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Sustainable Application of Copper Slag as Fine Aggregate in High-Strength Concrete

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Abstract: The growing consumption of natural river sand in concrete manufacturing has led to serious environmental degradation and material scarcity, emphasizing the need for sustainable substitute materials. Copper slag, a by-product generated during the copper smelting process, has emerged as a potential alternative to fine aggregate in high-strength concrete. This investigation examines the behavior of M60 grade concrete in which copper slag replaces natural sand at proportions of 0%, 20%, 40%, 60%, 80%, and 100%. The fresh concrete properties were assessed using slump cone tests, whereas the hardened properties were evaluated through compressive strength tests conducted at 7, 14, and 28 days, along with split tensile and flexural strength tests performed at 28 days. The experimental results revealed an increase in workability with rising copper slag content, attributed to its smooth surface characteristics and minimal water absorption capacity. The highest compressive strength was recorded at a 40% replacement level, showing noticeable improvement over the conventional mix. However, replacement levels exceeding 60% resulted in a reduction in strength due to increased free water content and weaker interfacial bonding between the paste and aggregates. Similar performance patterns were observed for split tensile and flexural strengths, with optimal results obtained within the 40–60% replacement range. The study concludes that copper slag can effectively substitute up to 60% of natural sand in M60 grade concrete without adversely affecting structural performance, thereby supporting sustainable construction and efficient utilization of industrial waste.
Keywords: Copper slag, M60 concrete, Fine aggregate substitution, Compressive strength, Split tensile strength, Flexural strength, Workability.

I. INTRODUCTION

Concrete remains the most extensively utilized construction material worldwide due to its adaptability, strength, and long-term durability. Its production, however, relies heavily on natural resources such as river sand and crushed stone, which serve as fine and coarse aggregates. Rapid urban growth and large-scale infrastructure development have dramatically increased the demand for river sand, resulting in excessive extraction from natural sources. This uncontrolled mining has caused severe environmental consequences, including riverbank instability, groundwater depletion, ecological imbalance, and loss of biodiversity. Furthermore, the rising cost and limited availability of natural sand have created significant challenges for the construction sector, prompting the exploration of alternative materials.

Copper slag, a waste material produced during copper smelting and refining operations, has gained attention as a potential replacement for natural fine aggregate. Large quantities of copper slag are generated annually worldwide, and improper disposal poses environmental risks such as land contamination and heavy metal leaching. Due to its favorable physical and chemical properties—such as high density, angular shape, low water absorption, and chemical inertness—copper slag has shown promise for use in concrete. Its application not only minimizes industrial waste disposal issues but also reduces reliance on natural resources, contributing to sustainable construction practices.

Previous research has demonstrated that partial substitution of fine aggregate with copper slag can improve workability, strength, and durability characteristics of concrete. These enhancements are largely attributed to improved particle packing and the glassy surface texture of slag, which lowers water demand. However, excessive replacement levels may negatively impact mechanical performance due to increased free water and reduced bonding at the aggregate–paste interface. While substantial research exists on conventional and moderate-strength concrete, limited studies have addressed the performance of copper slag in high-strength concrete, where material behavior is more critical.

In light of this, the present study focuses on evaluating the suitability of copper slag as a fine aggregate replacement in M60 grade high-strength concrete. Replacement levels of 0%, 20%, 40%, 60%, 80%, and 100% were adopted. Both fresh and hardened concrete properties were examined, including workability through slump testing, compressive strength at 7, 14, and 28 days, and split tensile and flexural strengths at 28 days.

The primary objective is to determine the optimal copper slag replacement level that ensures enhanced mechanical performance while promoting sustainability and responsible industrial waste utilization.

A. Objectives of the Study

The key objectives of this investigation are outlined below:

1) To examine the feasibility of incorporating copper slag as a fine aggregate in high-strength concrete.
2) To study the influence of copper slag on fresh and hardened concrete properties, including workability and strength characteristics.
3) To compare the performance of copper slag-modified concrete with that of conventional concrete.
4) To evaluate the sustainability and long-term performance aspects of copper slag-based concrete.
5) To assess the economic and environmental advantages of substituting natural sand with copper slag.

II. MATERIALS AND METHODOLOGY

An experimental program was formulated to evaluate the effectiveness of copper slag as a substitute for fine aggregate in M60 grade high-strength concrete. The methodology included material characterization, mix proportioning, specimen casting and curing, and testing of fresh and hardened concrete properties.

A. Materials Used

1) Cement: Ordinary Portland Cement of 53 grade was utilized and tested for standard consistency, setting times, and compressive strength to ensure compliance with relevant specifications.
2) Fine Aggregate (Sand and Copper Slag): Natural river sand conforming to standard grading requirements was used as the control fine aggregate. Copper slag obtained from a copper smelting facility was employed as a partial and complete replacement for sand. The slag was tested for particle size distribution, specific gravity, bulk density, and water absorption.
3) Coarse Aggregate: Crushed granite aggregates of 20 mm and 10 mm nominal sizes were used in a 60:40 ratio, meeting standard requirements.
4) Water: Clean potable water suitable for mixing and curing purposes was used throughout the study.
5) Chemical Admixture: A high-range water-reducing superplasticizer was incorporated to enhance the workability of high-strength concrete without increasing the water–cement ratio.

