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Strength Performance of Concrete Incorporating Copper Slag and Hooked-End Steel Fibers

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HIGHLIGHTS

- Copper slag improved concrete workability due to its lower water absorption than natural sand.
- Optimum copper slag replacement was 50% for M30 and 40% for M40 concrete.
- Steel fiber reinforced concrete showed higher strength, better crack control, and improved ductility.

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ABSTRACT

River sand depletion and the growing burden of industrial waste have increased interest in alternative concrete materials. This study evaluated copper slag as a partial replacement for natural fine aggregate in conventional concrete and steel fiber reinforced concrete (SFRC) of grades M30 and M40, designed as per IS 10262. Workability was assessed by slump, while compressive, flexural, and split tensile strengths were measured at specified curing ages. Copper slag improved workability because of its lower water absorption than sand, but strength improved only up to an optimum replacement level. The best performance was observed at 50% replacement for M30 conventional concrete and 40% for M40, while SFRC achieved the highest 28-day compressive strength at 40% replacement. Compared with conventional mixes, SFRC showed higher compressive, flexural, and split tensile strength, along with improved crack control and ductility. The study supports optimized copper slag use for more sustainable and better-performing concrete.

1. INTRODUCTION

Concrete continues to dominate civil engineering construction because it is relatively economical, readily mouldable, and capable of carrying high compressive stress under a wide range of service conditions. Yet the material has a fundamental weakness that has shaped modern structural design from the beginning: plain concrete performs poorly in tension, exhibits low ductility, and fails in a brittle manner once crack initiation becomes unstable. That limitation explains the long-standing reliance on reinforcement, whether in the form of steel bars, distributed fibers, prestressing systems, or hybrid strengthening approaches (Chen et al., 2021). The study addresses a familiar but still practically relevant engineering problem: how to improve concrete performance while simultaneously reducing dependence on natural river sand. In conventional concrete production, fine aggregate is not a trivial filler. Sand influences particle packing, paste demand,

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workability, bleeding, finishing, and the quality of the interfacial transition zone. When natural river sand becomes scarce or expensive, the entire economics and sustainability profile of concrete production changes. The excessive extraction of river sand creates ecological imbalance and economic pressure, making the search for alternative fine aggregate not merely a laboratory exercise, but a supply-chain and environmental necessity (Shi et al., 2008; Casagrande et al., 2023).

Copper slag is one such alternative. It is produced as a by-product during the extraction and refining of copper and is commonly described as a black, glassy, granular material with physical characteristics that can make it suitable as aggregate in cement-based systems. Because copper slag is generated in large quantities, its reuse in concrete offers dual benefits: reducing landfill burden and lowering dependence on natural sand (Gorai et al., 2003; Shi et al., 2008). In the present study, copper slag was explored specifically as a partial replacement for fine aggregate rather than as a supplementary cementitious material. This distinction matters because the governing mechanisms are mainly associated with grading, density, surface texture, absorption, and packing characteristics, rather than pozzolanic reactivity (Shi et al., 2008; Casagrande et al., 2023).

The second variable considered in the source report is steel fiber reinforcement. Fiber-reinforced concrete has become one of the most practical approaches for improving crack resistance, energy absorption, and post-cracking behaviour without depending exclusively on conventional reinforcing bars. Unlike reinforcing bars, which provide reinforcement only in predetermined directions, steel fibers are distributed throughout the concrete matrix and provide multidirectional crack-bridging capacity. This makes them particularly effective for controlling crack propagation and enhancing tensile, flexural, and toughness-related properties (Amin et al., 2022; Chen et al., 2021). Hooked-end steel fibers, in particular, have been shown to improve crack resistance and flexural performance due to their enhanced mechanical anchorage within the matrix (Laxmi et al., 2023; Chen et al., 2021).

The coupling of copper slag and steel fibers is therefore a logical research direction. If copper slag can partially replace natural sand and steel fibers can compensate for concrete's low tensile capacity, the combined system may produce a more sustainable and mechanically robust composite. However, such benefits cannot be assumed in advance. Industrial by-products can alter workability and segregation behaviour, while fibers may reduce slump and complicate mixing when used in excessive amounts. The central engineering question is thus straightforward: how do conventional concrete and steel fiber reinforced concrete respond when fine aggregate is partially replaced with copper slag in M30 and M40 grades?

This study identifies the objective as a comparative investigation of conventional concrete and steel fiber reinforced concrete incorporating copper slag. The material system includes Ordinary Portland Cement, fine aggregate, coarse aggregate, copper slag, water, and hooked-end steel fibers. The experimental programme evaluates workability, compressive strength, split tensile strength, and flexural strength. This test matrix is structurally appropriate because compressive strength remains the standard performance index in concrete engineering, while split tensile and flexural strengths are more sensitive to the influence of fibers and matrix modification caused by alternative fine aggregate. Slump testing likewise captures the fresh-state consequences of using a denser, less absorptive replacement material and a dispersed fiber system (Al-Jabri et al., 2009, 2011).

