

Experimental Investigation of Reinforced Concrete Incorporating Copper Slag and Steel Fibers

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HIGHLIGHTS

- Copper slag can sustainably replace natural sand in concrete, improving strength up to an optimum replacement level.
- Hooked-end steel fibers enhance tensile strength, ductility, and crack resistance of concrete.
- The combined use of copper slag and steel fibers produces high-performance, eco-friendly concrete when used within optimal limits..

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ABSTRACT

The increasing scarcity of natural river sand and the environmental hazards associated with its extraction have necessitated the exploration of sustainable alternative materials for concrete production. Copper slag, a by-product of the copper smelting industry, possesses physical and mechanical properties comparable to natural sand and presents a viable replacement option. Simultaneously, steel fiber reinforcement has gained prominence for improving the tensile strength, ductility, and crack resistance of concrete. This study investigates the combined influence of copper slag as a partial replacement of fine aggregate and hooked-end steel fibers on the mechanical performance of concrete. Experimental investigations were conducted on M30 and M40 grade concretes with copper slag replacement levels ranging from 0% to 60%, both in conventional concrete and steel fiber reinforced concrete (SFRC) containing 1% steel fibers by volume. Fresh properties, compressive strength, split tensile strength, and flexural strength were evaluated at different curing ages. The results indicate that copper slag significantly enhances strength properties up to an optimum replacement level of 50% for M30 concrete and 40% for M40 concrete. The incorporation of steel fibers further improved post-cracking behavior, tensile resistance, and flexural performance. Beyond the optimum replacement levels, a reduction in strength was observed due to increased free water content and void formation. The study concludes that the combined use of copper slag and steel fibers offers an environmentally sustainable and structurally efficient solution for high-performance concrete applications.

1 INTRODUCTION

Concrete is the most widely used construction material worldwide due to its versatility, availability of constituent materials, and suitability for a wide range of structural

forms. However, conventional concrete is inherently weak in tension and exhibits brittle failure with limited strain capacity, leading to early cracking and reduced toughness under flexural and tensile actions (Song & Hwang, 2004;

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Thomas & Ramaswamy, 2007). These limitations have motivated extensive research into improving concrete performance through reinforcement strategies (e.g., fiber reinforcement) and material substitution using industrial by-products to enhance strength, ductility, and sustainability (Ren et al., 2024; Zhang et al., 2023).

A major concern in modern construction is the heavy dependence on natural river sand as fine aggregate. Rapid urbanization and infrastructure expansion have increased demand for sand, resulting in unsustainable extraction practices. River sand mining alters channel morphology, destabilizes banks, changes sediment transport regimes, and can degrade freshwater ecosystems and associated services (KoeHNken & Rintoul, 2020; Rentier & Cammeraat, 2022). These environmental consequences have increased pressure on the construction sector to adopt alternative fine aggregates that are technically viable and environmentally responsible (Torres et al., 2017).

Copper slag is a significant industrial by-product generated during copper smelting and refining. Large volumes of slag are produced annually, creating disposal challenges and environmental burdens. Due to its relatively high density, angular particle shape, low water absorption, and favorable mechanical characteristics, copper slag has been widely investigated as a partial replacement of natural sand in cement-based materials (Shi et al., 2008). Experimental studies have demonstrated that replacing fine aggregate with copper slag can improve strength characteristics up to an optimum level, largely attributed to improved particle packing and interfacial bonding, while excessive replacement can adversely affect performance due to bleeding/segregation and reduced cohesiveness (Al-Jabri et al., 2006; Al-Jabri et al., 2011). Similar trends have also been reported for high-performance concrete incorporating copper slag (Al-Jabri et al., 2009) and in more recent reviews and experimental research confirming both strength and durability benefits under appropriate replacement ranges (Ahmad et al., 2022; Turkane et al., 2024).

