Performance of High-Performance Concrete Incorporating Copper Slag as Partial Replacement of Fine Aggregate under Acid and Sulfate Attack

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Abstract - *The increasing depletion of natural river sand and the accumulation of industrial waste have encouraged the search for sustainable alternatives in concrete production. Copper slag, a by-product of the copper smelting industry, possesses suitable physical characteristics that make it a potential substitute for fine aggregate. This study investigates the mechanical and durability performance of M40 grade concrete incorporating copper slag as a partial replacement of river sand at levels of 0%, 10%, 20%, 30%, 40%, and 50%. Fresh properties were evaluated using slump tests, while hardened properties were assessed through density, water absorption, compressive strength, split tensile strength, and flexural strength tests. Durability was examined by exposing specimens to sulfuric acid and sodium sulfate solutions to determine weight loss and residual compressive strength. The results indicate that concrete containing copper slag exhibits enhanced performance up to an optimum replacement level of 30%. At this level, compressive strength increased by approximately 15%, water absorption decreased significantly, and resistance to acid and sulfate attack improved markedly compared with conventional concrete. Replacement levels beyond 40% caused a reduction in workability and a slight decline in strength due to excess free water and reduced bonding. The study demonstrates that copper slag can be effectively utilized as a sustainable fine aggregate replacement in structural concrete.*

Key Words*: *M40 Grade Concrete, Copper Slag, Fine Aggregate Replacement, Compressive Strength, Water Absorption, Acid Attack, Sulfate Attack, Durability.

1.INTRODUCTION

1.1 General

Concrete is the most widely used construction material in the world due to its high compressive strength, durability, versatility, and cost-effectiveness. It is extensively used in structural elements such as beams, columns, slabs, foundations, bridges, and pavements. The performance of concrete depends on the quality and proportion of its constituent materials, namely cement, fine aggregate, coarse aggregate, water, and chemical admixtures. Among these components, fine aggregate plays a significant role in determining the workability, strength, and durability of concrete. Traditionally, natural river sand has been used as fine aggregate in concrete. However, the growing demand for construction materials has resulted in excessive mining of river sand, leading to environmental problems such as riverbank erosion, lowering of groundwater levels, and destruction of aquatic ecosystems. Therefore, the development of sustainable alternatives to river sand has become an important area of research in concrete technology.

1.2 Need for Sustainable Construction Materials

The construction industry is one of the largest consumers of natural resources and a major contributor to environmental degradation. At the same time, many industrial processes generate large quantities of solid wastes that create disposal and environmental challenges. The utilization of industrial by-products in concrete offers a practical solution to both problems by reducing the consumption of natural resources and promoting sustainable waste management.

Using industrial waste materials as substitutes for conventional concrete ingredients can improve the sustainability of concrete production while also enhancing certain engineering properties. Materials such as fly ash, silica fume, GGBS, steel slag, waste glass powder, and copper slag have been successfully used in concrete applications.

1.3 Copper Slag as a Fine Aggregate Replacement

Copper slag is a by-product generated during the smelting and refining of copper. Approximately 2.2 to 3.0 tonnes of copper slag are produced for every tonne of copper manufactured. Due to the large quantity generated worldwide, disposal of copper slag poses significant environmental concerns.

Copper slag has physical properties that make it suitable as a replacement for fine aggregate in concrete. It consists of hard, angular, glassy particles with high specific gravity and very low water absorption. In addition, copper slag contains a substantial amount of silica and iron oxides, which contribute to its excellent mechanical characteristics.

When used in concrete, copper slag can improve particle packing, reduce voids, and enhance the density of the hardened matrix. These characteristics may lead to improved strength and durability compared to conventional concrete.

1.4 Effect of Copper Slag on Concrete Properties

Numerous studies have reported that partial replacement of river sand with copper slag can improve the mechanical and durability properties of concrete.

1.4.1 Workability

Due to its smooth surface texture and low water absorption, copper slag generally increases the workability of fresh concrete. Excessive replacement, however, may cause bleeding and segregation because of increased free water in the mix.

1.4.2 Mechanical Strength

Compressive strength, split tensile strength, and flexural strength typically increase up to an optimum replacement level of 20–30%. This improvement is attributed to better particle packing and stronger aggregate interlocking.

