Performance Assessment of High-Strength Concrete Incorporating Copper Slag as Fine Aggregate

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Abstract - The increasing demand for natural sand in concrete production has resulted in scarcity and environmental issues, driving the need for sustainable alternatives. Copper slag, an industrial by-product of the copper smelting process, offers potential as a replacement for fine aggregate in high-strength concrete. This study investigates the performance of M60 grade concrete with copper slag as a partial and full replacement for natural sand at levels of 0%, 20%, 40%, 60%, 80%, and 100%. Fresh properties were evaluated through slump cone tests, while hardened concrete properties were assessed using compressive strength tests at 7, 14, and 28 days, as well as split tensile and flexural strength tests at 28 days. Results indicate that workability increased with higher copper slag content due to its smooth surface texture and low water absorption. Compressive strength achieved maximum performance at 40% replacement, with notable improvements compared to the control mix. However, beyond 60% replacement, a decline in strength was observed due to excess free water and weaker interfacial bonding. Split tensile and flexural strengths showed similar trends, with optimum values observed at 40–60% replacement levels. The findings suggest that copper slag can replace up to 60% of natural sand in M60 concrete without compromising structural performance, thereby contributing to sustainable construction practices and effective waste management.

Keywords: Copper slag, M60 concrete, Fine aggregate replacement, Compressive strength, Split tensile strength, Flexural strength, Workability.

1. INTRODUCTION

Concrete is the most widely used construction material across the globe, primarily due to its versatility, durability, and structural performance. However, its production heavily depends on natural resources such as river sand and gravel, which serve as the primary constituents of fine and coarse aggregates. The rapid pace of urbanization and infrastructural development has led to an unprecedented demand for sand, causing large-scale exploitation of riverbeds and natural reserves. This excessive extraction has resulted in severe ecological problems, including riverbank erosion, depletion of groundwater, habitat destruction, and loss of biodiversity. In addition, the escalating cost and scarcity of natural sand have posed significant challenges to the construction industry, necessitating the search for viable and sustainable alternatives.

One promising alternative is copper slag, an industrial by-product obtained during the smelting and refining of copper. Globally, millions of tons of copper slag are generated annually, and improper disposal often leads to land pollution, leaching of heavy metals, and other environmental hazards. Owing to its physical and chemical characteristics, including high density, angular particle shape, low water absorption, and inertness, copper slag has attracted considerable attention as a potential substitute for natural sand in concrete production. Its utilization not only addresses the problem of waste management but also reduces dependence on natural resources, thereby aligning with the principles of sustainable construction.

Several studies have reported that partial replacement of fine aggregates with copper slag can enhance the workability, compressive strength, and durability properties of concrete. Improvements are often

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attributed to the dense packing of particles and the smooth vitreous surface of slag, which reduce water demand. However, excessive replacement levels may adversely affect strength and durability due to poor interfacial bonding and increased free water in the mix. While past research has primarily focused on conventional- and medium-strength concretes, limited work has been reported on the use of copper slag in high-strength concrete mixes, where performance requirements are more stringent.

In this context, the present study investigates the use of copper slag as a fine aggregate replacement in M60 grade high-strength concrete. Copper slag is incorporated at replacement levels of 0%, 20%, 40%, 60%, 80%, and 100% by weight of fine aggregate. The study evaluates both fresh properties (slump cone test for workability) and hardened properties (compressive strength at 7, 14, and 28 days, along with split tensile and flexural strength at 28 days). By systematically comparing the performance of these mixes, the research aims to identify the optimum replacement level of copper slag that achieves superior mechanical performance while promoting sustainable construction and effective industrial waste utilization.

1.1 Objectives of the Study

The primary objectives of this research are as follows:

1. To assess the feasibility of using copper slag as a fine aggregate in high-strength concrete.
2. To evaluate its impact on the fresh and hardened properties of concrete, including workability, strength, and durability.
3. To compare the performance of copper slag-based concrete with conventional concrete mixes.
4. To analyze the long-term behavior and sustainability aspects of incorporating copper slag in concrete structures.
5. To explore the economic and environmental benefits of replacing natural sand with copper slag.

