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Original Research Paper

Sustainable Utilization Of Copper Slag, Iron Slag And Recycled Concrete Aggregate For High-Performance And Durable Concrete

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Abstract

The increasing demand for infrastructure has intensified the consumption of natural aggregates and the disposal burden of industrial and construction wastes. This study investigates the combined use of copper slag (CS), iron slag (IS), and recycled concrete aggregate (RCA) as sustainable replacements for conventional aggregates in M30 concrete. Twenty-eight concrete mixes, including a control mix, were prepared by varying CS and IS at 30%, 40%, and 50% as fine aggregate replacements and RCA at 20%, 25%, and 30% as coarse aggregate replacement. Mechanical performance was evaluated using compressive, flexural, and split tensile strength tests at 28 days, while durability was assessed through rapid chloride permeability test (RCPT), half-cell potential measurement, and accelerated corrosion/gravimetric weight loss evaluation. The optimum mix, M14, containing 40% CS, 40% IS, and 25% RCA, achieved compressive, flexural, and split tensile strengths of 34.0 N/mm², 6.9 N/mm², and 3.80 N/mm², respectively. Compared with the control concrete, these values represent improvements of 17.24%, 25.45%, and 9.51%, respectively. M14 also recorded the lowest reported RCPT charge passed of 392.36 C and the lowest corrosion rate of 5.38 mpy, confirming improved resistance to chloride ingress and steel reinforcement corrosion. The results demonstrate that the balanced incorporation of CS, IS, and RCA improves particle packing, matrix densification, interfacial bonding, and durability, while reducing natural resource consumption and industrial waste disposal. The proposed mix therefore offers a technically feasible and environmentally beneficial approach for sustainable concrete production.

Keywords: Sustainable concrete; copper slag; iron slag; recycled concrete aggregate; chloride permeability; corrosion resistance; industrial waste utilization.

1. Introduction

Concrete is the most widely used construction material in infrastructure development; however, its production consumes large quantities of natural sand, coarse aggregates, water, and cementitious resources. Rapid urbanization and industrialization have increased the demand for concrete and, at the same time, generated large volumes of industrial and construction waste. The continuous extraction of river sand and natural aggregates leads to resource depletion, ecological imbalance, and increased transportation-related emissions. Therefore, the development of concrete using alternative waste-derived materials has become an important strategy for sustainable construction.

Industrial by-products such as copper slag and iron slag are generated in large quantities by metallurgical industries. These materials are often disposed of in landfills despite possessing physical characteristics suitable for use in concrete. Copper slag is a glassy, dense and granular by-product obtained during copper smelting, while iron slag is produced during iron and steel manufacturing. Both materials can act as fillers or fine aggregate replacements and may improve concrete density, packing, and strength when used at appropriate levels. Similarly, recycled concrete aggregate obtained from construction and demolition waste can partially replace natural coarse aggregates, thereby conserving virgin aggregates and reducing landfill pressure.

Although previous studies have investigated individual use of copper slag, iron slag, or RCA in concrete, limited work has examined their combined influence on both mechanical and durability performance. The simultaneous incorporation of CS, IS and RCA may produce synergistic effects through improved particle packing and denser interfacial transition zones. However, excessive replacement may increase porosity, reduce cohesion, and weaken aggregate-matrix bonding. Hence, identifying an optimum combination is essential for developing high-performance and durable sustainable concrete.

The present study experimentally evaluates the combined utilization of CS, IS, and RCA in M30-grade concrete. The investigation focuses on compressive strength, flexural strength, split tensile strength, chloride permeability, corrosion resistance, and gravimetric weight loss. The study aims to establish an optimum replacement combination that improves performance while promoting resource conservation, industrial waste valorization, and sustainable construction practices.

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2. Literature Review and Research Gap

The use of industrial by-products in concrete has received significant attention because of its potential to reduce embodied carbon, conserve natural aggregates, and improve long-term durability. Copper slag has been widely studied as a replacement for natural sand. Previous investigations have reported that moderate replacement levels can improve workability, density, compressive strength, flexural strength, and split tensile strength due to the angularity, hardness, and filler effect of copper slag particles. However, excessive copper slag content may reduce cohesion and cause bleeding or segregation, particularly when the water-cement ratio is not properly controlled.

Iron slag and blast-furnace-derived slags have also shown promise in concrete production. Their cementitious and pozzolanic characteristics can contribute to matrix densification and improved durability. Iron slag can enhance particle packing and reduce capillary porosity when used in suitable proportions. However, high replacement levels may affect setting, density, and interfacial bonding if the slag grading and surface texture are not properly considered.