B. Mix Design

Concrete mix proportions were designed for M60 grade in accordance with standard mix design guidelines. A conventional control mix containing natural sand was prepared, followed by mixes in which copper slag replaced sand at 20%, 40%, 60%, 80%, and 100% by weight. A constant water–cement ratio of 0.30 was maintained to satisfy strength and durability criteria. Trial mixes were conducted to optimize workability using a superplasticizer.

C. Preparation of Specimens

Concrete mixing was carried out using a laboratory drum mixer to ensure uniform dispersion of copper slag. Fresh concrete was immediately tested for workability, and the remaining mix was used to cast specimens for strength evaluation.

1) Cubes of 150 × 150 × 150 mm were cast for compressive strength testing at 7, 14, and 28 days.
2) Cylinders measuring 150 mm in diameter and 300 mm in height were prepared for split tensile strength testing at 7, 14, and 28 days.
3) Beams of size 150 × 150 × 700 mm were cast for flexural strength evaluation at 7, 14, and 28 days.

After 24 hours, all specimens were demolded and cured in water at a controlled temperature of 27 ± 2°C until testing.

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III. RESULTS AND DISCUSSION

A. Slump Cone Test (Workability)

The workability of fresh concrete mixes was determined using the slump cone test. Workability represents the ease with which concrete can be mixed, placed, compacted, and finished. Due to the smooth surface texture and low water absorption capacity of copper slag, a noticeable influence on slump values was anticipated and subsequently observed during testing.

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

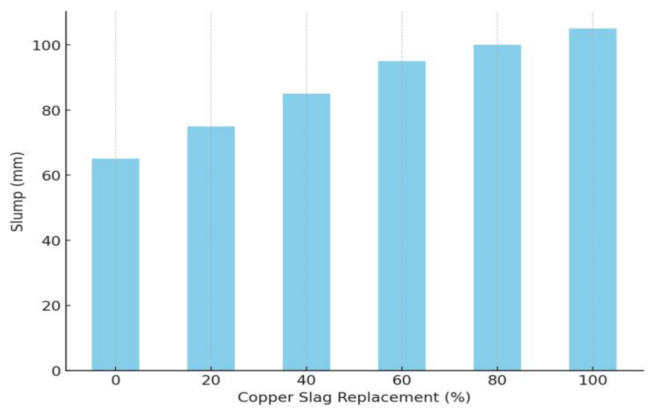

Fig. 1: Slump Cone Test Results

The test results show a consistent increase in slump values with increasing copper slag content, indicating enhanced workability of the concrete mixes. The highest slump value of 105 mm was recorded for the mix with 100% replacement of natural sand. However, excessively high workability at higher replacement levels can result in segregation and bleeding, which are undesirable characteristics in high-strength concrete. Therefore, the improvement in workability is considered effective and beneficial up to approximately 60% replacement of fine aggregate with copper slag.

B. Compressive Strength Test

Compressive strength represents the primary mechanical characteristic of concrete, as it directly reflects its ability to withstand applied loads. The compressive strength tests were conducted on cube specimens measuring 150 × 150 × 150 mm at curing ages of 7, 14, and 28 days in accordance with 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

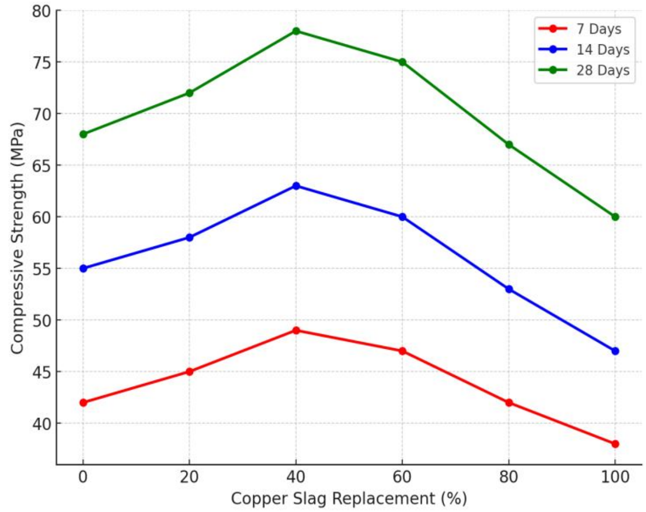

Fig. 3: Compressive Strength Test Results

The compressive strength showed a significant increase with the incorporation of copper slag up to a replacement level of 40%, at which the maximum 28-day strength of 78 MPa was recorded, exceeding that of the conventional control mix. When the replacement level exceeded 60%, a reduction in strength was observed, primarily due to the increased availability of free water in the mix and the formation of weaker interfacial transition zones between the aggregate and cement paste. These findings indicate that a replacement range of 40–60% copper slag provides optimal strength performance.