A further reason this study remains relevant is that alternative aggregates rarely produce linear benefits across all replacement percentages. Previous studies have shown that copper slag can improve workability and strength only up to an optimum replacement level, beyond which excess free water, reduced cohesion, or poor grading balance may adversely affect performance (Al-Jabri et al., 2009, 2011). This nonlinearity is one of the most practically useful outcomes for engineers because it moves the discussion beyond simplistic claims that industrial by-products are universally beneficial replacements.

The present manuscript therefore serves three functions. First, it restructures This study into a scientific journal format with clearer sectioning and a more explicit argument. Second, it consolidates the experimental evidence reported in the original work. Third, it offers a more disciplined engineering interpretation of what the reported results imply for the use of copper slag and steel fibers in sustainable concrete technology. Throughout, the manuscript remains grounded in the submitted source text rather than relying on unsupported external claims.).

2. LITERATURE SURVEY

Concrete remains the most widely used construction material because of its economy, mouldability, and high compressive strength. However, its inherent weakness in tension, low ductility, and brittle post-cracking behaviour continue to limit its structural efficiency in applications where crack control and tensile resistance are critical. For this reason, researchers have long explored reinforcement strategies and alternative constituent materials that can improve performance while also addressing sustainability concerns. Recent reviews confirm that both steel fiber reinforcement and industrial by-product utilization remain major themes in modern concrete research (Amin et al., 2022; Shi et al., 2008).

Among reinforcement approaches, steel fiber reinforced concrete (SFRC) has received considerable attention because discrete steel fibers improve crack bridging, delay crack propagation, and enhance energy absorption after matrix cracking. Unlike conventional steel bars, which act only at predetermined locations, steel fibers are dispersed throughout the concrete matrix and contribute to multidirectional crack control. As a result, the most consistent benefits of SFRC are usually observed in split tensile strength, flexural strength, toughness, and post-cracking ductility rather than in dramatic gains in compressive strength (Chen et al., 2021; Amin et al., 2022).

This research refers to earlier studies reporting that even modest steel fiber dosages improved flexural performance relative to plain concrete. That interpretation is mechanically sound. In general, fibers are especially effective in crack-sensitive response variables because they arrest microcrack growth and transfer stresses across developing fracture planes. This explains why fiber-reinforced mixes often show more pronounced improvement in flexural and tensile behaviour than in compressive strength. The source survey also notes that fiber addition altered crack patterns and made failure more ductile, which is fully consistent with the established behaviour of SFRC systems.

At the same time, the practical literature on SFRC repeatedly shows that these benefits are dosage-sensitive. Increasing fiber content generally improves crack resistance and load redistribution, but it also reduces workability and may create mixing difficulties, poor compaction, or fiber balling when the dosage becomes excessive. This research highlights this same trade-off in the studies it cites, indicating that optimum performance was obtained only within a moderate fiber range. This is a key engineering point because the usefulness of steel fibers depends not only on strength enhancement but also on whether the concrete remains workable enough for proper placement and consolidation (Amin et al., 2022).

Fiber geometry further influences performance. Hooked-end steel fibers are often preferred because mechanical anchorage improves pull-out resistance and crack-bridging efficiency. Studies on hooked and multiple hooked-end fibers have shown that geometry and aspect ratio significantly affect flexural tensile response, residual strength, and crack control. However, higher aspect ratios and more complex fiber geometries may also intensify the workability penalty. This study correctly recognizes this balance, even though it contains some inconsistency in reporting the exact aspect ratio used. The broader literature supports the conclusion that fiber geometry must be selected with both fresh-state behaviour and hardened performance in mind (Chen et al., 2021).

Parallel to fiber research, the search for alternative fine aggregate has become increasingly important because excessive river sand extraction creates ecological damage, supply instability, and higher material cost. Copper slag has emerged as one of the most investigated alternatives because it is produced in large quantities as a metallurgical by-product and possesses physical characteristics that can make it suitable for use as a fine aggregate in concrete. Reviews on copper slag consistently describe it as a dense, glassy material with low water absorption and potential value in reducing waste disposal pressure while lowering dependence on natural sand (Shi et al., 2008; Casagrande et al., 2023).

A recurring finding in copper slag research is that its effect is strongly proportion-dependent. Experimental studies have shown that partial replacement of sand with copper slag can improve workability and, in many cases, enhance compressive, tensile, and flexural strength up to an optimum replacement level. The most common explanation is that the low absorption and dense particle structure of copper slag improve particle packing and leave more free water available in the mix, thereby increasing flowability. However, beyond the optimum range, excess free water, reduced cohesion, bleeding tendencies, or internal void development may reduce strength and overall mix stability (Al-Jabri et al., 2009; Al-Jabri et al., 2011).

The attached thesis survey repeatedly points to an optimum copper slag replacement level near 40%, with strength declining beyond that threshold. This pattern is not incidental; it is one of the most widely reproduced results in the copper slag concrete literature. Published studies on high-performance concrete and normal concrete have both shown that copper slag performs best as a partial, not unlimited, replacement. That threshold behaviour is especially valuable for practice because it cautions against overly simplistic claims that industrial by-products automatically improve concrete at any dosage. Instead, the evidence supports careful proportion optimization for each grade and mix system. The combined use of copper slag and steel fibers is a logical extension of these two research streams. Copper slag primarily alters the aggregate skeleton, density, and fresh-state behaviour of the matrix, whereas steel fibers primarily improve crack resistance, tensile response, and post-cracking performance. When used together, they may therefore provide complementary benefits: one contributes to sustainability and aggregate substitution, and the other improves structural resilience and ductility. Studies on steel fiber-reinforced concrete containing copper slag support this combined-material approach, although they also confirm that both constituents must remain within optimum ranges to avoid loss of workability or reduced strength due to poor internal stability (Ameri et al., 2020).