In parallel, steel fiber reinforcement has emerged as an effective technique to enhance ductility, crack control, and post-cracking energy absorption. Steel fiber reinforced concrete (SFRC) benefits from crack-bridging action, which delays crack propagation and improves toughness and residual load capacity after cracking (Song & Hwang, 2004; Thomas & Ramaswamy, 2007). Recent systematic reviews further emphasize SFRC's advantages in crack control and structural reliability in demanding applications, supporting its broader adoption in structural concrete (Ren et al., 2024; Zhang et al., 2023).

Although copper slag concrete and steel fiber reinforced concrete have been widely studied independently, fewer studies address their combined use in commonly adopted structural grades such as M30 and M40. Understanding the synergistic effect of copper slag (as a dense, angular fine aggregate replacement) and hooked-end steel fibers (as crack-bridging reinforcement) is essential for developing sustainable, high-performance mixes suitable for practical construction. Therefore, the present investigation evaluates copper slag as a partial replacement of fine aggregate and

examines its influence on the compressive, split tensile, and flexural strength of M30 and M40 grade concrete, both with and without hooked-end steel fibers. The study also aims to identify optimum replacement levels that deliver enhanced mechanical performance while supporting sustainable construction through industrial waste utilization and conservation of natural sand resources.

2. MATERIALS AND METHODS

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269 was used in this study. The cement exhibited a specific gravity of 3.09, normal consistency of 31.22%, initial setting time of 98 minutes, and final setting time of 260 minutes.

Natural river sand conforming to Zone III of IS 383 was used as fine aggregate. The sand had a specific gravity of 2.648 and fineness modulus of 2.78.

Copper slag obtained from a local copper processing unit was used as partial replacement of fine aggregate. The slag was black, glassy, and granular in nature. It exhibited a higher specific gravity (3.50) and fineness modulus (3.449) compared to natural sand.

Crushed angular coarse aggregates of 12.5 mm and 20 mm sizes conforming to IS 383 were used. The specific gravity of coarse aggregate was 2.72, with a fineness modulus of 7.61.

Hooked-end steel fibers with a length of 35 mm and diameter of 0.7 mm (aspect ratio 50) were used. The fibers had a tensile strength of approximately 1100 MPa and were added at 1% by volume of concrete. Potable water free from impurities was used for mixing and curing.

Table 1. Physical Properties of Materials

Material	Specific Gravity	Bulk Density (kg/m ³)	Fineness Modulus
Cement	3.09	—	—
Natural Sand	2.648	1649.1	2.78
Copper Slag	3.50	1711.9	3.449
Coarse Aggregate	2.72	1684.5	7.61

Concrete mix design was carried out as per IS 10262:2009 guidelines. Two grades of concrete, M30 and M40, were designed with target mean strengths corresponding to their characteristic strengths.

Table 2. Mix Proportions

Grade	Cement (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (kg/m ³)	W/C Ratio
M30	390	582	1298	175.5	0.45
M40	420	569.5	1278	180.6	0.43

Fine aggregate was replaced by copper slag at levels of 0%, 10%, 20%, 30%, 40%, 50%, and 60%. Steel fibers were added at 1% by volume for SFRC mixes.

3 EXPERIMENTATIONS

Concrete specimens were cast in the form of cubes (150 × 150 × 150 mm), cylinders (150 × 300 mm), and beams (100 × 100 × 500 mm). For each mix, specimens were prepared for 7-day and 28-day strength testing. After casting, specimens were demoulded after 24 hours and cured in water until the testing age. Fresh concrete properties were evaluated using the slump cone test. Hardened concrete tests included compressive strength, split tensile strength, and flexural strength tests conducted as per relevant IS standards.

4 RESULTS AND DISCUSSIONS

The workability of concrete mixes was evaluated using the slump cone test for both conventional concrete and steel fiber reinforced concrete incorporating copper slag. The results indicated a gradual reduction in slump values with an increase in the percentage of copper slag replacement. This reduction can be attributed to the angular shape, higher density, and lower water absorption capacity of copper slag particles compared to natural sand. The inclusion of 1% hooked-end steel fibers further reduced workability due to fiber interlocking and increased internal friction within the mix. However, despite the reduction in slump, all mixes exhibited workable consistency suitable for proper compaction, indicating that copper slag concrete remains practically viable for field applications

The variation of compressive strength with different percentages of copper slag replacement for M30 and M40 grade conventional concrete is presented in Figure 1.