1.4.3 Durability

Copper slag reduces water absorption and permeability by producing a denser concrete matrix. As a result, concrete containing copper slag shows improved resistance to aggressive environmental conditions.

2. METHODOLOGY

2.1 Materials Used

2.1.1 Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used throughout the study. The cement was tested for standard consistency, initial and final setting time, fineness, and specific gravity in accordance with IS 4031 (Part 1 to Part 6). The results confirmed that the cement satisfied the requirements of the relevant Indian Standard specifications. The physical properties of cement are presented in Table 2.1.

Table - 2.1 Physical Properties of Cement

Test	Results
Standard consistency	30.12%
Initial setting time	49 min
Final setting time	420 min
Fineness	6.2%
Specific gravity	3.11

2.1.2 Fine Aggregate

Locally available natural river sand conforming to Zone II of IS 383:2016 was used as fine aggregate. The sand was clean, free from organic impurities, and well graded. Physical properties such as fineness modulus, water absorption, silt content, and specific gravity were determined according to IS 2386 (Part III). The test results are summarized in Table 2.2.

Table - 2.2 Properties of Fine Aggregate

Test	Results
Zone	II
Silt content	7.8%
Water absorption	0.50%
Fineness modulus	2.80
Specific gravity	2.65

2.1.3 Copper Slag

Copper slag obtained from a copper smelting industry was used as a partial replacement for natural fine aggregate. The material consisted of dark black, angular, glassy particles with a rough surface texture. Copper slag exhibited very low water absorption and higher specific gravity than river sand, making it suitable for use in concrete.

The physical and chemical properties of copper slag were determined before use. The specific gravity of copper slag was approximately 3.5, and water absorption was less than 0.3%. Its major chemical constituents included iron oxide (Fe_2O_3), silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO). The low porosity and angular particle shape of copper slag were expected to improve packing density and enhance the mechanical and durability properties of concrete.

2.1.4 Coarse Aggregate

Crushed granite coarse aggregate of nominal sizes 20 mm and 10 mm was used. The aggregates were proportioned to achieve continuous grading in accordance with IS 383:2016. The coarse aggregate had a specific gravity of 2.80 and water absorption of 0.61%.

2.1.5 Water

Potable water free from harmful amounts of oils, acids, alkalis, salts, and organic matter was used for both mixing and curing of concrete specimens.

2.1.6 Superplasticizer

A sulphonated naphthalene-based superplasticizer, SP-430, conforming to IS 9103:1999, was used as a water-reducing admixture to maintain the required workability. The dosage was maintained at 1.0% by weight of cement. The specific gravity of the superplasticizer was 1.10.

2.2 Mix Proportion

The mix design for M40 grade concrete was carried out according to IS 10262:2019, targeting a slump of 75–100 mm. Natural River sand was partially replaced with copper slag at six levels: 0%, 10%, 20%, 30%, 40%, and 50% by weight of fine aggregate.

The concrete mixes were designated as CS0, CS10, CS20, CS30, CS40, and CS50, where the number indicates the percentage replacement of fine aggregate by copper slag.

Based on previous studies, the optimum replacement level was expected to be around 30%.

Table 2.3 Mix Proportion Used in the Study

Materials	Quantity (kg/m^3)
Cement	400
Fine aggregate (sand + copper slag)	650
Coarse aggregate	1180
Water	160
Water–cement ratio	0.40
Superplasticizer	4.0 (1% of cement)
Copper slag	0–50% replacement of fine aggregate

2.2.1 Mix Designations

Mix ID	Copper Slag Replacement (%)
CS0	0
CS10	10
CS20	20
CS30	30
CS40	40
CS50	50

2.3 Mixing Procedure

The concrete mixes were prepared in a laboratory tilting drum mixer with a capacity of 100 L. For each mix, natural river sand was partially replaced with copper slag at the specified proportions of 0%, 10%, 20%, 30%, 40%, and 50% by weight of fine aggregate. To ensure uniform distribution of materials and consistent concrete quality, the following mixing procedure was adopted:

1. Cement, natural sand, copper slag, and coarse aggregates were dry mixed for approximately 1 minute to obtain a homogeneous blend.
2. About 70% of the total mixing water was added gradually and the materials were mixed for 2 minutes.
3. The superplasticizer was dissolved in the remaining water and added to the mixer.
4. Mixing was continued for an additional 3 minutes until a uniform and workable concrete mix was obtained.
5. The fresh concrete was immediately tested for slump to assess workability before casting.

