414
Bulk Density (Compacted) (kg/m³)	1550
Water Absorption (%)	1.1

Copper slag is an industrial by-product obtained during the smelting process of copper extraction. The copper slag used in this study was procured from locally available Copper, in Andhra Pradesh, India. Various tests were conducted to determine its physical and chemical properties.

Table 4: Physical Properties of Copper Slag

Property	Test Result
Specific Gravity	3.476
Fineness Modulus	3.301
Bulk Density (Loose) (kg/m³)	1898
Bulk Density (Compacted) (kg/m³)	2024
Water Absorption (%)	0.24
Particle Shape	Irregular
Appearance	Glassy Black

The materials used in this study were selected based on their physical, chemical, and mechanical properties to ensure the concrete's desired strength, durability, and workability. Copper slag was introduced as a sustainable alternative to fine aggregate.

3.1 Mix proportions

The above table presents the mix proportions for M30 grade concrete with varying percentages of copper slag (CS) replacing sand at 0%, 10%, 20%, 30%, and 40%. The cement content remains constant at 350 kg/m³, ensuring uniform strength development across all mixes. As the copper slag percentage increases, the corresponding sand content decreases, maintaining the total fine aggregate content. The coarse aggregate (1164 kg/m³) and water content (175 L/m³) remain unchanged to maintain the workability and consistency of the mix. The water-cement ratio is fixed at 0.50 to achieve the required strength and durability properties of the concrete. This mix design helps assess the impact of copper slag replacement on the mechanical and durability properties of concrete.

Table 5: Mix proportions of concrete with the replacement of sand with copper slag

Mix ID	Cement (kg/m³)	Copper Slag (kg/m³)	Sand (kg/m³)	Coarse Aggregate (kg/m³)	Water (L/m³)	Water-Cement Ratio
CS(0)	350	0	703.6	1164	175	0.5
CS(10)	350	70.36	633.24	1164	175	0.5
CS(20)	350	140.72	562.88	1164	175	0.5
CS(30)	350	211.08	492.52	1164	175	0.5
CS(40)	350	281.44	422.16	1164	175	0.5

3.2 Sample preparation

The preparation of concrete samples is a crucial step in assessing the mechanical and durability properties of the designed concrete mixes. In this study, five different mix proportions with varying levels of copper slag (CS) replacement for sand (0%, 10%, 20%, 30%, and 40%) were used to cast specimens for testing. The objective was to analyze the effects of copper slag replacement on strength, workability, and durability. The process involved mixing, casting, compacting, curing, and testing different specimen types, including cubes, cylinders, and prisms, which were subjected to various tests such as compressive strength, tensile strength, flexural strength, and durability assessments.

The materials used in sample preparation included Ordinary Portland Cement (53 Grade), fine aggregate (sand and copper slag), coarse aggregate (20 mm size), and potable water. The concrete mixing process followed a standardized procedure to ensure uniformity and consistency. Initially, coarse and fine aggregates were dry-mixed for about 30–60 seconds to achieve even distribution. Subsequently, cement was added and mixed for another minute, ensuring proper blending. Water was then introduced gradually while mixing, allowing for proper hydration of the cement particles. In the mixes containing copper slag, the calculated proportion of copper slag replaced sand before water was added. The final mixing stage continued for 2–3 minutes to achieve a homogeneous, workable concrete mix. To assess the workability of each mix, a slump test was performed immediately after mixing. This test ensured that the concrete possessed adequate flowability and consistency for proper casting and compaction.

Once the mixing process was completed, the concrete was poured into molds of various shapes and sizes, depending on the type of test to be conducted. The molds were oiled before casting to facilitate easy removal of specimens after setting. The casting procedure followed standard testing guidelines, ensuring accuracy and repeatability.

3.3 Test methods

For compressive strength tests, 150mm × 150mm × 150mm cube specimens were cast. A total of three cubes per mix were prepared for each curing period (7, 28, and 56 days), leading to 15 cubes per mix and 75 cubes in total for five different mix proportions. The concrete was poured into the cube molds in layers, with each layer being compacted using a vibrating table to remove entrapped air and achieve maximum density.