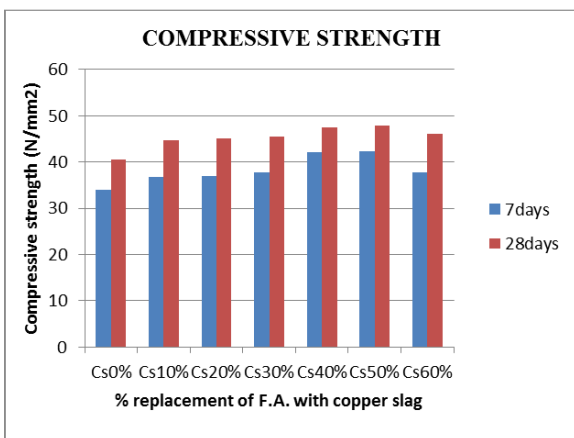


Figure 1. Compressive Strength V/S % Replacement of F.A With Copper Slag

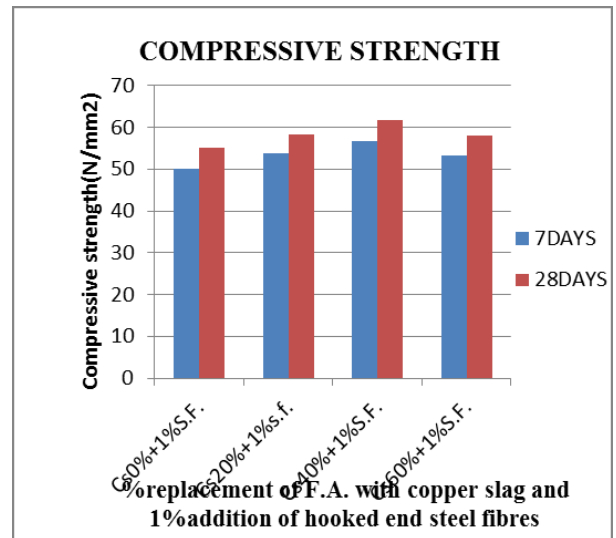


Figure 2. Compressive Strength V/S % Replacement of F.A With Copper Slag And 1% Addition of Hooked End Steel Fibres

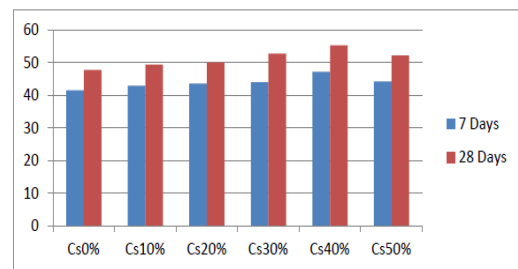


Figure 3. Variation of Compressive Strength (7 Days & 28 Days)

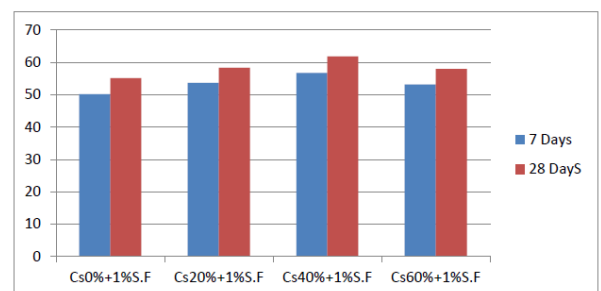


Figure 4. Variation of Compressive Strength with SFRC (7 Days & 28 Days)