This procedure ensured proper dispersion of copper slag within the concrete matrix and minimized segregation.

2.4 Casting and Curing

After completion of the mixing process, the fresh concrete was placed into standard steel molds in three layers. Each layer was compacted using a table vibrator to eliminate entrapped air and ensure full compaction.

The following specimens were prepared for testing:

1. **Compressive strength:** Cubes of size 150 mm × 150 mm × 150 mm.
2. **Split tensile strength:** Cylinders of 100 mm diameter × 200 mm height.
3. **Flexural strength:** Beams of size 150 mm × 150 mm × 700 mm.
4. **Water absorption and density:** Cube specimens.
5. **Chemical attack tests:** Additional cube specimens for acid and sulphate exposure.

Fig: 1 Casting and Curing

After casting, the specimens were covered with plastic sheets to prevent moisture loss and kept undisturbed for 24 hours at room temperature. The specimens were then demoulded and cured in clean water at 27 ± 2°C until the designated testing ages of 7, 14, and 28 days.

For chemical durability studies, 28-day water-cured specimens were immersed in:

- 5% sulfuric acid (H_2SO_4) solution for acid attack, and
- 5% sodium sulfate (Na_2SO_4) solution for sulfate attack.

The specimens were exposed for 28 days, after which weight loss and residual compressive strength were determined.

2.5 Tests Performed

To evaluate the fresh, physical, mechanical, and durability properties of M40 grade concrete incorporating copper slag as a partial replacement for fine aggregate, a comprehensive experimental program was conducted. The tests performed and the corresponding Indian Standard codes are summarized in Table 2.4.

Table 2.4 Tests Performed

Test	Standard	Description
Slump test	IS 1199:2018	To determine workability of fresh concrete
Density test	IS 516 (Part 2):2018	To measure unit weight of hardened concrete
Water absorption	IS 2386 (Part 3):1963	To assess porosity and permeability
Compressive strength	IS 516 (Part 1/Sec 1):2021	150 mm cube specimens
Split tensile strength	IS 5816:1999	100 mm × 200 mm cylinders
Flexural strength	IS 516 (Part 1/Sec 4):2018	150 mm × 150 mm × 700 mm beams
Acid attack test	ASTM C267 / adapted procedure	To determine weight loss and residual strength after H_2SO_4 exposure
Sulphate attack test	ASTM C1012 / adapted procedure	To determine weight loss and residual strength after Na_2SO_4 exposure

The results obtained from these tests were analyzed to determine the optimum copper slag replacement level and to evaluate its influence on the strength and durability performance of M40 grade concrete.

3. RESULTS AND DISCUSSION

3.1 Slump Test

Table 5 presents the slump values of M40 grade concrete containing different percentages of copper slag as a partial replacement for natural fine aggregate. The results indicate that the workability of concrete increased progressively with increasing copper slag content, as illustrated in Fig. 1.

This improvement in slump is primarily attributed to the very low water absorption and smooth glassy surface texture of copper slag particles. Unlike natural river sand, copper slag absorbs minimal mixing water, resulting in a higher amount of free water available in the concrete mix. Consequently, the concrete becomes more fluid and exhibits improved workability.

The control mix (CS0) showed a slump of 78 mm, while the slump increased to 84 mm, 92 mm, 101 mm, 108 mm, and 115 mm for mixes CS10, CS20, CS30, CS40, and CS50, respectively. The maximum increase in workability was observed at 50% replacement, representing an increase of approximately 47.4% compared to the control mix.

Although higher copper slag contents improved workability, replacement levels above 40% resulted in excessive fluidity and slight bleeding, which may adversely affect strength and durability. Therefore, moderate replacement levels between 20% and 30% were found to provide satisfactory workability without segregation.