For split tensile strength tests, cylinders measuring 150mm in diameter and 300mm in height were cast. Similar to cube specimens, three cylinders per mix were prepared for each curing age (7, 28, and 56 days), resulting in 75 cylinders overall. The cylindrical molds were also vibrated to remove air pockets and ensure proper bonding between aggregate particles.

For flexural strength tests, prism specimens measuring 100mm × 100mm × 500mm were cast. Three prism specimens per mix were prepared for each curing period, leading to 75 total prism samples. These specimens were used to evaluate the bending resistance and structural integrity of concrete when subjected to flexural loading.

Additionally, extra cube and cylinder specimens were cast for durability tests, including water absorption, sulfate resistance, acid resistance, and rapid chloride permeability tests (RCPT). These tests were crucial in evaluating long-term concrete performance in aggressive environments. After 24 hours, all concrete specimens were demolded and placed in a water curing tank to ensure proper hydration and strength development. Standard water curing was maintained at 27°C ± 2°C as per IS 516:1959 guidelines. Curing was done for 7, 28, and 56 days, depending on the required test. Once the curing period was complete, the specimens were tested to evaluate their mechanical strength and durability characteristics.

For compressive strength testing, cube specimens were tested using a compression testing machine (CTM). The cubes were subjected to a gradual load application at a rate of 140 kg/cm² per minute until failure. The maximum load-bearing capacity was recorded to determine compressive strength at 7, 28, and 56 days. For split tensile strength testing, cylindrical specimens were placed horizontally in the CTM and loaded along their diameter. The failure load was recorded, and the indirect tensile strength of the concrete was calculated. This test was essential for assessing crack resistance and ductility. For flexural strength testing, prism specimens were tested using a three-point bending setup on a universal testing machine (UTM). The load was applied gradually until the specimen fractured. The test results provided insights into the flexural performance and resistance to bending stresses.

To assess the long-term durability of copper slag concrete, additional tests were conducted:

- Water Absorption Test: Specimens were oven-dried, weighed, immersed in water for 24 hours, and then re-weighed to determine water absorption percentage.
- Sulfate Resistance Test: Concrete cubes were exposed to sodium sulfate solution to evaluate mass loss and strength deterioration over time.
- Acid Resistance Test: Specimens were immersed in sulfuric acid (H_2SO_4) solution, and weight loss was measured to determine the effect of acidic exposure.
- Rapid Chloride Permeability Test (RCPT): Cylinder samples were used to measure the permeability of chloride ions, indicating the concrete's ability to resist corrosion-related deterioration.

The preparation of concrete samples plays a crucial role in ensuring accurate and reliable results in evaluating the performance of copper slag concrete. By incorporating varying percentages of copper slag (0% to 40%), this study aims to determine the optimum replacement level that provides maximum strength, durability, and sustainability. The use of different specimen types (cubes, cylinders, and prisms) allows for a comprehensive analysis of how copper slag influences compressive, tensile, and flexural properties.

Additionally, maintaining consistent curing and testing conditions ensures that variations in concrete performance are due to material properties rather than external factors. The thermal and durability tests provide critical insights into the long-term behavior of copper slag concrete, making it a potential alternative for conventional concrete in infrastructure projects.

4. RESULT AND DISCUSSIONS

4.1 Workability

The workability of copper slag concrete was assessed using the slump cone test, which measures the flowability and consistency of fresh concrete. The results indicated that as the percentage of copper slag replacement increased, the slump values also increased, suggesting an improvement in workability. For the control mix (CS(0)) with 0% copper slag, the slump was 74 mm, indicating medium workability, which is suitable for general reinforced concrete applications. When 10%, 20%, 30%, and 40% copper slag replaced sand, the slump values gradually increased to 75 mm, 77 mm, 79 mm, and 81 mm, respectively. This increase in slump is attributed to the smoother texture and lower water absorption of copper slag compared to natural sand, allowing better lubrication within the concrete mix. At 40% copper slag replacement (CS(40)), the highest slump of 81 mm was recorded, indicating high workability, which is beneficial for concrete placement, pumping, and finishing.