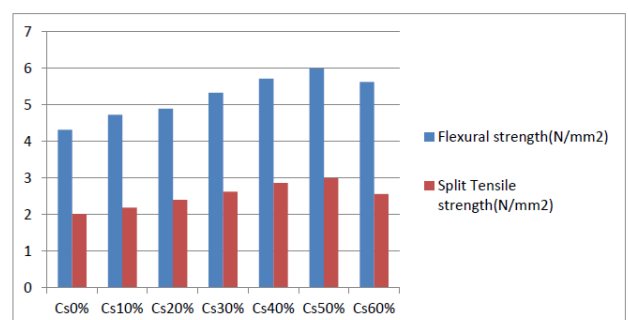


Figure 5. Variation of Flexural Strength and Split Tensile Strength with Copper Slag of M30 Grade

The results show a consistent increase in compressive strength with increasing copper slag content up to an optimum level, followed by a decline beyond that point. For M30 grade concrete, the compressive strength increased steadily up to 50% replacement of fine aggregate with copper slag, whereas for M40 grade concrete, the maximum strength was observed at 40% replacement. The improvement in strength at moderate replacement levels is attributed to enhanced particle packing, reduced voids, and improved interfacial bonding between the cement paste and copper slag particles. Beyond the optimum replacement level, excess copper slag leads to increased free water content and reduced cohesiveness, resulting in strength reduction.

The influence of steel fibers on compressive strength is illustrated in Figure 2 to 4. The addition of 1% hooked-end steel fibers resulted in higher compressive strength values compared to corresponding conventional concrete mixes at all copper slag replacement levels. Steel fibers contributed to delaying crack initiation and restricting crack propagation under compressive loading. The fiber-reinforced mixes exhibited improved post-peak behavior and reduced brittleness, confirming the beneficial role of steel fibers in enhancing the structural integrity of copper slag concrete.

The comparison of compressive strength development at 7 and 28 days for both conventional and steel fiber reinforced concrete is presented in Figure 3. The results indicate that copper slag concrete shows improved early-age strength development compared to control mixes. This behavior can be attributed to the dense packing and improved hydration process facilitated by the low water absorption of copper slag. The strength gain between 7 and 28 days was more pronounced in mixes containing steel fibers, highlighting their contribution to long-term performance.

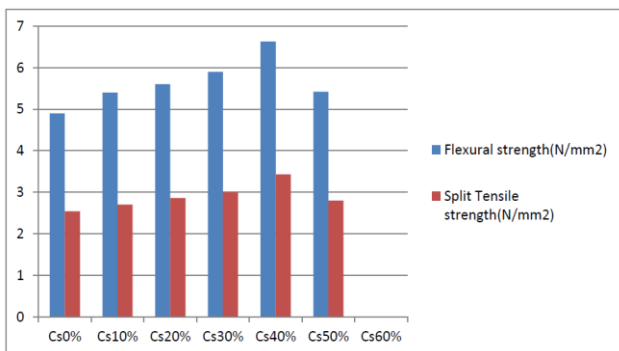


Figure 6. Variation of Flexural Strength and Split Tensile Strength with Copper Slag of M40 Grade

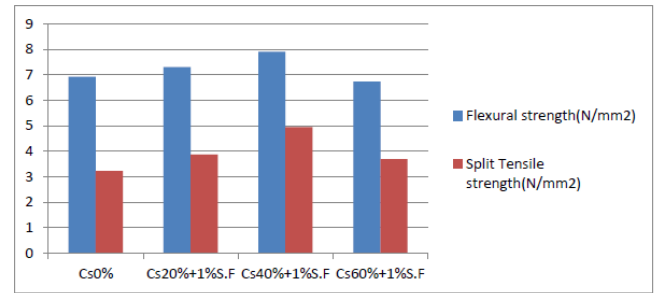


Figure 7. Variation of Flexural Strength and Split Tensile with Copper Slag and SFRC of M30 Grade

Flexural strength results for both grades of concrete are illustrated in Figure 9 and Figure 10. Flexural strength showed the highest percentage improvement among all mechanical properties tested. Maximum flexural strength was observed at 40% copper slag replacement for both M30 and M40 grades. The presence of steel fibers further enhanced flexural performance by providing crack-bridging action and increased energy absorption capacity. The combined effect of copper slag and steel fibers resulted in ductile failure behavior rather than sudden brittle fracture, which is highly desirable for structural applications.