Table 3.1: Slump Values of Different Concrete Mixes

Mix	Copper Slag (%)	Slump (mm)
CS0	0	78
CS10	10	84
CS20	20	92
CS30	30	101
CS40	40	108
CS50	50	115

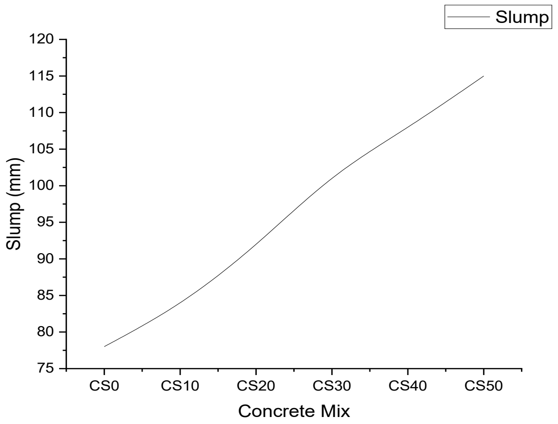

Chart -1:Slump Graph

3.2 Density Test

The density of hardened concrete increased with the incorporation of copper slag up to an optimum replacement level, as shown in Fig. 2. This increase is mainly due to the higher specific gravity of copper slag (approximately 3.5) compared with natural river sand (2.65).
The control mix exhibited a density of 2420 kg/m^3, which increased to 2438 kg/m^3, 2455 kg/m^3, 2472 kg/m^3, 2468 kg/m^3, and 2459 kg/m^3 for CS10, CS20, CS30, CS40, and CS50, respectively. The maximum density was observed at

30% copper slag replacement, representing an increase of approximately 2.15%.

The higher density indicates improved packing of aggregate particles and reduced internal voids. Beyond 30–40% replacement, the increase in density became marginal, and a slight reduction was observed due to bleeding and non-uniform particle distribution.

Table 3.2: Density of Hardened Concrete

Mix	Copper Slag (%)	Density (kg/m^3)
CS0	0	2420
CS10	10	2438
CS20	20	2455
CS30	30	2472
CS40	40	2468
CS50	50	2459

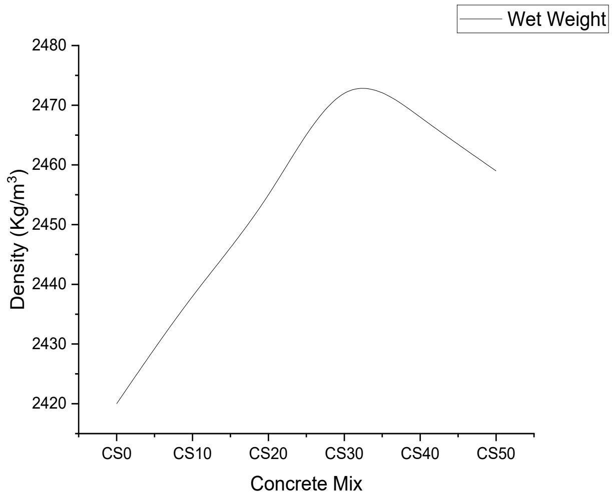

Chart -2: Density Graph

3.3 Water Absorption Test

The water absorption results are shown in Fig. 3. A continuous reduction in water absorption was observed as copper slag content increased up to 30%, indicating improved impermeability and reduced porosity.

The water absorption decreased from 2.45% for the control mix to 2.18%, 1.95%, and 1.72% for CS10, CS20, and CS30, respectively. This corresponds to a reduction of approximately 29.8% at 30% replacement.

The reduction is attributed to improved particle packing and the dense microstructure developed due to the angular and non-porous nature of copper slag particles. At replacement levels above 30%, water absorption increased slightly because excess free water caused minor bleeding and pore formation.

Table 3.3: Water Absorption of Different Concrete Mixes

Mix	Copper Slag (%)	Water Absorption (%)
CS0	0	2.45
CS10	10	2.18
CS20	20	1.95
CS30	30	1.72
CS40	40	1.80
CS50	50	2.02