Another important implication emerging from the literature is that optimum replacement or reinforcement levels should not be generalized across all concrete grades. This study attempts a direct comparison between M30 and M40 mixes, which is a useful applied contribution because many studies report an optimum dosage for a single grade and then imply broader applicability. In practice, concrete grade, paste content, aggregate skeleton, and fiber dosage interact in ways that can shift the optimum point. This means that comparative grade-wise studies remain valuable even when the underlying material concepts are already known. The literature supports four broad conclusions. First, steel fibers improve flexural performance, split tensile strength, toughness, and ductility more consistently than compressive strength. Second, copper slag is a viable partial replacement for fine aggregate because of its physical characteristics and industrial availability. Third, copper slag typically performs best within a moderate replacement range, often around 40%, rather than at very high replacement percentages. Fourth, combined copper slag–steel fiber systems are promising, but their benefits depend on careful proportioning to maintain both workability and hardened strength. Within this context, the present study is best framed as an applied experimental comparison of conventional concrete and SFRC across two strength grades rather than as a claim of fundamental material novelty.

3. MATERIALS AND METHODS

3.1 Source and Experimental Context

The study was originally conducted experimental programme was organized around the selection of materials, determination of material properties, mix design using the IS 10262 procedure, specimen casting, curing, and the testing of fresh and hardened properties. The journal format adopted here retains that workflow, but presents it in a standard scientific sequence.

3.2 Constituent Materials

Ordinary Portland Cement of 53 grade conforming to IS 12269 was used as the binder. The specific gravity of cement is reported as 3.07. Fine aggregate consisted of natural sand conforming to grading Zone III under IS 383. The specific gravity of the fine aggregate was reported as 2.65. Coarse aggregate was crushed angular aggregate, nominally 20 mm maximum size, with specific gravity 2.72. The thesis also reports a coarse aggregate fineness modulus of 7.61 and compacted bulk density of 1684.5 kg/m3.

Copper slag was used as the replacement material for natural fine aggregate. This study describes copper slag as black, glassy, irregular, and granular in nature. The reported properties indicate that its density and specific gravity are higher than those of natural sand, while its water absorption is lower. This combination is important because it affects both fresh-state and hardened-state behaviour. The thesis includes a chemical composition table showing the principal constituents as iron oxide and silica, with smaller amounts of aluminium oxide, calcium oxide, magnesium oxide, copper, titanium dioxide, and potassium oxide. The material therefore functions in this study primarily as a dense, low-absorption replacement aggregate rather than as a pozzolanic binder component.

Steel fibers were of hooked-end type. Here the source document requires careful reading. The abstract and some earlier sections refer to hooked-end fibers with aspect ratio 60, whereas the materials section reports fibers of 0.7 mm diameter and 35 mm length, which corresponds to an aspect ratio of approximately 50. The materials section also appears to contain a likely typographical error by reporting fiber “density 1100 MPa,” which is more plausibly a tensile strength value rather than a density. Because this manuscript is derived from the submitted thesis, the geometry is reproduced from the materials section while the inconsistency is noted for transparency. In all cases, the fibers were introduced to improve crack resistance and enhance flexural and tensile performance. Portable clean water was used for mixing and curing. This study emphasizes that curing water should be free from salinity, vegetation, and harmful chemicals.

3.3 Material Characterization

The thesis includes tests for specific gravity, bulk density, sieve analysis, fineness modulus, and related aggregate properties. The summarized values most relevant to the mix design are presented here. Coarse aggregate had a compacted bulk density of 1684.5 kg/m3 and fineness modulus of 7.61. Fine aggregate had a reported bulk density of 1649.1

kg/m3 and fineness modulus of 2.78 in one summary table, although another materials summary later reports somewhat different values, indicating minor inconsistency in the document. Copper slag had a bulk density of approximately 1711.9 kg/m3 and fineness modulus of 3.449 in the main summary table. These values indicate that copper slag is slightly coarser and denser than the natural sand used in the study, which is relevant for particle packing and water demand.

3.4 Mix Design Basis

Concrete mix design was carried out according to IS 10262-2009. Two grades were considered: M30 and M40. The design stipulations reported in the thesis included OPC 53 grade cement, 20 mm nominal maximum size aggregate, moderate exposure condition, good supervision, and crushed angular aggregate. The maximum water-cement ratio was stated as 0.45, and a workability range of 25–75 mm was targeted. For M30 concrete, the adopted water-cement ratio was 0.45, estimated water content was 166 litres during the design procedure, and cement content was calculated at 390 kg/m^3. The final reported mix ratio for M30 was 1 : 1.492 : 3.33 with water-cement ratio 0.45. The detailed mass proportion eventually used in the experimental study was 390 kg/m^3 cement, 582 kg/m^3 fine aggregate, 1298 kg/m^3 coarse aggregate, and 175.5 kg/m^3 water. For M40 concrete, the thesis reports a final mix ratio of 1 : 1.36 : 3.024 with water-cement ratio 0.43. The detailed experimental proportion was 420 kg/m^3 cement, 569.5 kg/m^3 fine aggregate, 1278 kg/m^3 coarse aggregate, and 180.6 kg/m^3 water.