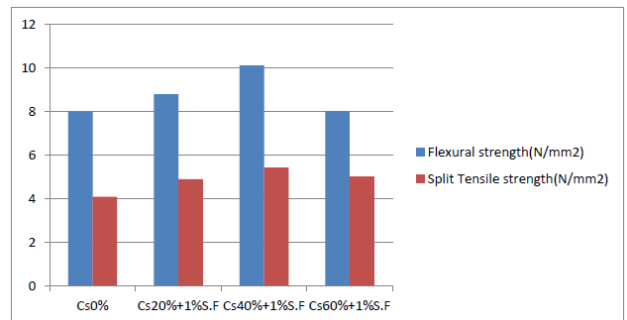


Figure 8. Variation of Flexural Strength and Split Tensile with Copper Slag and SFRC of M40 Grade

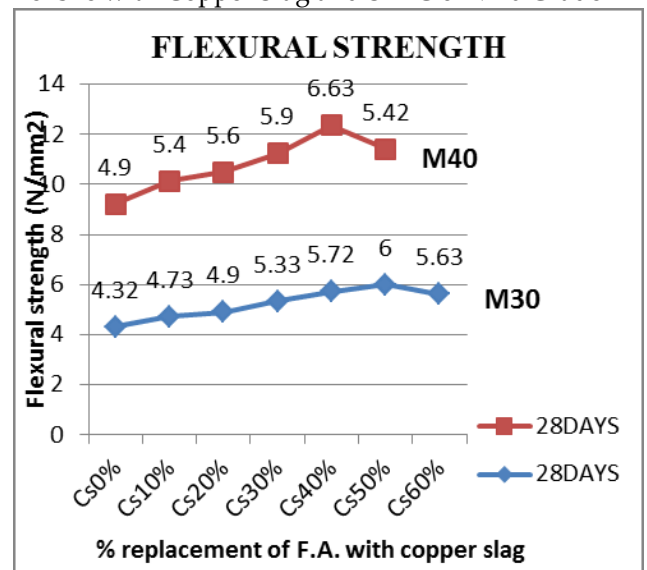


Figure 9. Flexural Strength V/S % Replacement of F.A. With Copper Slag

The variation of split tensile strength with copper slag replacement for M30 and M40 grade concrete is shown in Figure 11 and Figure 12. Split tensile strength increased significantly with copper slag replacement up to 40–50%, beyond which a reduction was observed. The improvement is primarily due to the enhanced bond between copper slag particles and cement paste, leading to improved resistance against tensile stresses. Steel fiber reinforced concrete exhibited substantially higher split tensile strength than conventional concrete, as fibers effectively bridged micro-cracks and redistributed tensile stresses across the concrete matrix.

The combined influence of copper slag and steel fibers on flexural and split tensile strength is presented in Figure 5 to Figure 8. These figures clearly demonstrate that steel fiber reinforced concrete containing copper slag exhibits superior mechanical performance compared to conventional concrete. The synergistic interaction between the dense packing of copper slag particles and the crack-arresting capability of steel fibers significantly improved tensile resistance, flexural strength, and overall toughness of concrete.

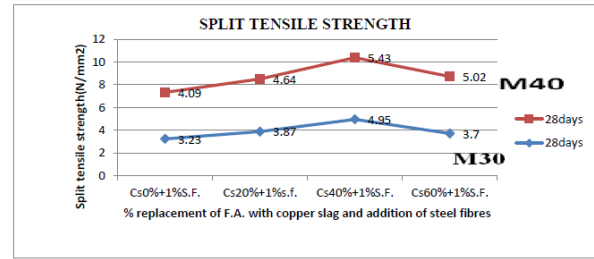


Figure 12. Split tensile strength v/s % replacement of FA with copper slag and addition of 1% steel fibers for M30 & M40 grades

Based on the experimental results, the optimum replacement level of fine aggregate with copper slag was identified as 50% for M30 grade and 40% for M40 grade concrete. At these levels, the concrete exhibited maximum compressive, split tensile, and flexural strength. Replacement beyond the optimum level resulted in strength reduction due to excess free water, increased bleeding, and reduced cohesiveness of the mix. The inclusion of steel fibers effectively compensated for brittleness and enhanced post-cracking performance, making the copper slag-based SFRC suitable for high-performance and sustainable construction applications.