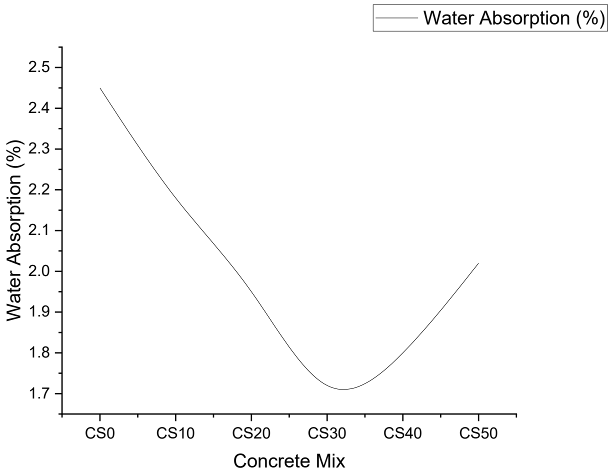

Chart -3: Water Absorption Graph

3.4 Compressive Strength Test

Table 8 presents the compressive strength results at 7, 14, and 28 days. Concrete containing copper slag showed a significant improvement in compressive strength compared with the control mix.

At 28 days, the compressive strength increased from 46.0 MPa for the control mix to 48.5 MPa, 50.2 MPa, and 52.8 MPa for CS10, CS20, and CS30, respectively. The maximum strength at 30% replacement was approximately 14.8% higher than the control mix.

The improvement in compressive strength is attributed to better particle packing, enhanced aggregate interlocking, and reduced porosity. Copper slag particles are angular and dense, which strengthens the interfacial transition zone between the aggregate and cement paste.

At 40% and 50% replacement, compressive strength decreased slightly, although values remained higher than the control mix. This decline is associated with excess free water and reduced cohesion at higher copper slag contents.

Table 3.4: Compressive Strength of Different Concrete Mixes

Mix	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
CS0	30.5	39.8	46.0
CS10	33.0	42.5	48.5
CS20	35.4	44.8	50.2
CS30	37.2	47.0	52.8
CS40	36.0	45.9	51.0
CS50	34.5	44.0	48.0

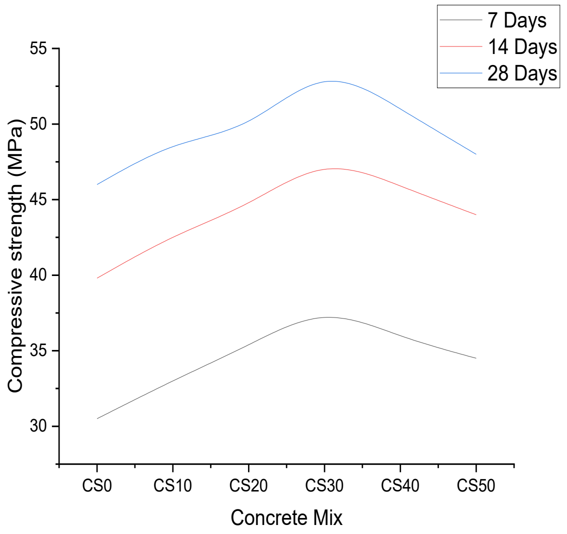

Chart -4: Compressive Strength Graph

3.5 Split Tensile Strength Test

The split tensile strength results followed a trend similar to compressive strength. The 28-day split tensile strength increased from 3.95 MPa for the control mix to 4.18 MPa, 4.42 MPa, and 4.68 MPa for CS10, CS20, and CS30, respectively.

The highest value at 30% replacement represented an increase of approximately 18.5%. This enhancement is due to the improved bond between the cement paste and copper slag particles, resulting in better crack resistance and stress transfer.

Table 3.5: Split Tensile Strength of Different Concrete

Mix	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
CS0	2.80	3.35	3.95
CS10	3.05	3.58	4.18
CS20	3.18	3.78	4.42
CS30	3.35	4.02	4.68
CS40	3.26	3.90	4.55
CS50	3.10	3.70	4.20

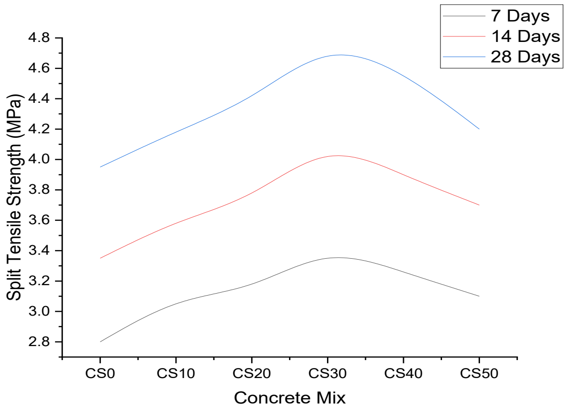

Chart -5: Split Tensile Strength Graph

3.6 Flexural Strength Test

The flexural strength results at 28 days are presented in Table 10. Like compressive and tensile strength, flexural strength improved with copper slag replacement up to 30%. The control mix exhibited a flexural strength of 5.10 MPa, which increased to 5.35 MPa, 5.68 MPa, and 5.96 MPa for CS10, CS20, and CS30, respectively. The increase at 30% replacement was approximately 16.9%.

