



Strength Studies on Concrete by Replacement of Coarse Aggregate with Steel Slag

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Abstract: Rapid industrial development and growing construction activity have created significant volumes of waste materials that strain landfills and deplete natural aggregate resources. Steel slag, a by-product of steel manufacturing, is durable, hard, and highly resistant to biological, chemical, and physical degradation, presenting a viable alternative to conventional coarse aggregate. This study investigates the compressive strength of M30 grade concrete when natural coarse aggregate is replaced with steel slag at 10%, 20%, 30%, 40%, and 50% by volume. Standard 150 mm × 150 mm × 150 mm cube specimens were cast and tested at 7, 14, and 28 days in accordance with IS 516-1965. The results demonstrate that compressive strength increases progressively from 10% to 30% replacement, with 30% replacement achieving the peak compressive strength at all test ages. Beyond 30%, strength declines noticeably, making 20%–30% replacement the optimal range. The findings support the use of steel slag as an economical, environment-friendly coarse aggregate substitute that helps divert industrial waste from landfills while maintaining or enhancing concrete performance.

Key Words: Steel slag; coarse aggregate replacement; M30 concrete; compressive strength; recycled aggregate; sustainable construction; waste utilisation.

I. INTRODUCTION

Rapid industrial development has caused serious problems worldwide, including the depletion of natural aggregates and the generation of enormous quantities of waste from construction and demolition activities. Construction and demolition waste contributes approximately 75% of solid waste globally, with ceramic and industrial materials accounting for a significant share [5]. The increasing demand for construction materials, combined with mounting environmental concerns, has prompted extensive research into alternative and recycled aggregate sources.

Steel slag is an industrial by-product generated during the manufacture of steel. It is a hard, durable material resistant to biological, chemical, and physical degradation. Its high specific gravity, rough surface texture, and angular shape offer potential advantages as a coarse aggregate replacement in concrete [6]. Additionally, using steel slag in concrete represents a cost-effective waste management strategy that reduces the burden on landfills and conserves natural quarried stone resources.

Concrete is the most widely consumed construction material today, comprising approximately 60–80% aggregate by volume and 70–85% by weight [5]. The properties of coarse aggregate — including shape, texture, specific gravity, gradation, and strength — significantly influence the fresh and hardened properties of concrete. Replacing even a portion of conventional coarse aggregate with steel slag therefore requires careful evaluation of workability, compressive strength, and durability parameters.

This study evaluates the effect of partial replacement of natural coarse aggregate with waste steel slag at 10%, 20%, 30%, 40%, and 50% on the compressive strength of M30 grade concrete at 7, 14, and 28 days, with a view to identifying the optimum replacement percentage for sustainable construction.

II. LITERATURE REVIEW

De Brito et al. [2] studied the mechanical behaviour of non-structural concrete made with recycled ceramic aggregates, reporting that compressive and splitting tensile strengths were slightly lower than reference concrete but remained acceptable for non-structural applications. They emphasised the importance of controlling aggregate absorption in recycled aggregate concretes.

Medina et al. [3] investigated the reuse of sanitary ceramic wastes as coarse aggregate in eco-efficient concretes. Their results showed that up to 25% replacement of natural coarse aggregate with ceramic waste could be achieved without significant loss in compressive strength, while contributing to reduced environmental impact.

Correia et al. [7] examined the effects on concrete durability of using recycled ceramic aggregates and concluded that concrete produced with up to 20%–30% recycled ceramic aggregate exhibited comparable durability to conventional concrete,

provided mix proportions were suitably adjusted.

Neville [5] documented that aggregate properties including gradation, shape, and surface texture govern paste requirements and ultimately control workability and strength development. Coarse aggregates with rough, angular surfaces improve mechanical bonding with cement paste but require slightly higher water content to achieve equivalent workability.

Shetty [6] outlined that the compressive strength of concrete depends on the water-to-cement ratio, degree of compaction, ratio of cement to aggregate, bond between mortar and aggregate, and grading, strength and size of the aggregate. These principles underpin the mix design adopted in the present study.

Studies from the literature consistently indicate that the optimal replacement of natural coarse aggregate with waste ceramic or industrial slag material lies in the range of 20%–30%, beyond which compressive strength begins to decline due to higher porosity, weaker interfacial transition zones, and reduced aggregate impact resistance.

III. MATERIALS AND PROPERTIES

3.1 Cement

Ordinary Portland Cement (OPC) 53 grade conforming to IS 12269-2013 was used throughout the investigation. Physical properties were determined as per IS 4031. The results are presented in Table 1.

S.No.	Property	Test Result	IS Limit
1	Specific gravity	3.16	3.10–3.16
2	Normal consistency	32%	–
3	Initial setting time	30 min	≥ 30 min
4	Final setting time	600 min	≤ 600 min
5	Compressive strength – 3 days	29.2 MPa	≥ 27 MPa
6	Compressive strength – 7 days	44.6 MPa	≥ 37 MPa
7	Compressive strength – 28 days	56.6 MPa	≥ 53 MPa

Table 1: Physical Properties of OPC 53 Grade Cement

3.2 Fine Aggregate

Locally sourced river sand conforming to Zone II of IS 383-1970 was used as fine aggregate, passing through a 4.75 mm IS sieve. Key properties are shown in Table 2.