2. MATERIALS AND METHODOLOGY

The experimental program was designed to investigate the feasibility of utilizing copper slag as a fine aggregate replacement in M60 grade high-strength concrete. The methodology involved careful selection of materials, preparation of mix designs, casting and curing of specimens, and testing for both fresh and hardened properties of concrete.

2.1 Materials Used

- **Cement**
Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used. It was tested for consistency, initial and final setting time, and compressive strength to ensure compliance with standards.

- **Fine Aggregate (Sand and Copper Slag)**
Locally available river sand conforming to IS 383:2016 was used as the natural fine aggregate. Copper slag, obtained as a by-product from a copper smelting plant, was used as a partial and full replacement for sand. The copper slag was tested for particle size distribution, specific gravity, bulk density, and water absorption as per IS 2386 (Part 1–8):1963.

- **Coarse Aggregate**
Crushed granite aggregates of nominal maximum size 20 mm and 10 mm, conforming to IS 383:2016, were used in a proportion of 60:40.

- **Water**
Potable water, free from impurities and suitable for mixing and curing, was used as per IS 456:2000.

- **Admixture (if applicable)**
A high-range water-reducing superplasticizer (conforming to IS 9103:1999) was added to improve the workability of high-strength concrete without increasing the water–cement ratio.

2.2 Mix Design

The concrete mix proportions were designed for M60 grade in accordance with IS 10262:2019 guidelines. A control mix (0% replacement) was prepared using conventional river sand as fine aggregate. Copper slag was introduced as a replacement for sand at levels of

20%, 40%, 60%, 80%, and 100% by weight of fine aggregate.

The water–cement ratio was maintained at 0.30, optimized for strength and durability requirements. Trial mixes were conducted to achieve desired workability with the aid of a superplasticizer.

2.3 Preparation of Specimens

Concrete was mixed in a laboratory drum mixer ensuring uniform distribution of copper slag. The fresh concrete was immediately tested for workability. The remaining concrete was cast into molds for hardened property tests.

- **Cube specimens** of size 150 × 150 × 150 mm were cast for compressive strength testing at 7, 14, and 28 days**.**
- **Cylindrical specimens** of size 150 mm diameter × 300 mm height were prepared for split tensile strength testing at 7, 14, and 28 days.
- **Beam specimens** of size 150 × 150 × 700 mm were cast for flexural strength testing at 7, 14, and 28 days**.**

After 24 hours of casting, specimens were demolded and cured in a water tank at 27 ± 2°C until the age of testing.

3. RESULTS AND DISCUSSION

3.1 Slump Cone Test (Workability)

The slump cone test was conducted as per IS 1199:1959 to evaluate the workability of fresh concrete mixes. Workability reflects the ease of placing, compacting, and finishing concrete. Since copper slag has a smooth texture and low water absorption, its presence was expected to influence the slump values significantly.

Table 1: Slump Cone Test Results

Replacement of Fine Aggregate with Copper Slag (%)	Slump (mm)
0 (Control)	65
20	75
40	85
60	95
80	100
100	105