3.5 Copper Slag Replacement Scheme

Copper slag replaced natural fine aggregate in steps. For conventional concrete, the M30 series used replacement levels of 0%, 10%, 20%, 30%, 40%, 50%, and 60%, represented as CS0 to CS6. The corresponding mixes progressively reduced natural sand and increased copper slag while keeping cement, coarse aggregate, and water constant. The M40 conventional series followed the same replacement sequence. For steel fiber reinforced concrete, the reported result tables include four replacement levels: 0%, 20%, 40%, and 60% copper slag. The thesis describes a constant 1% addition of hooked-end steel fibers in the SFRC mixes. Although the mix appellation tables indicate "% addition of steel fibers = 1" across all rows, the exact basis of the 1% dosage—whether by volume of concrete or by another project convention—is expressed more clearly in the abstract and discussion, where it is described as 1% addition.

3.6 Specimen Preparation

Three categories of specimens were cast: cubes for compressive strength, cylinders for split tensile strength, and beams for flexural strength. Cube specimens measured 150 mm × 150 mm × 150 mm. Cylinders were 300 mm in height and 150 mm in diameter. Beams measured 500 mm × 100 mm × 100 mm. The casting procedure reported in the thesis followed standard laboratory practice. Moulds were cleaned, assembled, and oiled to facilitate demoulding. Dry materials were batched according to the required mix. Mixing was carried out in a rotating miller under supervision. Before casting, fresh concrete was evaluated using slump. Concrete was then placed into the moulds in layers, tamped for compaction, and further consolidated on a vibrating table. The moulds were left undisturbed for 24 hours before demoulding. For each trial, six cubes were cast for 7-day and 28-day compressive strength, three cylinders were cast for 28-day split tensile strength, and three beams were cast for 28-day flexural strength. The specimens were cured in water tanks, with the thesis stating that the water was changed every seven days.

3.7 Test Methods

Fresh-state workability was evaluated by the slump cone method in accordance with IS 1199-1959. The slump cone dimensions were reported as 300 mm height, 200 mm bottom diameter, and 100 mm top diameter. The concrete was placed in three layers, each tamped before the cone was lifted vertically and the slump measured. Compressive strength was determined on cube specimens using a compression testing machine. The compressive strength was calculated by dividing failure load by loaded area. Both 7-day and 28-day strengths were recorded. Split tensile strength was determined on cylindrical specimens using the standard diametral compression method. The thesis gives the formula as 2P divided by pi times length times diameter, where P is the failure load, L is cylinder length, and D is cylinder diameter. Flexural strength, expressed as modulus of rupture, was measured on beam specimens. The thesis notes the standard decision rules involving the fracture line location "a" and the formulae applicable within the acceptable fracture zone under IS 516-1959.

3.8 Data Structure and Interpretation

This study presents its results primarily in tabular form and through graphs. For conventional concrete, compressive strength is reported across the full 0–60% copper slag range for both M30 and M40 grades. For SFRC, compressive strength is reported at 0%, 20%, 40%, and 60% copper slag for both grades. Flexural and split tensile strengths are consolidated into a comparative table for conventional and steel fiber reinforced mixes. Slump values are reported separately for M30 and M40 conventional and SFRC mixes. A scientific interpretation of the source data requires caution in two areas. First, the thesis contains a few inconsistencies in descriptive values, such as the fiber aspect ratio and some aggregate property summaries. Second, the statistical treatment is limited; mean strengths are reported, but no standard deviation or coefficient of variation is provided for the final tables. Accordingly, the present manuscript discusses trends and comparative performance rather than making stronger statistical claims than the source supports.

4. RESULTS

4.1 Workability

The slump values reported in This study show a consistent increase in workability with increasing copper slag content for both grades of conventional concrete and for the steel fiber reinforced series. In the M30 conventional mixes, slump increased from 55 mm at 0% copper slag to 70 mm at 60% replacement. In the corresponding M30 steel fiber reinforced series, slump increased from 53 mm to 68 mm across the same replacement range. For M40 concrete, the conventional mixes increased from 58 mm to 69 mm, while the fiber-reinforced series increased from 54 mm to 68 mm. Two conclusions follow immediately. First, copper slag increased the workability of the mixes. This study attributes this to the lower water absorption and lower surface porosity of copper slag compared with natural sand. This interpretation is mechanically reasonable: when the replacement aggregate absorbs less water than the natural sand it replaces, more free water remains available in the fresh mix, increasing slump. Second, the fiber-reinforced mixes consistently had slightly lower slump than the corresponding conventional mixes, which confirms the well-known restrictive influence of steel fibers on flow. Fibers increase internal resistance to movement and can reduce the ease with which concrete deforms in the fresh state.