C. Split Tensile Strength Test

Split tensile strength is used to assess the tensile cracking resistance of concrete. The test was performed on cylindrical specimens with dimensions of 150 mm diameter and 300 mm height in accordance with IS 5816:1999. Specimens were tested at curing periods of 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

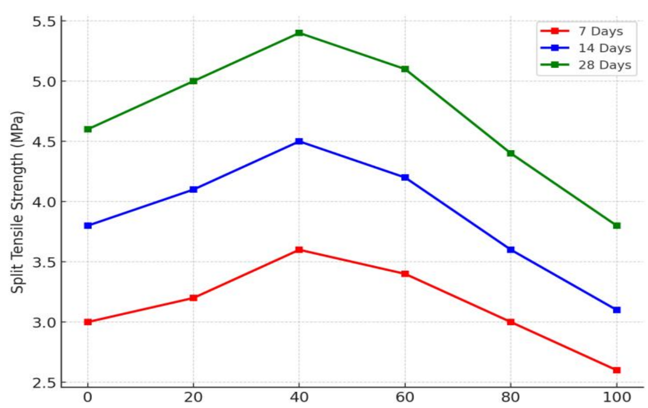

Fig. 5: Split Tensile Strength Test Results

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The split tensile strength exhibited a trend comparable to that of compressive strength. The highest tensile strength of 5.4 MPa was achieved at a 40% replacement level of copper slag. A distinct reduction in tensile strength was observed beyond 60% replacement, which can be attributed to reduced interfacial transition zone bonding and an increase in free water content within the concrete matrix. However, tensile strength values remained higher than those of the control mix up to a replacement level of 60%.

D. Flexural Strength Test

Flexural strength represents the capacity of concrete to withstand bending stresses and is a critical parameter for both pavement and structural applications. Flexural strength tests were conducted on beam specimens measuring 150 × 150 × 700 mm using a two-point loading arrangement, in accordance with IS 516 (Part 1):2020, at curing ages of 7, 14, and 28 days.

Fig. 6: 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

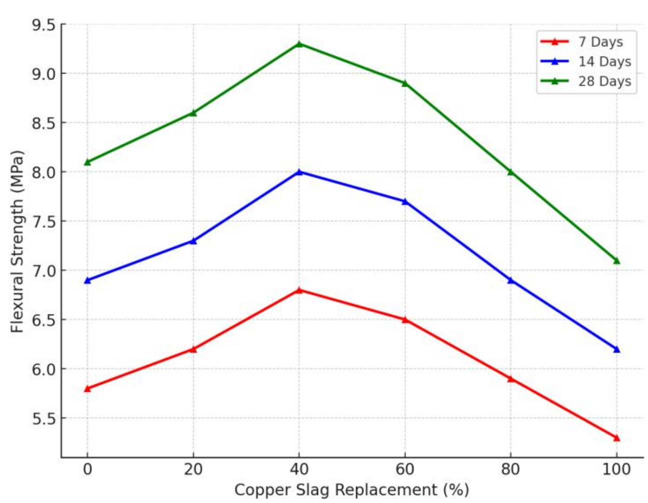

Fig. 7: Flexural Strength Test Results

Flexural strength showed a progressive increase with the incorporation of copper slag up to a 40% replacement level, at which a peak value of 9.3 MPa was recorded at 28 days. This represents an improvement of approximately 15% compared to the control mix. When the replacement level exceeded 60%, a gradual reduction in flexural strength was observed, primarily due to reduced cohesion and weaker bonding between the aggregate and cement paste. These results confirm that the inclusion of copper slag at moderate levels enhances the flexural performance of high-strength concrete.

IV. CONCLUSION

1) The workability of concrete increased steadily with higher copper slag content as a result of its smooth surface characteristics and low water absorption capacity. However, excessive workability observed at replacement levels of 80–100% may cause segregation and bleeding.
2) Maximum compressive strength was attained at a 40% replacement level, achieving 78 MPa at 28 days, which corresponds to an improvement of nearly 15% over the conventional control mix. A reduction in strength was noted beyond 60% replacement.
3) Split tensile strength followed a trend similar to compressive strength, reaching a peak value of 5.4 MPa at 40% replacement. This indicates improved resistance to tensile cracking at moderate levels of copper slag incorporation.
4) Flexural strength also benefited from the inclusion of copper slag, with the highest value of 9.3 MPa recorded at 40% replacement. This demonstrates enhanced bending resistance in high-strength concrete containing copper slag at optimal levels.
5) All strength parameters exhibited a decline when copper slag replacement exceeded 60%, mainly due to weaker interfacial transition zone bonding and increased free water content.
6) Based on the experimental findings, a replacement range of 40–60% of natural fine aggregate with copper slag is recommended as the optimum for M60 grade high-strength concrete.
7) The incorporation of copper slag contributes to improved mechanical performance while simultaneously promoting sustainable construction practices by reducing dependence on natural sand and facilitating the effective utilization of industrial waste.
8) From an economic perspective, copper slag serves as a cost-efficient alternative to natural sand, particularly in areas where it is readily available.

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