5 CONCLUSION

Based on the experimental investigation carried out on M30 and M40 grade concrete incorporating copper slag as a partial replacement of fine aggregate, with and without the addition of hooked-end steel fibers, the following conclusions are drawn:

The results confirm that copper slag can be effectively utilized as a partial replacement for natural fine aggregate in concrete without compromising its mechanical performance. The incorporation of copper slag led to a noticeable improvement in compressive, split tensile, and flexural strengths up to an optimum replacement level. For M30 grade concrete, the maximum strength was achieved at 50% replacement of fine aggregate with copper slag, while for M40 grade concrete, the optimum replacement level was identified as 40%. Beyond these levels, a reduction in strength was observed, primarily due to increased free water content, bleeding, and reduced cohesiveness of the concrete mix.

The inclusion of 1% hooked-end steel fibers significantly enhanced the strength behavior of copper slag concrete. Steel fiber reinforced concrete exhibited superior compressive strength, improved tensile resistance, and markedly higher flexural strength compared to conventional concrete. The

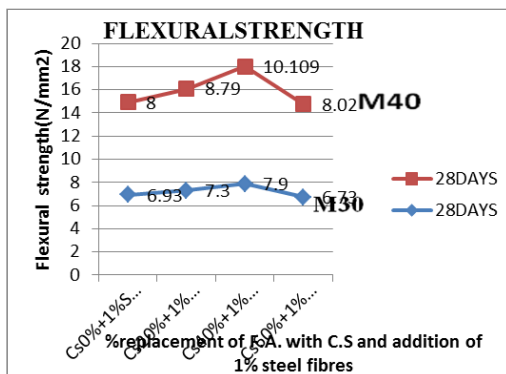


Figure 10. Flexural Strength V/S % Replacement Of F.A With Copper Slag and addition of 1% Steel Fibers

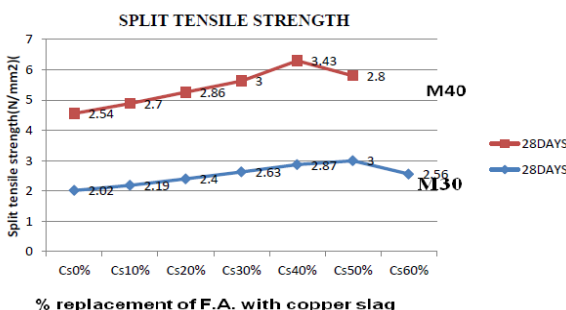


Figure 11. Split Tensile Strength V/S % Replacement of F.A With Copper Slag for M30 & M40 Grades

fibers effectively bridged micro-cracks, delayed crack propagation, and transformed the failure mode from brittle to ductile, thereby improving post-cracking performance and energy absorption capacity.

Workability of concrete decreased with increasing copper slag content and further reduced with the addition of steel fibers; however, all mixes remained within acceptable limits for practical applications. The combined use of copper slag and steel fibers demonstrated a synergistic effect, resulting in dense concrete with enhanced mechanical properties and improved structural performance.

Overall, the study establishes that the partial replacement of fine aggregate with copper slag, particularly at optimum levels, in combination with steel fiber reinforcement, provides a sustainable and efficient alternative for producing high-performance concrete. The utilization of copper slag not only conserves natural sand resources but also offers an environmentally responsible solution for the disposal of industrial waste, making it a viable material for sustainable construction practices.

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Conflicts of Interest: The authors declare no conflicts of interest.

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