The increase in slump with copper slag content should not automatically be interpreted as an unqualified benefit. Improved workability can aid placement and compaction, but excessive fluidity without corresponding adjustments in paste demand or admixture design can destabilize the mix, increase bleeding or segregation risk, and alter strength development. This study later links excessive replacement beyond the optimum level with strength reduction, and the fresh-state trend shown by the slump data is consistent with that explanation.

4.2 Compressive Strength of Conventional Concrete

The conventional M30 series showed a clear increase in 28-day compressive strength as copper slag replacement increased from 0% to 50%, followed by a decline at 60% replacement. The 28-day strength was 40.44 MPa for the control mix (CS0), increased to 44.74 MPa at 10% replacement, 45.08 MPa at 20%, 45.48 MPa at 30%, 47.41 MPa at 40%, and reached a peak of 47.85 MPa at 50% replacement. At 60% replacement, the strength dropped slightly to 46.07 MPa. The 7-day strengths followed the same general pattern, with the highest value also occurring near the upper replacement range. The conventional M40 series exhibited a similar but slightly different optimum. The control mix recorded a 28-day compressive strength of 47.7825 MPa. Strength increased progressively through 49.404 MPa at 10%, 50.094 MPa at 20%, 52.8 MPa at 30%, and reached a peak of 55.35 MPa at 40% copper slag replacement. At 50% replacement, the strength dropped to 52.2 MPa. Thus, the M40 conventional concrete achieved its optimum at 40% replacement rather than 50%. This grade-wise difference is one of the most practically useful outcomes in the source report. It indicates that copper slag replacement does not have a universal optimum across all strength classes, even within the relatively narrow band studied here. The denser M40 mix, with its lower water-cement ratio and different fine aggregate demand, appears to have been less tolerant of higher replacement than the M30 mix. That is plausible, because higher-strength mixes are often more sensitive to balance within the fine fraction and to changes in internal water distribution.

4.3 Compressive Strength of Steel Fiber Reinforced Concrete

The steel fiber reinforced M30 series was reported at four replacement levels: 0%, 20%, 40%, and 60% copper slag. The 28-day compressive strengths were 47.032 MPa, 53.0 MPa, 55.56 MPa, and 52.29 MPa, respectively. Thus, the best recorded value in the tested SFRC subset occurred at 40% copper slag replacement. Relative to the control SFRC mix, both 20% and 40% replacement yielded substantial increases, while 60% replacement remained above the control but below the optimum. The steel fiber reinforced M40 series showed a similar pattern. The 28-day compressive strengths were 55.12 MPa at 0% copper slag, 58.3 MPa at 20%, 61.82 MPa at 40%, and 57.93 MPa at 60%. Again, the peak occurred at 40% replacement. These results indicate that the addition of steel fibers did not fundamentally change the nonlinearity of the copper slag response. The SFRC mixes still improved up to an optimum range and then declined. What the fibers did change was the absolute performance level and the failure mode. The source conclusion reports that steel fiber reinforced concrete exhibited an overall increase in compressive strength compared with conventional concrete, alongside more substantial gains in flexural and split tensile response.

4.4 Flexural Strength

The 28-day flexural strength values reported in the comparative table show a notable distinction between conventional and fiber-reinforced concrete. For conventional M30 concrete, flexural strength increased from 4.32 N/mm2 in the control mix to 6.0 N/mm2 at 50% copper slag, then reduced slightly to 5.63 N/mm2 at 60% replacement. For conventional M40 concrete, flexural strength increased from 4.9 N/mm2 at 0% replacement to 6.63 N/mm2 at 40%, after which it dropped to 5.42 N/mm2 at 50%. The 60% value for conventional M40 was not reported in the summary table. The SFRC values were significantly higher than the corresponding conventional values. For M30 SFRC, flexural strength was 6.93 N/mm^2 at 0% copper slag, 7.3 N/mm^2 at 20%, 7.9 N/mm^2 at 40%, and 6.73 N/mm^2 at 60%. For M40 SFRC, flexural strength was 8.0 N/mm^2 at 0%, 8.79 N/mm^2 at 20%, 10.109 N/mm^2 at 40%, and 8.02 N/mm2 at 60%. These trends confirm the engineering role of fibers more clearly than the compressive strength results do. Flexural failure is crack-governed, and any material modification that improves crack arrest, bridging, or energy dissipation is more likely to appear strongly in the modulus of rupture than in compressive strength. This study therefore makes a defensible claim when it emphasizes that steel fiber reinforced concrete has superior resistance to cracking and a better post-failure response.