S.No.	Property	Value
1	Specific gravity	2.60
2	Fineness modulus	2.85 (Zone II)
3	Water absorption	1.0%
4	Bulk density (loose)	1530 kg/m ³

Table 2: Properties of Fine Aggregate

3.3 Natural Coarse Aggregate

Crushed granite rock with a maximum size of 20 mm conforming to IS 383-1970 was used as the reference coarse aggregate. Properties are given in Table 3.

S.No.	Property	Value
1	Specific gravity	2.52
2	Fineness modulus	7.47
3	Aggregate impact value	18.56%
4	Water absorption	0.5%

Table 3: Properties of Natural Coarse Aggregate (Crushed Granite)

3.4 Steel Slag (Waste)

Steel slag obtained from a local steel manufacturing plant was used as a partial replacement for coarse aggregate. It was cleaned, separated into appropriate size fractions (passing 20 mm, retained on 4.75 mm sieve), and tested. Comparative properties of steel slag and conventional coarse aggregate are presented in Table 4.

S.No.	Test	Steel Slag	Coarse Aggregate
1	Fineness modulus	7.46	7.47
2	Specific gravity	2.45	2.52
3	Aggregate impact value	32.96%	18.56%

Table 4: Comparison of Steel Slag and Natural Coarse Aggregate Properties

It is noted that while the fineness modulus and specific gravity of steel slag are comparable to natural coarse aggregate, its aggregate impact value is higher (32.96% vs. 18.56%), indicating lower toughness. This characteristic is considered in analysing compressive strength trends at higher replacement levels.

IV.MIX DESIGN

The concrete mix was designed for M30 grade as per IS 10262-2009 with the following design stipulations: characteristic compressive strength (fck) = 30 N/mm², maximum aggregate size = 20 mm, degree of quality control = Good, and water-cement ratio = 0.45. The target mean strength was calculated as:

$$fck' = fck + 1.65 \times S = 30 + (1.65 \times 5.0) = 38.25 \text{ N/mm}^2$$

From IS 10262-2009 Table 2, the maximum water content for 20 mm nominal maximum size aggregate and 100 mm slump = 186 litres. Adjusted water content for 100 mm slump = 197.16 litres. Cement content = 197.16 / 0.45 = 438.13 kg/m³ (> minimum 320 kg/m³ for mild exposure per IS 456-2000). The final mix proportions are presented in Table 5.

Parameter	W/C Ratio	Water (litres)	Cement (kg/m ³)	FA (kg/m ³)
Value	0.45	197.16	438.13	618.70

Table 5a: M30 Mix Proportions (Part I)

Parameter	CA (kg/m ³)	Volume of CA	Volume of FA
Value	1184.51	0.64	0.36

Table 5b: M30 Mix Proportions (Part II) – FA: Fine Aggregate, CA: Coarse Aggregate

V.EXPERIMENTAL METHODOLOGY

Standard 150 mm × 150 mm × 150 mm cast iron cube moulds were used for compressive strength tests. Cylinders of 150 mm diameter × 300 mm height were used for split tensile tests. The following mix proportions were prepared: (i) Control – 100% natural coarse aggregate; (ii) 10% steel slag replacement; (iii) 20% steel slag replacement; (iv) 30% steel slag replacement; (v) 40% steel slag replacement; and (vi) 50% steel slag replacement.

Concrete ingredients were mixed by hand mixing on an impervious floor as per IS procedures. Water was sprinkled over the dry mixture gradually until a homogeneous and workable consistency was achieved. Workability was assessed using the slump cone test and compaction factor test. The moulds were filled in layers and compacted by hand to ensure full compaction without segregation. After 24 hours, specimens were demoulded and immersed in a clean water curing tank. Compressive strength tests were conducted at 7, 14, and 28 days in accordance with IS 516-1965 using a compression testing machine. The split tensile strength was calculated using the formula:

$$T = 2P / (\pi \times L \times D)$$

where T = splitting tensile strength (MPa), P = maximum applied load (N), L = length of specimen (mm), D = diameter (mm).