The improvement is attributed to the denser matrix and stronger aggregate–paste bond, which enhanced crack resistance and load transfer capacity.

Table 3.6: Flexural Strength of Different Concrete Mixes at 28 Days

Mix	Copper Slag (%)	Flexural Strength (MPa)
CS0	**0**	**5.10**
CS10	**10**	**5.35**
CS20	**20**	**5.68**
CS30	**30**	**5.96**
CS40	**40**	**5.82**
CS50	**50**	**5.45**

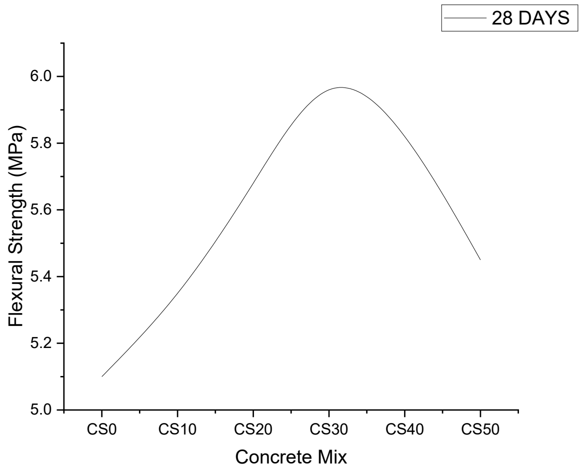

Chart -6: Flexural Strength Graph

3.7 Acid Attack Test

The resistance of concrete to acidic environments was evaluated by immersing 28-day water-cured cube specimens in a 5% sulfuric acid (H_2SO_4) solution for 28 days. After exposure, the specimens were removed, washed with clean water, surface dried, and tested for percentage weight loss and residual compressive strength.

The results indicated that concrete containing copper slag exhibited significantly better resistance to acid attack compared with the control mix. The control concrete (CS0) showed severe surface deterioration, including softening, edge rounding, and slight scaling. In contrast, specimens containing copper slag remained comparatively intact, with less visible damage.

The percentage weight loss decreased from 6.4% for the control mix to 5.6%, 4.7%, and 3.5% for CS10, CS20, and CS30, respectively. This represents a reduction in weight loss of approximately 45% at 30% copper slag replacement. Similarly, the residual compressive strength increased with increasing copper slag content up to 30%.

The improved acid resistance is attributed to the denser concrete matrix and lower permeability resulting from the incorporation of copper slag. The angular and non-porous particles improved packing density and reduced the ingress of acidic ions. As a result, the dissolution of calcium hydroxide and decalcification of the cement matrix were minimized.

At replacement levels above 30%, a slight increase in weight loss and strength reduction was observed. This may be due to increased bleeding and the formation of weak zones caused by excess free water.

Overall, the results demonstrate that copper slag significantly enhances the resistance of concrete to sulfuric acid attack, with the optimum performance observed at 30% replacement of fine aggregate.

Table 3.7: Acid Attack Results after 28 Days Exposure to 5% H_2SO_4

Mix	Copper Slag (%)	Weight Loss (%)	Residual Compressive Strength (MPa)	Strength Loss (%)
CS0	0	6.40	38.6	16.1
CS10	10	5.60	42.0	13.4
CS20	20	4.70	45.4	9.6
CS30	30	3.50	48.8	7.6
CS40	40	3.90	46.6	8.6
CS50	50	4.80	43.2	10.0

3.8 Sulfate Attack Test

To assess sulfate resistance, 28-day water-cured cube specimens were immersed in a 5% sodium sulfate (Na_2SO_4) solution for an additional 28 days. After exposure, the specimens were evaluated for weight loss and residual compressive strength.