4.5 Split Tensile Strength

The conventional M30 series showed 28-day split tensile strength values of 2.02, 2.19, 2.4, 2.63, 2.87, 3.0, and 2.56 N/mm2 for 0%, 10%, 20%, 30%, 40%, 50%, and 60% copper slag, respectively. The conventional M40 series increased from 2.54 N/mm2 at 0% to 3.43 N/mm2 at 40%, before declining to 2.8 N/mm2 at 50%. The SFRC values were again substantially higher. For M30 SFRC, split tensile strength increased from 3.23 N/mm2 at 0% to 3.87 N/mm2 at 20%, reached 4.95 N/mm2 at 40%, and then reduced to 3.70 N/mm2 at 60%. For M40 SFRC, the values were 4.09, approximately 4.9, 5.43, and 5.02 N/mm2 at 0%, 20%, 40%, and 60% replacement, respectively. The highest values in both grades occurred at 40% copper slag replacement. These values again demonstrate that the major advantage of steel fibers lies in tensile-related response. Concrete is intrinsically weak in tension because microcracking begins at relatively low stress and the matrix lacks the ability to redistribute stress once a dominant crack forms. Steel fibers act as crack bridges and delay crack widening, which explains the consistently higher split tensile strengths in the SFRC mixes. The following peaks are especially noteworthy. In conventional M30 concrete, 50% copper slag produced the highest 28-day compressive strength of 47.85 MPa and the highest split tensile strength of 3.0 N/mm2, while flexural strength also peaked at 6.0 N/mm2 at 50%. In conventional M40 concrete, 40% copper slag yielded the highest 28-day compressive strength of 55.35 MPa, the highest split tensile strength of 3.43 N/mm2, and the highest flexural strength of 6.63 N/mm2. In the SFRC subsets that were reported, 40% copper slag yielded the highest 28-day compressive, flexural, and split tensile strengths in both M30 and M40 series. This study synthesizes these outcomes into a compact conclusion: the optimum strength for conventional M30 and M40 grade concrete occurred at 50% and 40% copper slag replacement, respectively, and steel fibers improved mechanical performance, especially in crack-sensitive properties.

Table 1. Summary of base mix design and principal material properties

Parameter	M30	M40	Remarks
Cement content (kg/m3)	390	420	OPC 53 grade
Water-cement ratio	0.45	0.43	IS 10262-based design
Fine aggregate (kg/m3)	582	569.5	Natural sand, Zone III
Coarse aggregate (kg/m3)	1298	1278	20 mm nominal max size
Water (kg/m3)	175.5	180.6	Potable water
Copper slag role	Partial replacement	Partial replacement	Lower absorption than sand
Steel fibers	Hooked-end, 1% addition	Hooked-end, 1% addition	Aspect ratio reported inconsistently as 50 or 60

Table 2. Slump values reported for conventional concrete and steel fiber reinforced concrete.

Mix designation	M30 conventional (mm)	M30 SFRC (mm)	M40 conventional (mm)	M40 SFRC (mm)
CS0	55	53	58	54
CS1	57	56	60	57
CS2	58	58	62	59
CS3	60	60	63	60
CS4	62	62	65	63
CS5	65	65	68	65
CS6	70	68	69	68

Table 3. Reported 28-day strength results for conventional concrete.

Copper slag replacement (%)	M30 compressive (MPa)	M30 flexural (N/mm^2)	M30 split tensile (N/mm^2)	M40 compressive (MPa)	M40 flexural (N/mm^2)	M40 split tensile (N/mm^2)
0	40.44	4.32	2.02	47.7825	4.9	2.54
10	44.74	4.73	2.19	49.404	5.4	2.70
20	45.08	4.90	2.40	50.094	5.6	2.86
30	45.48	5.33	2.63	52.8	5.9	3.00
40	47.41	5.72	2.87	55.35	6.63	3.43
50	47.85	6.0	3.0	52.2	5.42	2.8
60	46.07	5.63	2.56	-	-	-

Table 4. Reported 28-day strength results for steel fiber reinforced concrete.

Copper slag replacement (%)	M30 compressive (MPa)	M30 flexural (N/mm^2)	M30 split tensile (N/mm^2)	M40 compressive (MPa)	M40 flexural (N/mm^2)	M40 split tensile (N/mm^2)
0	47.032	6.93	3.23	55.12	8.0	4.09
20	53.0	7.3	3.87	58.3	8.79	4.9
40	55.56	7.9	4.95	61.82	10.109	5.43
60	52.29	6.73	3.70	57.93	8.02	5.02

5. DISCUSSION

5.1 Why Copper Slag Improved Strength up to an Optimum

This study interprets the beneficial effect of copper slag in terms of its low water absorption and its suitability as a partial replacement for fine aggregate. From a concrete technology perspective, the improvement up to an optimum replacement level can be understood through several interacting mechanisms. First, copper slag appears to have contributed to a denser particle system than the control fine aggregate at moderate replacement levels. A denser and somewhat coarser fine fraction can reduce internal voids, improve packing, and decrease the amount of weak paste-rich zones in the matrix. That can improve compressive strength and, indirectly, flexural and tensile performance as well. Second, because the copper slag absorbed less water than natural sand, more effective water remained available in the mix. At moderate replacement levels, that increase in free water likely improved workability enough to aid compaction without destabilizing the system. Better compaction means lower entrapped air, fewer internal discontinuities, and improved contact between paste and aggregate. The slump results are consistent with this explanation. Third, the greater density of copper slag may have contributed to a better aggregate skeleton when the replacement percentage remained within the optimum band. Denser fine aggregate can change the internal load-transfer pathway in a beneficial way, especially when the grading remains balanced. However, once the replacement exceeded the optimum level, the same low-absorption characteristic that initially helped workability may have become detrimental. This study explicitly states that higher replacement beyond the optimum causes increased workability and consequent strength reduction, attributing the latter to increased free water and internal void effects. In other words, the system seems to have crossed from improved packing and compaction into excessive fluidity and reduced matrix stability. That explanation is credible and consistent with the observed downturn at high replacement percentages.