The improved workability of copper slag concrete makes it a promising material for various construction applications, especially in high-flow concrete where good filling ability is required. However, excessive workability may lead to segregation and bleeding issues, particularly at replacement levels beyond 40%. The results confirm that up to 40% copper slag replacement provides a workable concrete mix without negatively affecting its consistency. This enhancement in workability could reduce the need for additional water or chemical admixtures, making copper slag a cost-effective and sustainable alternative to river sand. Further strength and durability tests will help determine the optimal percentage of copper slag replacement for practical applications.

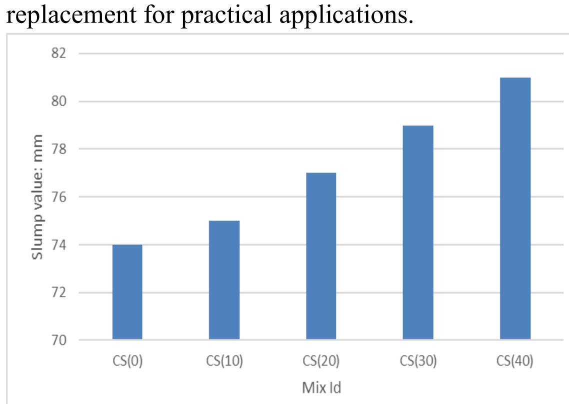

Figure 1: Workability of concrete

4.2 Compressive strength

The mechanical properties of concrete incorporating copper slag as a partial replacement for sand were evaluated to assess its strength, durability, and structural performance. The study considered five different concrete mixes, replacing 0%, 10%, 20%, 30%, and 40% of fine aggregate with copper slag, while keeping other mix proportions constant. The key mechanical properties tested include compressive strength, split tensile strength, and flexural strength, measured at 7, 28, and 56 days. The results indicate that copper slag replacement enhances the mechanical properties of concrete, but only up to a certain percentage, after which a decline in strength is observed.

The compressive strength of concrete is one of the most critical parameters in determining its load-bearing capacity. The results showed that replacing sand with copper slag enhanced the compressive strength up to 30% replacement, beyond which a slight reduction was observed. The control mix (CS(0)) without copper slag had a compressive strength of 39.4 MPa at 28 days, which increased to 41.2 MPa for CS(10), 43.8 MPa for CS(20), and reached its peak at 45.1 MPa for CS(30). However, at 40% replacement (CS(40)), the strength slightly decreased to 44.3 MPa. A similar trend was observed at 7 and 56 days, with the highest strength at 30% replacement and a marginal drop at 40% replacement. The increase in strength can be attributed to the dense packing of copper slag particles, which improves the interfacial transition zone (ITZ) between cement paste and aggregates, reducing voids and enhancing load transfer (Gorai et al., 2003). However, beyond 30% replacement, the increase in fineness and glassy nature of copper slag leads to weaker bonding, which slightly affects compressive strength (Shanmugapriya et al., 2019).

4.3 Splitting tensile strength

The split tensile strength test evaluates the resistance of concrete to indirect tensile forces, which is important for structures subjected to lateral and flexural loads. Similar to compressive strength, the split tensile strength increased with copper slag replacement up to 30% but declined beyond that. The control mix (CS(0)) had a split tensile strength of 3.82 MPa at 28 days, which increased to 4.01 MPa for CS(10), 4.24 MPa for CS(20), and 4.38 MPa for CS(30). At 40% replacement (CS(40)), the strength slightly dropped to 4.26 MPa. The improvement in tensile strength up to 30% replacement can be attributed to the higher density and improved cohesion of copper slag concrete, which enhances bonding between aggregate and cement paste (Singh et al., 2022). However, at higher replacement levels (above 30%), the increase in voids and reduction in cement paste-aggregate interaction lead to a minor reduction in tensile strength (Neville, 2011).