Recycled concrete aggregate is a major component of construction and demolition waste. Its reuse in concrete supports circular construction by reducing natural aggregate consumption and landfill disposal. RCA typically contains attached mortar and has higher water absorption than natural aggregate, which may reduce workability and strength at high replacement levels. Nevertheless, moderate RCA replacement can provide acceptable mechanical performance, especially when combined with dense fine aggregate replacements or industrial by-products.

The major research gap identified from previous studies is that most investigations focus on single-waste replacement systems. Limited experimental evidence is available on the combined use of copper slag, iron slag, and RCA in concrete, particularly with respect to both mechanical strength and corrosion-related durability indicators. The present work addresses this gap by evaluating a systematic combination of CS, IS, and RCA replacement levels and identifying the optimum sustainable concrete mix.

3. Materials and Methods

3.1 Materials

Ordinary Portland Cement of 53 grade was used as the primary binder. Natural fine aggregate and natural coarse aggregate were used in the control mix, while copper slag and iron slag were used as partial replacements for fine aggregate and recycled concrete aggregate was used as partial replacement for coarse aggregate. The physical properties of aggregates and waste materials were determined in accordance with IS 2386 provisions. The materials used in the study are summarized below.

Table 1. Materials and characterization details required for reproducibility

Material	Role in mix	Important properties to report	Test standard / remarks
OPC 53 grade cement	Primary binder	Specific gravity, fineness, consistency, setting time, strength class	IS 12269 / relevant cement test standards
Natural fine aggregate	Reference fine aggregate	Specific gravity, fineness modulus, grading zone, water absorption	IS 383 and IS 2386
Natural coarse aggregate	Reference coarse aggregate	Nominal size, specific gravity, impact/crushing value, water absorption	IS 383 and IS 2386
Copper slag	Fine aggregate replacement at 30%, 40%, 50%	Specific gravity, bulk density, water absorption, particle shape, chemical composition	Industrial by-product; laboratory values should be reported
Iron slag	Fine aggregate replacement at 30%, 40%, 50%	Specific gravity, bulk density, water absorption, grading, chemical composition	Industrial by-product; laboratory values should be reported
Recycled concrete aggregate	Coarse aggregate replacement at 20%, 25%, 30%	Specific gravity, water absorption, attached mortar content, grading, crushing value	Processed construction and demolition waste

3.2 Mix Proportioning

M30-grade concrete was designed with a water-cement ratio of 0.45. Copper slag and iron slag were used as fine aggregate replacements at 30%, 40%, and 50%, while RCA was used as coarse aggregate replacement at 20%, 25%, and 30%. A total of 27 waste-modified mixes and one control mix were considered. The control mix was designated as M28. The corrected mix designation matrix is presented in Table 2.

Table 2. Corrected mix designation matrix for CS, IS and RCA combinations

Mix No.	RCA (%)	Iron slag (%)	Copper slag (%)
1	20	30	30
2	25	30	30
3	30	30	30
4	20	40	30
5	25	40	30
6	30	40	30
7	20	50	30
8	25	50	30
9	30	50	30
10	20	30	40
11	25	30	40
12	30	30	40
13	20	40	40
14	25	40	40
15	30	40	40
16	20	50	40
17	25	50	40
18	30	50	40
19	20	30	50
20	25	30	50
21	30	30	50
22	20	40	50
23	25	40	50
24	30	40	50
25	20	50	50
26	25	50	50
27	30	50	50
28	0	0	0

3.3 Casting and Curing

Concrete was mixed in a laboratory mixer to ensure uniform distribution of cement, aggregates and replacement materials. Immediately after mixing, the fresh concrete was placed in standard moulds and compacted to minimize entrapped air. Cubes were cast for compressive strength, prisms for flexural strength, and cylinders for split tensile strength. For each mix and test, replicate specimens were prepared, and average test values were reported. The specimens were demoulded after 24 hours and cured in clean water at room temperature for 28 days before testing.

3.4 Mechanical Testing

Compressive strength was determined using standard cube specimens in a compression testing machine of 2000 kN capacity in accordance with IS 516. Flexural strength was evaluated on prism specimens using a 1000 kN flexural testing machine under two-point loading, with the loading rate maintained at approximately 1.4 kN/min. Split tensile strength was determined using cylindrical specimens under diametral compression. All mechanical properties were evaluated at 28 days to compare the effect of different CS, IS and RCA replacement combinations.