5.2 Why the Optimum Differed Between M30 and M40

One of the more interesting results in the study is the difference in optimum copper slag replacement between the two conventional grades: 50% for M30 and 40% for M40. This is not an anomaly; it reflects the fact that concrete grade is not simply a compressive strength label but a combination of water-cement ratio, paste demand, aggregate proportions, and internal sensitivity. The M40 mix had a lower water-cement ratio and a different fine-to-coarse proportion than the M30 mix. Higher-strength mixes typically rely on tighter control of paste quality and internal volumetric balance. When a denser, lower-absorption replacement material such as copper slag is introduced into such a matrix, the margin for beneficial change may be narrower. A replacement level that still improves compaction and packing at M30 may begin to upset the water balance or fine aggregate behaviour in M40. The reported data fit that interpretation: M40 benefited significantly up to 40% but declined at 50%, whereas M30 continued to improve through 50% before reducing at 60%. This grade-dependent optimum is exactly the kind of result that practitioners need, because it warns against the simplistic transfer of a single replacement percentage from one mix class to another.

5.3 Role of Steel Fibers in Mechanical Performance

The data make it clear that steel fibers had their greatest effect on flexural and split tensile strength. This study reports broad increases of approximately 50% in flexural strength and 68% in split tensile strength for steel fiber reinforced concrete compared with conventional concrete. Even if those percentage values are treated as thesis-level summary figures rather than rigorously generalized universal values, the direction and magnitude of the improvement are fully consistent with the tabulated data.

Fibers function after crack initiation. Before cracking, the matrix and aggregate govern most of the response. After microcracks begin to form, however, the fibers bridge crack faces, redistribute stress, and delay localization. That mechanism is particularly important under flexural loading and split tension, where a single critical crack can control failure. The higher SFRC values observed in both M30 and M40 confirm that the fibers were effective in modifying crack behaviour. This study also records a qualitative observation during testing: plain cement concrete specimens showed a typical crack propagation pattern leading to splitting into two parts, whereas steel fiber addition caused the cracks to cease or become restrained, resulting in more ductile behaviour. This is not a trivial remark. In practical structural engineering, a shift from brittle splitting to more restrained crack development can influence serviceability, warning before failure, residual capacity, and impact resistance.

5.4 Interaction Between Copper Slag and Steel Fibers

The source data suggest that copper slag and steel fibers were complementary rather than antagonistic, provided the replacement level remained within the beneficial range. Copper slag improved matrix-level properties and workability up to a point, while steel fibers improved crack-bridging performance. The best SFRC results occurred at 40% copper slag in both M30 and M40 series. That may indicate that the optimum matrix condition for fiber effectiveness was achieved near this level, where workability remained sufficient for good dispersion and compaction without excessive free-water effects.

This is an important practical point. Fibers do not work well in a poorly compacted or segregated matrix. If the paste-aggregate system becomes unstable, the fibers cannot compensate for all internal defects. Therefore, the fact that the best SFRC results appeared near 40% copper slag supports the idea that moderate replacement created a favourable matrix for fiber engagement, whereas higher replacement began to erode that benefit.

5.5 Workability: Benefit and Constraint

The slump results show that copper slag increased workability and fibers slightly reduced it. This dual effect is not contradictory; it is a useful design lever. A replacement material that increases slump can partially offset the loss of workability caused by fibers. But This study also states, correctly, that increasing slump by adding extra water is not advisable and that plasticizers would be the proper route where further workability adjustment is required.

In a publication-quality interpretation, this point needs to be stated plainly: increased slump is not automatically equal to better concrete. The right question is whether workability is adequate for placement and compaction without encouraging segregation or bleeding. The data suggest that the mixes remained workable throughout the tested range, but the strength decline at higher replacement levels indicates that excessive free water or reduced internal stability became an issue. A future study should therefore include compaction factor, Vee-Bee time, or segregation assessment if the aim is to optimize field placement behaviour.

5.6 Limitations of the Source Study

A proper journal discussion must identify the limitations of the evidence base rather than presenting the thesis as more precise than it is. Several limitations are clear from the source document. First, the source report presents limited statistical treatment. Mean strengths are reported from multiple specimen tests, but variability measures such as standard deviation, coefficient of variation, or confidence bounds are not presented in the final results tables. This limits the strength of any claim about the significance of differences between nearby mixes. Second, the SFRC data are reported only for selected copper slag replacement levels rather than for the full 0–60% sequence used in conventional concrete. That reduces the resolution of the optimum search in the fiber-reinforced series. Third, the document contains a few internal inconsistencies in material description, most notably the fiber aspect ratio, which is reported both as 60 and as approximately 50 based on the dimensions listed. There are also some differences between earlier and later values for aggregate fineness parameters. These inconsistencies do not invalidate the entire experimental programme, but they do require caution when converting the work into a journal manuscript. Fourth, the study focuses only on strength and slump. No durability tests, microstructural observations, density measurements of hardened concrete, water absorption of concrete, shrinkage, or long-term deformation characteristics were reported as part of the final results. Yet the engineering relevance of copper slag extends beyond early strength. For publication in a higher-tier materials journal, durability and microstructural evidence would be expected. Fifth, the claim in the conclusion that steel fiber reinforced concrete had 7% higher compressive strength than conventional concrete is presented as a broad summary, but the detailed tables show that the actual improvement depends strongly on grade and replacement level. A stronger publication would present percentage comparisons mix by mix and distinguish between control-versus-control and optimum-versus-optimum comparisons.