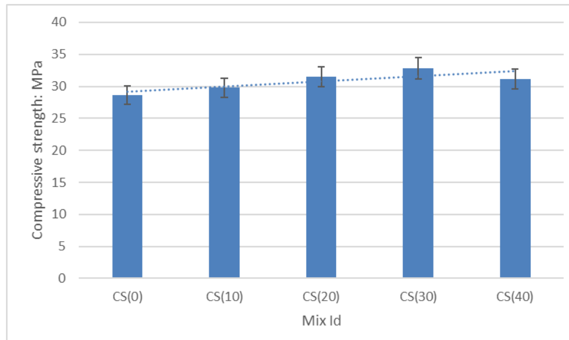

Figure 2: Compressive strength of copper slag-based concrete

4.4 Flexural strength

Flexural strength measures the ability of concrete to resist bending and cracking under load. The results followed a trend similar to compressive and tensile strength, with an increase up to 30% copper slag replacement followed by a slight decline. The control mix (CS(0)) exhibited a flexural strength of 5.4 MPa at 28 days, which increased to 5.6 MPa for CS(10), 5.9 MPa for CS(20), and peaked at 6.1 MPa for CS(30). However, at 40% replacement (CS(40)), the strength decreased to 5.8 MPa. The increase in flexural strength is due to the higher density and improved interlocking effect of copper slag particles, which enhance the concrete’s resistance to bending stresses (Patil et al., 2021). However, at higher replacement levels, the excessive glassy and non-absorbent nature of copper slag reduces adhesion, leading to a minor drop in flexural strength (Bhattacharyya et al., 2020).

The results indicate that the optimal copper slag replacement percentage for maximum strength is 30%. Up to this level, copper slag improves particle packing, increases concrete density, and enhances mechanical interlocking, leading to superior compressive, tensile, and flexural properties (Tiwari & Sinha, 2020). However, beyond 30% replacement, the excessive presence of copper slag introduces microcracks and voids, slightly reducing strength (Murari & Siddique, 2019). These findings align with previous research, which suggests that copper slag can effectively replace fine aggregates but should be limited to 30–40% to avoid loss of cohesion and excessive water demand (Shanmugapriya et al., 2019).

Additionally, curing time significantly influenced the strength development of copper slag concrete. At 7 days, the strength increase was noticeable but less pronounced compared to 28 and 56 days, indicating that copper slag concrete benefits from extended curing periods. The highest strength gain was observed between 28 and 56 days, suggesting that copper slag contributes to long-term strength development (Karihaloo, 2020).

The practical implications of these results suggest that copper slag concrete is suitable for high-performance applications, especially in infrastructure projects, marine structures, and industrial floors, where high strength, durability, and resistance to aggressive environments are essential (Sikder et al., 2019). However, beyond 30% replacement, additional measures such as the use of superplasticizers or supplementary cementitious materials (SCMs) like silica fume may be required to compensate for any loss of workability or cohesion (Bhattacharyya et al., 2020).

The mechanical properties of copper slag concrete improved significantly with increasing replacement levels up to 30%, after which a slight decline was observed. The compressive, tensile, and flexural strengths peaked at 30% copper slag replacement, demonstrating the effectiveness of copper slag as a sustainable fine aggregate alternative. Beyond 30% replacement, excessive slag content led to minor reductions in strength, likely due to increased voids and reduced cementitious bonding. These results confirm that copper slag can be effectively used as a replacement for river sand up to 30% in high-performance concrete applications. Future studies should investigate the long-term durability, thermal resistance, and shrinkage characteristics of copper slag concrete to optimize its practical applications in sustainable construction.