3.5 Durability and Corrosion Resistance Testing

Durability performance was evaluated using rapid chloride permeability, half-cell potential and accelerated corrosion/gravimetric weight loss tests. In the RCPT, disc specimens of 100 mm diameter and 50 mm thickness were subjected to a 60 V DC potential for six hours, and the charge passed in coulombs was recorded. The test was used to evaluate resistance to chloride ion penetration. Half-cell potential measurements were carried out according to ASTM C876 principles using a copper/copper sulphate reference electrode to assess the electrochemical corrosion tendency of embedded steel. Readings were recorded at regular intervals up to 600 hours. In the accelerated corrosion and gravimetric weight loss method, reinforced specimens were exposed to chloride solution under an impressed voltage condition, and the corrosion rate was determined from the initial and final steel weights. These durability tests were used to compare the corrosion resistance of the different concrete mixes.

4. Results and Discussion

4.1 Mechanical Strength Results

The 28-day mechanical strength results for all mixes are presented in Table 3. The control mix M28 showed compressive, flexural, and split tensile strengths of 29.0 N/mm², 5.5 N/mm², and 3.47 N/mm², respectively. The optimum mix M14, containing 40% CS, 40% IS, and 25% RCA, achieved the highest compressive strength of 34.0 N/mm², flexural strength of 6.9 N/mm², and split tensile strength of 3.80 N/mm². This corresponds to improvements of 17.24%, 25.45%, and 9.51%, respectively, compared with the control mix.

Table 3. Mechanical strength results of concrete mixes at 28 days

Mix No.	Compressive strength (N/mm²)	Flexural strength (N/mm²)	Split tensile strength (N/mm²)
1	23	3.5	3.0
2	23	3.7	3.05
3	24	3.6	3.02
4	25	4.2	3.16
5	25	4.1	3.14
6	25	4.6	3.26
7	27.5	4.7	3.28
8	27.5	4.9	3.33
9	27.5	4.8	3.31
10	28	5.2	3.4
11	28	5.5	3.47
12	27	4.9	3.33
13	33	6.8	3.78
14	34	6.9	3.8
15	33.5	6.8	3.78
16	32	6.7	3.75
17	32	6.6	3.73
18	31.5	6.5	3.71
19	31	6.1	3.61
20	30.5	6.2	3.64
21	30	6.2	3.64
22	30	6.0	3.59
23	29	5.6	3.49
24	28	5.6	3.49
25	27.5	4.9	3.33

26	26	4.6	3.26
27	25.5	4.5	3.24
28	29	5.5	3.47

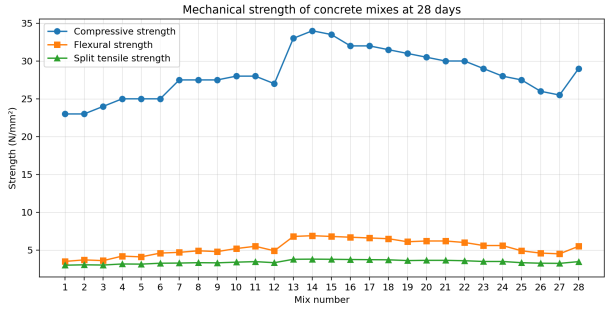


Figure 1. Variation of compressive, flexural and split tensile strengths for different concrete mixes.

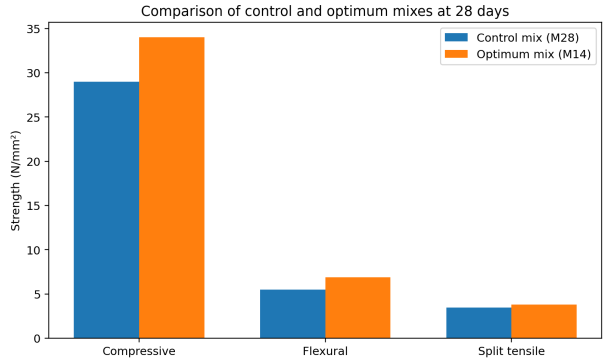


Figure 2. Comparison of control mix M28 and optimum mix M14.