Concrete incorporating copper slag showed improved resistance to sulfate attack compared to conventional concrete. The control mix exhibited minor surface cracking and a weight loss of 3.1%, while the CS30 mix showed only 1.5% weight loss and negligible visible deterioration.

The residual compressive strength of the CS30 mix was 50.9 MPa, which was significantly higher than the control mix. The superior sulfate resistance is attributed to reduced permeability and a denser microstructure that limited sulfate ion penetration and minimized the formation of expansive products such as gypsum and ettringite.

Table 8: Sulfate Attack Results after 28 Days Exposure to 5% Na_2SO_4

Mix	Copper Slag (%)	Weight Loss (%)	Residual Compressive Strength (MPa)	Strength Loss (%)
CS0	0	3.10	42.5	7.6
CS10	10	2.60	45.8	5.6
CS20	20	2.00	48.5	3.4
CS30	30	1.50	50.9	3.6
CS40	40	1.70	49.0	3.9
CS50	50	2.30	45.9	4.4

4. CONCLUSION

This study investigated the effect of partially replacing natural fine aggregate with copper slag in M40 grade concrete. Copper slag was used at replacement levels of 0%, 10%, 20%, 30%, 40%, and 50% by weight of fine aggregate. The performance of concrete was evaluated in terms of workability, density, water absorption, compressive strength, split tensile strength, flexural strength, and resistance to acid and sulfate attack. Based on the experimental results, the following conclusions are drawn:

1. **Workability increased with increasing copper slag content.**
   The slump value increased progressively as the percentage of copper slag increased due to its very low water absorption and smooth glassy surface texture. These characteristics reduced the water demand of the concrete mix and increased the amount of free water available. However, at replacement levels above 40%, excessive workability and slight bleeding were observed.
2. **The density of hardened concrete increased with copper slag incorporation.**
   The higher specific gravity of copper slag compared with natural sand resulted in a gradual increase in density. The maximum density was observed at 30% copper slag replacement, indicating improved particle packing and a more compact concrete matrix.
3. **Water absorption decreased significantly up to the optimum replacement level.**
   The incorporation of copper slag reduced water absorption due to improved packing density and reduced porosity. The lowest water absorption was recorded for the mix containing 30% copper slag, confirming the formation of a denser and less permeable microstructure.
4. **Mechanical properties improved substantially with moderate copper slag replacement.**
   Compressive strength, split tensile strength, and flexural strength increased with increasing copper slag content up to 30%. This enhancement is attributed to the angular shape, high density, and better interlocking characteristics of copper slag particles, which improved the interfacial transition zone (ITZ) and reduced internal voids.
5. **The optimum copper slag replacement level was found to be 30%.**
   At this replacement level, the concrete exhibited the highest compressive strength, split tensile strength, and flexural strength, along with the lowest water absorption and best overall durability performance.
6. **Concrete containing copper slag showed superior resistance to acid attack.**
   Specimens immersed in 5% sulfuric acid solution exhibited lower weight loss and higher residual compressive strength compared with conventional concrete. The best performance was observed at 30% copper slag replacement due to reduced permeability and a denser matrix.
7. **Sulfate resistance improved significantly with copper slag addition.**
   Exposure to 5% sodium sulfate solution resulted in lower deterioration and smaller strength losses in copper slag concrete. Reduced pore connectivity limited sulfate ion ingress and minimized the formation of expansive products such as gypsum and ettringite.
8. **Performance declined slightly at higher replacement levels.**
   Although concrete containing 40% and 50% copper slag still performed satisfactorily, a slight reduction in strength and durability was observed due to excess free water, bleeding, and weaker paste cohesion.
9. **Copper slag is a sustainable alternative to natural river sand.**
   The use of copper slag reduces the consumption of natural fine aggregate and provides an effective method for utilizing an industrial by-product, thereby minimizing environmental impact and promoting sustainable construction practices.

Overall Conclusion

The experimental investigation demonstrates that copper slag can be effectively used as a partial replacement for natural fine aggregate in M40 grade concrete. Among all mixes, the concrete containing **30% copper slag** exhibited the best overall performance, with improved workability, higher mechanical strength, lower water absorption, and superior resistance to acid and sulfate attack. Therefore, replacing 30% of river sand with copper slag is recommended for producing durable, high-performance, and environmentally sustainable concrete suitable for structural applications exposed to aggressive environments.

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