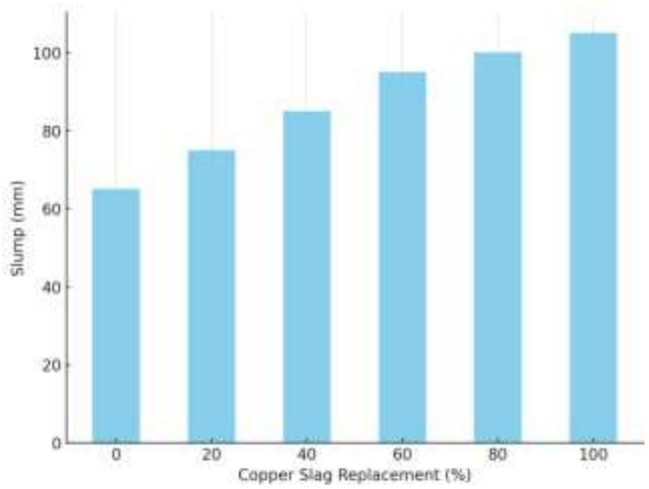

Fig. 1: Slump Cone Test Results

The results indicate that slump values increased steadily with higher copper slag content, confirming improved workability. The maximum slump was observed at 100% replacement (105 mm). However, excessively high workability at higher replacement levels may lead to segregation and bleeding, which is undesirable for high-strength concrete. Thus, the workability enhancement is beneficial up to about 60% replacement.

3.2 Compressive Strength Test

Compressive strength is the most important mechanical property of concrete, reflecting its load-carrying capacity. Tests were carried out on 150 × 150 × 150 mm cube specimens at ages of 7, 14, and 28 days as per IS 516 (Part 1):2020.

Table 2: Compressive Strength Test Results

Replacement (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
0 (Control)	42	55	68
20	45	58	72

40	49	63	78
60	47	60	75
80	42	53	67
100	38	47	60

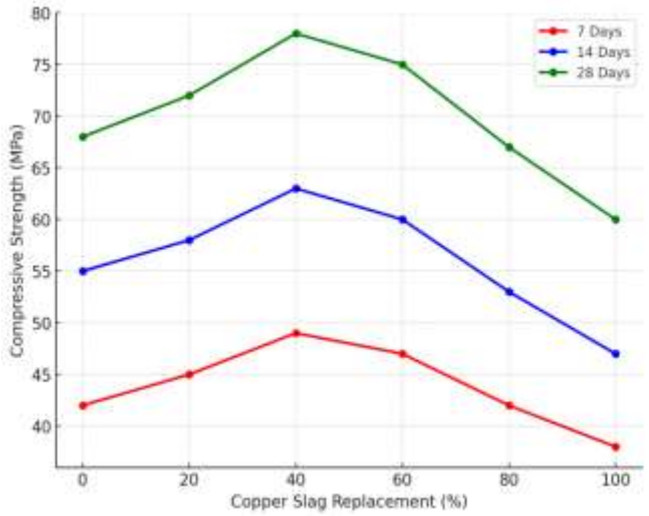

Fig. 2: Compressive Strength Test Results

Compressive strength improved with the inclusion of copper slag up to 40% replacement, where the highest strength of 78 MPa at 28 days was achieved, surpassing the control mix. Beyond 60% replacement, strength decreased due to the presence of excess free water and weaker interfacial transition zones (ITZ). The results suggest that 40–60% replacement is optimum for strength development.

3.3 Split Tensile Strength Test

Split tensile strength evaluates the resistance of concrete to tensile cracking, tested on cylindrical specimens of 150 mm diameter × 300 mm height as per IS 5816:1999. Tests were conducted at 7, 14, and 28 days.

Table 3: Split Tensile Strength Test Results

Replacement (%)	**7 Days (MPa)**	**14 Days (MPa)**	**28 Days (MPa)**
0 (Control)	3.0	3.8	4.6
20	3.2	4.1	5.0
40	3.6	4.5	5.4
60	3.4	4.2	5.1
80	3.0	3.6	4.4
100	2.6	3.1	3.8