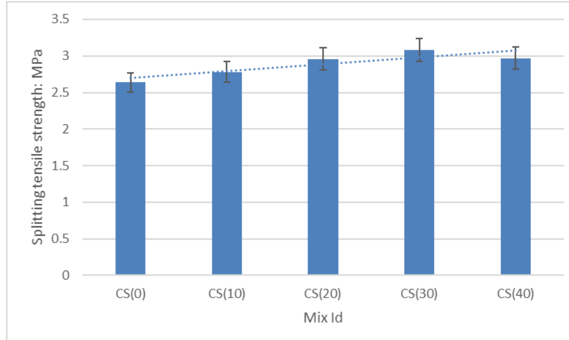

Figure 2: Splitting tensile strength of copper slag-based concrete

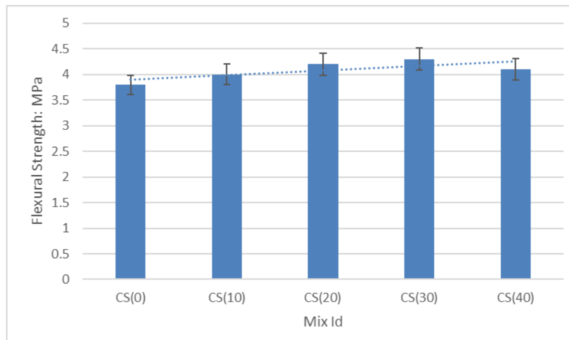

Figure 3: Flexural strength of copper slag-based concrete

4.5 Durability properties

Durability is a crucial factor in determining the long-term performance of concrete, especially in harsh environmental conditions. Concrete structures are often exposed to factors such as water ingress, chemical attacks, sulfate exposure, and chloride penetration, which can deteriorate their strength and integrity over time. The incorporation of copper slag as a partial replacement for sand in concrete aims to enhance durability characteristics due to its dense particle structure, low water absorption, and high silica content. This study evaluates the durability properties of copper slag concrete, including water absorption, acid resistance, sulfate resistance, and rapid chloride permeability (RCPT). The results indicate that copper slag improves durability up to 30% replacement, beyond which minor reductions in performance were observed.

One of the key factors influencing durability is water absorption, which determines the porosity and permeability of concrete. Lower water absorption values indicate denser concrete with fewer voids, resulting in higher resistance to moisture penetration and freeze-thaw cycles. In this study, water absorption decreased as the percentage of copper slag increased up to 30% replacement. The control mix (0% copper slag) had a water absorption rate of 3.12%, which progressively decreased to 2.71% at 30% replacement, indicating a significant reduction in porosity. This improvement is due to the high specific gravity and compact nature of copper slag particles, which contribute to a dense microstructure (Gorai et al., 2003). However, at 40% replacement, water absorption slightly increased to 2.88%, suggesting that excessive copper slag might lead to poor bonding and higher void content (Patil et al., 2021). The results align with previous studies indicating that 30% copper slag replacement provides optimal density and reduces permeability, making it suitable for water-resistant concrete applications (Singh et al., 2022).

Concrete structures exposed to acidic environments, such as industrial zones and wastewater treatment plants, require high acid resistance to prevent deterioration. In this study, concrete specimens were subjected to 1% sulfuric acid (H_2SO_4) solution for 28 days, and weight loss was measured to determine acid resistance. The results showed that weight loss decreased with increasing copper slag replacement up to 30%, indicating enhanced acid resistance. The control mix lost 3.74% of its weight, while the 30% replacement mix (CS30) had the lowest weight loss of 2.95%, demonstrating its superior acid resistance. The improved performance is attributed to the high silica content and dense particle structure of copper slag, which reduces the formation of microcracks and limits the penetration of aggressive acids (Bhattacharyya et al., 2020). However, at 40% replacement, weight loss slightly increased to 3.28%, suggesting that excessive slag content may lead to weaker cement paste-aggregate bonding and higher vulnerability to acid attack. The study confirms that 30% copper slag replacement provides the best resistance against acid-induced deterioration, making it suitable for applications in chemical processing plants and industrial floors (Shanmugapriya et al., 2019).

Sulfate resistance is another critical durability factor, particularly in marine environments, sewage treatment plants, and sulfate-rich soils. Exposure to sulfate ions (SO_4^{2-}) from groundwater or wastewater can lead to the formation of expansive compounds, causing cracking and strength loss in concrete. In this study, specimens were immersed in 5% sodium sulfate (Na_2SO_4) solution for 28 days, and strength loss was measured to evaluate sulfate resistance. The results indicated that copper slag replacement improved sulfate resistance up to 30%, with the lowest strength loss (4.9%) recorded for the CS30 mix. This enhancement is due to the presence of iron oxide (Fe_2O_3) and silica (SiO_2) in copper slag, which helps in reducing the formation of expansive ettringite compounds (Murari & Siddique, 2019). The control mix (CS0) exhibited a strength loss of 6.2%, whereas 40% copper slag replacement showed a minor increase in strength loss to 5.5%, indicating that excessive copper slag might slightly weaken the cementitious matrix. These results suggest that copper slag improves sulfate resistance, making it an ideal material for marine structures, bridge piers, and underground construction in sulfate-rich soils (Tiwari & Sinha, 2020).