5.7 Engineering Implications

Even with those limitations, the study has practical value. It shows that copper slag can be used as a meaningful partial replacement for fine aggregate in structural-grade concrete without sacrificing strength, provided the replacement is optimized. It also confirms that adding hooked-end steel fibers improves flexural and tensile-related properties and suppresses brittle crack behaviour. For practitioners, the message is straightforward. Copper slag should not be treated as a full or universal replacement for sand based only on the positive effect at moderate levels. Instead, trial mixes remain necessary. In the context of the present study, 40% replacement was a robust level for M40 and also the best tested level for the SFRC series, while M30 conventional concrete tolerated up to 50% before reaching its reported peak. That kind of mix-specific conclusion is much more useful than generic claims about “waste material utilization.” For researchers, the study suggests that the copper slag-fiber combination deserves broader evaluation under durability, shrinkage, permeability, abrasion, and impact loading, especially because the qualitative crack-control observations indicate good promise beyond compressive strength.

5.8 Publication Positioning of the Present Study

If this work is to be positioned for journal publication, it should not be oversold as a breakthrough in sustainable concrete materials. Similar studies already exist, and This study itself cites several of them. The defensible contribution is more specific: a comparative experimental assessment of conventional and steel fiber reinforced M30 and M40 concrete incorporating copper slag as partial fine aggregate replacement, with identification of optimum replacement levels and documentation of the associated trends in workability, compressive strength, flexural strength, and split tensile strength. That is a solid applied materials paper when written honestly. It becomes weak only when authors inflate novelty claims, ignore inconsistencies, or avoid discussing the limits of the dataset. The strongest version of this manuscript is the one that presents the evidence directly, explains the mechanisms carefully, and states exactly what the study does and does not establish.

6. CONCLUSIONS

Based strictly on the submitted thesis data and its reported interpretations, the following conclusions can be drawn. Copper slag is a feasible partial replacement for natural fine aggregate in both conventional concrete and steel fiber reinforced concrete. Its higher density and lower water absorption relative to natural sand altered the fresh and hardened performance of the mixes in a favourable way up to an optimum replacement level. Workability increased with increasing copper slag content in both M30 and M40 grades. In the conventional series, slump increased from 55 to 70 mm for M30 and from 58 to 69 mm for M40 over the replacement range studied. The corresponding SFRC series also showed increasing slump, although values remained slightly lower than those of the conventional mixes because of the restraining influence of steel fibers. For conventional concrete, the optimum copper slag replacement level was not the same for both grades. The M30 mixes reached maximum 28-day compressive strength at 50% replacement, where the reported strength was 47.85 MPa. The M40 mixes reached maximum 28-day compressive strength at 40% replacement, where the reported strength was 55.35 MPa. In the steel fiber reinforced subsets reported in the thesis, the best overall performance occurred at 40% copper slag replacement for both M30 and M40. The highest recorded 28-day compressive strengths were 55.56 MPa for M30 SFRC and 61.82 MPa for M40 SFRC at this replacement level. The addition of hooked-end steel fibers substantially improved tensile- and flexure-related properties. At 40% copper slag replacement, M30 SFRC achieved split tensile and flexural strengths of 4.95 N/mm2 and 7.9 N/mm2, respectively, while M40 SFRC achieved 5.43 N/mm2 and 10.109 N/mm2. These values were significantly higher than those of the corresponding conventional mixes. This study reports that steel fiber reinforced concrete exhibited about 7% higher compressive strength, 50% higher flexural strength, and 68% higher split tensile strength than conventional concrete. While those summary percentages should be interpreted alongside the detailed tables, the general conclusion is fully supported: steel fibers improved mechanical performance, especially for crack-sensitive properties. The qualitative behaviour of the specimens during testing is consistent with the numerical results. Plain concrete showed a typical crack propagation pattern leading to brittle splitting, whereas fiber-reinforced concrete showed restrained cracking and more ductile response. Copper slag replacement beyond the optimum range resulted in strength reduction. This study attributes this to increased workability, excess free water effects, and the resulting internal void structure. This explanation is credible and supported by the simultaneous increase in slump and decline in strength at higher replacement levels. The study supports the practical use of copper slag in structural concrete, but only under controlled mix proportioning. It does not support indiscriminate high-percentage replacement without trial optimization. Future work should extend the present investigation to durability, permeability, shrinkage, acid resistance, sulphate resistance, microstructural behaviour, and field-scale constructability. A more rigorous statistical treatment of replicate results would also strengthen the evidence base for publication. This study demonstrates that copper slag can be effectively incorporated as a partial fine aggregate replacement and that hooked-end steel fibers further enhance the mechanical performance of the resulting concrete. The best engineering outcome lies not in maximizing replacement blindly, but in identifying the replacement range that improves particle packing and workability without destabilizing the matrix. Within the limits of the submitted thesis, that range lies around 40–50% for the grades investigated.

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