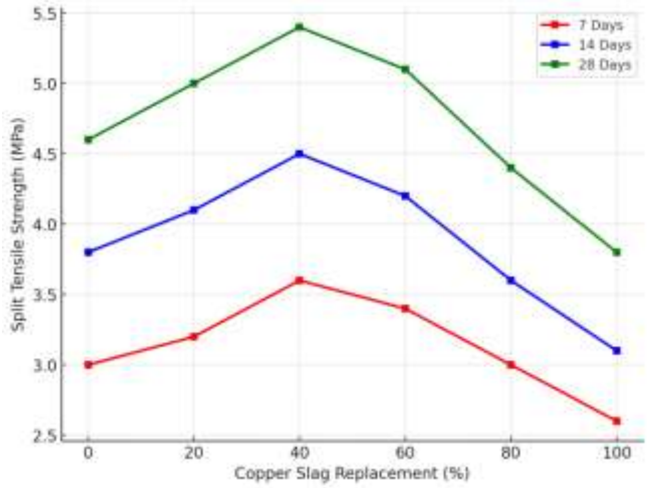

Fig. 3: Split Tensile Strength Test Results

The split tensile strength followed a similar trend to compressive strength. The maximum value of 5.4 MPa was recorded at 40% replacement. Beyond 60%, a noticeable reduction was observed, which may be attributed to weaker ITZ bonding and higher free water content. Nevertheless, up to 60% replacement levels, tensile strength values were higher than the control mix.

3.4 Flexural Strength Test

Flexural strength measures the ability of concrete to resist bending and is a critical property for pavement and structural applications. Tests were carried out **on** beam specimens of size 150 × 150 × 700 mm under two-point loading as per IS 516 (Part 1):2020 at 7, 14, and 28 days.

Fig. 4: Flexural Strength Testing

Table 4: Flexural Strength Test Results

Replacement (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
0 (Control)	5.8	6.9	8.1
20	6.2	7.3	8.6
40	6.8	8.0	9.3
60	6.5	7.7	8.9
80	5.9	6.9	8.0
100	5.3	6.2	7.1

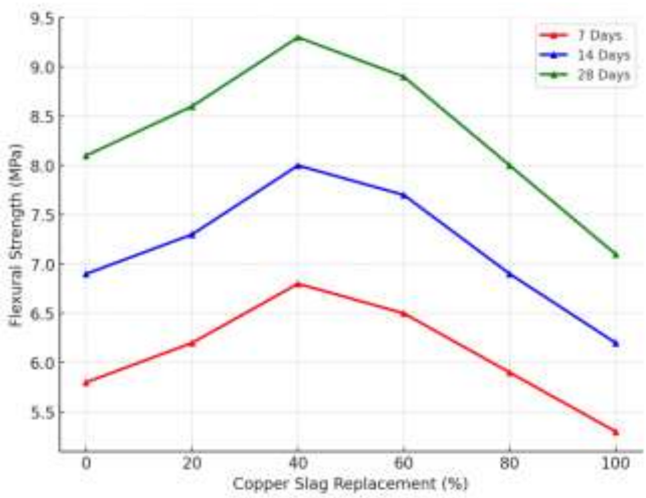

Fig. 5: Flexural Strength Test Results

Flexural strength increased up to 40% replacement, achieving a maximum of 9.3 MPa at 28 days, which is about 15% higher than the control mix. A gradual decline was noted beyond 60% replacement due to poor cohesion and weaker aggregate–paste bonding. The findings confirm that moderate copper slag replacement enhances flexural performance of high-strength concrete.

4. CONCLUSION

- The workability of concrete improved consistently with an increase in copper slag content due to its smooth surface texture and low water absorption. However, very high workability at 80–100% replacement may lead to segregation and bleeding.
- The optimum compressive strength was achieved at 40% replacement (78 MPa at 28 days), showing about a 15% improvement over the control mix. Strength values declined beyond 60% replacement.
- Split tensile strength followed a similar trend, with a maximum of 5.4 MPa at 40% replacement, indicating enhanced resistance to cracking up to moderate replacement levels.
- Flexural strength also improved with copper slag, peaking at 9.3 MPa at 40% replacement. This demonstrates that copper slag enhances the bending resistance of high-strength concrete at moderate levels.
- Beyond 60% replacement, all strength properties showed a decline due to weak interfacial bonding and the presence of excess free water.
- Overall, 40–60% replacement of fine aggregate with copper slag can be recommended as the optimum range for M60 grade high-strength concrete.
- The use of copper slag not only enhances mechanical performance but also addresses sustainability concerns by reducing reliance on natural sand and enabling effective disposal of industrial by-products.
- Economically, copper slag offers a cost-effective alternative to natural sand, especially in regions where it is locally available

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