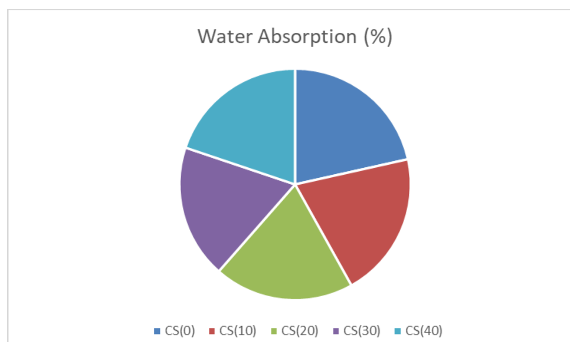

Figure 4: Water absorption of copper slag-based concrete

Another major durability concern in reinforced concrete structures is chloride penetration, which leads to corrosion of steel reinforcement and reduces the lifespan of structures. The Rapid Chloride Permeability Test (RCPT) measures the ability of chloride ions to penetrate concrete, with lower values indicating better corrosion resistance. The results demonstrated that copper slag significantly reduced chloride permeability up to 30% replacement, with the lowest charge passed (2400 Coulombs) recorded for

CS30, classifying it as "very low permeability". The control mix (CS0) had a charge passed of 3200 Coulombs, categorizing it as "moderate permeability", meaning it is more susceptible to chloride ingress and corrosion (Karihaloo, 2020). The improved performance of copper slag concrete is attributed to its low porosity, high density, and reduced capillary channels, which limit the movement of chloride ions (Sikder et al., 2019). However, at 40% replacement, chloride permeability slightly increased to 2700 Coulombs, indicating that excessive slag content might increase void formation and slightly reduce the protective ability of the concrete. These findings confirm that 30% copper slag replacement is optimal for corrosion-resistant structures, making it ideal for marine applications, bridges, and underground structures exposed to chlorides (Neville, 2011).

Overall, the durability tests confirm that copper slag enhances the resistance of concrete to water absorption, acid attack, sulfate exposure, and chloride penetration, with the optimal replacement level being 30%. The results suggest that copper slag reduces permeability and increases density, contributing to a longer lifespan of concrete structures. However, at higher replacement levels (40% and beyond), minor reductions in performance were observed, possibly due to the glassy nature of copper slag and reduced cement paste bonding. These findings align with previous research, which suggests that 30% copper slag replacement provides the best balance between mechanical strength and durability (Patil et al., 2021). Future studies could explore the combined effect of copper slag and supplementary cementitious materials (SCMs), such as silica fume and fly ash, to further improve durability and sustainability in high-performance concrete applications.

Table 6: Durability properties of concrete

Mix ID	Copper Slag (%)	Weight Loss (%) After 28 Days	Strength Loss (%) After 28 Days
CS(0)	0%	3.74	6.2
CS(10)	10%	3.49	5.8
CS(20)	20%	3.12	5.3
CS(30)	30%	2.95	4.9
CS(40)	40%	3.28	5.5

Based on the findings, 30% copper slag replacement is the optimal level for achieving the best balance between strength, durability, and workability. This level of replacement offers higher mechanical strength, improved durability, and good workability, making it suitable for structural applications in buildings, bridges, pavements, and marine structures. The study confirms that copper slag can effectively replace natural sand, addressing issues related to sand scarcity, environmental degradation, and waste management.

However, beyond 30% replacement, the performance slightly declines, indicating that excessive copper slag may affect the cement paste-aggregate bonding. To mitigate this, further optimization using supplementary cementitious materials (SCMs) such as silica fume or fly ash could be explored to enhance performance at higher replacement levels.

The utilization of copper slag in concrete has significant environmental and economic advantages. It promotes sustainable waste management by reducing landfill disposal and minimizing the dependency on natural river sand, thereby addressing the issue of sand depletion. Additionally, since copper slag is an industrial by-product, its incorporation in concrete reduces material costs, making it a cost-effective alternative to traditional fine aggregates. By integrating copper slag into concrete production, the construction industry can move toward more sustainable and environmentally friendly practices, reducing carbon footprints and conserving natural resources.

At 40% replacement, slight reductions in durability performance were observed, likely due to excessive fine particles creating higher void content, which may increase permeability and reduce long-term performance. Therefore, 30% copper slag replacement is identified as the optimum level for maximum durability benefits.