The strength improvement in M14 can be attributed to the combined filler and packing effects of copper slag and iron slag, which reduce voids and produce a denser matrix. Copper slag contributes hardness and angularity, while iron slag improves packing and may enhance the interfacial transition zone. RCA at 25% replacement appears to provide a balanced contribution without introducing excessive porosity associated with higher recycled aggregate contents. At replacement levels beyond the optimum, strength decreased because excessive waste replacement can reduce cohesion, increase internal voids, and weaken bonding between aggregate particles and the cement paste.

4.2 Rapid Chloride Permeability

The RCPT results indicated low chloride ion penetration for the tested mixes. The optimum M14 mix recorded the lowest reported charge passed of 392.36 C, confirming improved resistance to chloride ingress. The highest reported charge passed was 480.65 C for M27. Thus, the M14 mix showed approximately 18.36% lower charge passed than the poorest-performing mix. The reduced permeability may be explained by matrix densification, better packing of fine particles, and a refined pore structure produced by the balanced combination of CS, IS and RCA. Lower chloride permeability is important because chloride ingress is one of the major causes of reinforcement corrosion in concrete structures exposed to aggressive environments.

4.3 Half-Cell Potential and Corrosion Resistance

Half-cell potential measurements were used to compare the corrosion tendency of embedded reinforcement in different concrete mixes under accelerated exposure. The M14 mix showed a comparatively less severe corrosion potential of about -789 mV after 600 hours, whereas M23 showed a more negative potential of about -932 mV and the reference mix was reported around -917 mV in the original data. Under the specific accelerated test configuration, this indicates that M14 had lower corrosion tendency than mixes with excessive replacement levels. The results support the conclusion that a balanced mix proportion enhances corrosion resistance, whereas high replacement percentages may increase porosity and reduce the protective quality of the concrete cover.

4.4 Gravimetric Weight Loss

The gravimetric weight loss test further confirmed the durability advantage of the optimum mix. Among the investigated mixes, M14 exhibited the lowest reported corrosion rate of 5.38 mpy. The reduction in corrosion rate is consistent with the RCPT findings and indicates that the denser microstructure of M14 restricts the movement of chloride ions, moisture, and oxygen toward the embedded steel. The combined results of RCPT, half-cell potential and gravimetric weight loss show that M14 provides the most favorable balance between mechanical strength and corrosion resistance.

4.5 Overall Performance of the Optimum Mix

The combined performance evaluation confirms that M14 is the optimum concrete mix among all 28 investigated combinations. This mix contains 40% copper slag, 40% iron slag and 25% RCA. It provides the highest compressive, flexural and split tensile strengths, and also shows superior chloride permeability and corrosion resistance behavior. The improvement is not due to any single material alone, but to the balanced interaction among the dense slag particles, recycled aggregate content and cement paste. This demonstrates that industrial by-products and recycled aggregates can be used effectively in sustainable concrete when their proportions are carefully optimized.

5. Conclusions

This study examined the combined use of copper slag, iron slag and recycled concrete aggregate in M30-grade concrete. Based on the experimental results, the following conclusions are drawn:

- The combined replacement of fine and coarse aggregates using CS, IS and RCA can improve the mechanical and durability performance of concrete when used within optimum limits.
- The optimum mix was M14, containing 40% copper slag, 40% iron slag and 25% recycled concrete aggregate.
- M14 achieved compressive, flexural and split tensile strengths of 34.0 N/mm², 6.9 N/mm² and 3.80 N/mm², respectively.
- Compared with the control mix M28, M14 improved compressive strength by 17.24%, flexural strength by 25.45% and split tensile strength by 9.51%.

- The M14 mix recorded the lowest reported RCPT value of 392.36 C and the lowest corrosion rate of 5.38 mpy, indicating improved resistance to chloride penetration and reinforcement corrosion.
- The superior performance of M14 is attributed to improved particle packing, matrix densification, enhanced interfacial bonding and reduced permeability.
- Excessive replacement levels beyond the optimum reduced performance due to increased porosity, lower cohesion and weaker aggregate-paste bonding.
- The use of CS, IS and RCA contributes to sustainable construction by reducing natural aggregate consumption, diverting industrial and construction waste from landfills, and promoting circular resource utilization.

6. Future Scope

Future research should include long-term durability testing under sulphate, chloride, carbonation, wetting-drying and freeze-thaw exposure conditions. Microstructural investigations such as SEM, XRD, FTIR and mercury intrusion porosimetry can be used to confirm matrix densification and interfacial transition zone improvements. Field-scale trials, life-cycle assessment, cost analysis and carbon footprint evaluation are also recommended to support large-scale implementation of CS-IS-RCA-based sustainable concrete.

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