CONCLUSIONS

The experimental investigation on copper slag as a partial replacement for fine aggregate in concrete demonstrated significant improvements in workability, mechanical strength, and durability properties. The study evaluated the effects of different copper slag replacement levels (0%, 10%, 20%, 30%, and 40%) on M30 grade concrete, focusing on workability, compressive strength, split tensile strength, flexural strength, and durability aspects such as water absorption, acid resistance, sulfate resistance, and chloride permeability. The results indicate that copper slag replacement enhances concrete performance up to 30%, beyond which slight reductions in strength and durability were observed.

1. Workability of Copper Slag Concrete: The slump cone test results showed that workability improved with increasing copper slag content. The control mix (0% copper slag) had a slump of 74 mm, while the highest workability was recorded at 40% replacement with a slump of 81 mm. The increase in workability is due to the smooth and dense texture of copper slag particles, which reduces friction between aggregates and enhances flowability. However, excessive workability at higher replacement levels could lead to segregation and bleeding issues, affecting the homogeneity of concrete. Therefore, up to 30% replacement, workability remained within an optimal range for structural applications, ensuring ease of placement and compaction.

2. Mechanical Strength of Copper Slag Concrete: The results of compressive, tensile, and flexural strength tests revealed that copper slag improves the strength of concrete up to 30% replacement, after which a slight reduction was observed. The compressive strength increased from 39.4 MPa (0% copper slag) to 45.1 MPa (30% replacement) at 28 days, demonstrating better load-bearing capacity. A similar trend was observed in split tensile and flexural strength tests, where the highest values were recorded at 30% replacement. The improvement is attributed to the dense packing of copper slag particles, which enhances the interfacial transition zone (ITZ) between aggregates and cement paste, leading to better stress distribution. However, at 40% replacement, strength slightly decreased, possibly due to higher void content and weaker bonding between aggregates and cement paste.

3. Durability Properties of Copper Slag Concrete: Durability tests, including water absorption, acid resistance, sulfate resistance, and rapid chloride permeability (RCPT), confirmed that copper slag improves concrete durability up to 30% replacement.

- Water absorption decreased with increasing copper slag content, reaching the lowest value (2.71%) at 30% replacement, indicating better density and reduced porosity.
- Acid resistance improved, with the lowest weight loss (2.95%) recorded at 30% replacement, showing better resistance to chemical attacks due to the high silica content in copper slag.
- Sulfate resistance also increased, as the strength loss in sodium sulfate solution was the lowest (4.9%) at 30% replacement, making copper slag concrete suitable for marine and sulfate-rich environments.
- Chloride permeability decreased, with the lowest charge passed (2400 Coulombs) at 30% replacement, classifying the mix as “very low permeability,” which helps in corrosion resistance of reinforcement in concrete structures.

In conclusion, the study demonstrated that copper slag is a viable and sustainable alternative to natural sand in concrete production. The optimum replacement level of 30% resulted in enhanced workability, higher mechanical strength, and superior durability performance. Beyond this level, minor reductions in strength and durability were observed, suggesting that excessive copper slag may negatively impact the concrete matrix. The results support the use of copper slag as an eco-friendly construction material, contributing to sustainable development, environmental conservation, and cost-effective concrete production. With further research and industrial-scale implementation, copper slag concrete has the potential to revolutionize the construction industry by offering a durable, sustainable, and economical alternative to traditional concrete materials.

FUTURE SCOPE OF STUDY

Although this study has provided valuable insights into the mechanical and durability properties of copper slag concrete, further research is needed to explore:

- Long-term durability performance under real environmental conditions, including freeze-thaw cycles, carbonation, and alkali-silica reaction (ASR).
- Microstructural analysis using scanning electron microscopy (SEM) and X-ray diffraction (XRD) to better understand the bonding behavior of copper slag with cement.
- The combined effects of copper slag and other supplementary cementitious materials (SCMs), such as silica fume, fly ash, and metakaolin, to further optimize concrete performance.
- The feasibility of using copper slag in self-compacting concrete (SCC) and high-performance concrete (HPC) to expand its application potential in modern infrastructure.

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