VI.RESULTS AND DISCUSSIONS

6.1 Compressive Strength

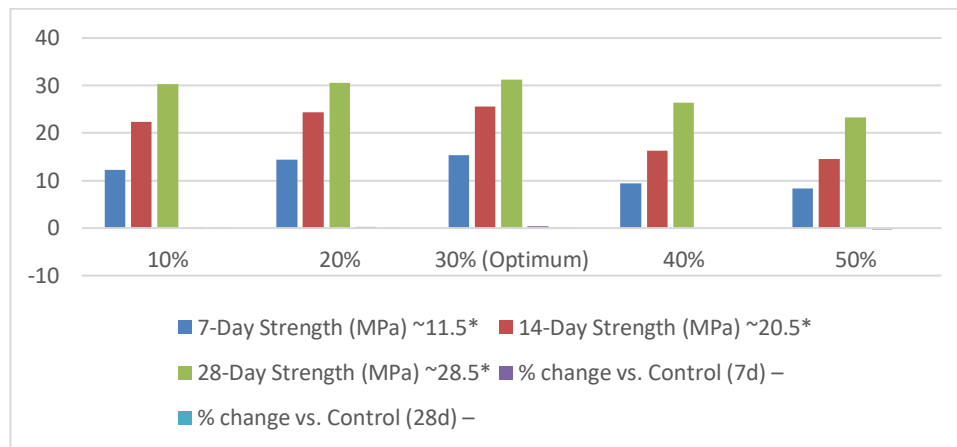
Compressive strength was measured on 150 mm cubes at 7, 14, and 28 days for all six mix types. The complete set of results is presented in Table 6.

Steel Slag Replacement (%)	7-Day Strength (MPa)	14-Day Strength (MPa)	28-Day Strength (MPa)	% change vs. Control (7d)	% change vs. Control (28d)
0% (Control)	~11.5*	~20.5*	~28.5*	–	–
10%	12.30	22.34	30.30	+7.0%	+6.3%
20%	14.41	24.36	30.60	+25.3%	+7.4%

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30% (Optimum)	15.31	25.64	31.20	+33.1%	+9.5%
40%	9.42	16.31	26.42	-18.1%	-7.3%
50%	8.34	14.56	23.34	-27.5%	-18.1%

Table 6: Compressive Strength Results at 7, 14, and 28 Days (* estimated control values from mix design)



Graph 1: Compressive Strength Results at 7, 14, and 28 Days (* estimated control values from mix design)

The compressive strength data clearly shows a parabolic trend with increasing steel slag replacement. From 10% to 30% replacement, compressive strength increases progressively at all test ages, with 30% replacement yielding the peak values: 15.31 MPa at 7 days, 25.64 MPa at 14 days, and 31.20 MPa at 28 days. This improvement may be attributed to the angular, rough surface texture of steel slag particles, which enhances mechanical interlocking and the interfacial transition zone (ITZ) between aggregate and cement paste.

Beyond 30% replacement, a marked decline in compressive strength occurs. At 40% replacement, the 7-day strength drops to 9.42 MPa, and the 28-day strength falls to 26.42 MPa — below the M30 target. At 50% replacement, further reductions to 8.34 MPa (7d) and 23.34 MPa (28d) are observed. This deterioration is attributed to the higher aggregate impact value of steel slag (32.96% vs. 18.56%), increased aggregate crushing during mixing and loading, and higher void content at elevated replacement levels.

The 28-day compressive strength at 30% replacement (31.20 MPa) slightly exceeds the M30 characteristic compressive strength requirement (30 MPa), confirming the adequacy of this replacement level for M30 grade concrete.

6.2 Workability

Slump cone tests performed on fresh concrete mixes indicated that slump values remained in the medium workability range (35–70 mm) for all mixes. The presence of angular steel slag particles slightly reduced slump compared to rounded river gravel, consistent with findings in the literature [5]. Compaction factor values were in the range of 0.85–0.92 across all replacement levels, confirming adequate workability for hand compaction.

6.3 Discussion

The optimum replacement of natural coarse aggregate with steel slag is 30% by volume. At this level, the concrete meets the M30 grade target strength at 28 days while offering environmental and economic benefits. The higher impact value of steel slag compared to natural aggregate is the primary limiting factor at replacement levels above 30%, as it leads to greater particle fragmentation during mixing and under compressive loading, weakening the aggregate skeleton.

From an environmental standpoint, incorporating steel slag into concrete production reduces landfill disposal of industrial waste, conserves natural quarried stone, and potentially lowers the overall cost of concrete production. These benefits align with the goals of sustainable construction and circular economy principles.

VII. CONCLUSIONS

Based on the experimental investigation on M30 grade concrete with partial replacement of coarse aggregate by waste steel slag at 10%, 20%, 30%, 40%, and 50%, the following conclusions are drawn:

1. Compressive strength increases progressively from 10% to 30% steel slag replacement at 7, 14, and 28 days, confirming the beneficial effect of steel slag angular surface texture on aggregate–paste bonding.
2. The maximum compressive strength is obtained at 30% steel slag replacement: 15.31 MPa (7 days), 25.64 MPa (14 days), and 31.20 MPa (28 days), exceeding the M30 minimum requirement of 30 MPa.
3. Beyond 30% replacement, compressive strength declines sharply due to the higher aggregate impact value of steel slag (32.96% vs. 18.56%), leading to greater particle fragmentation and a weaker aggregate skeleton.
4. The optimal replacement range for steel slag in M30 concrete is 20%–30%, balancing strength improvement and workability retention.

5. The use of steel slag as coarse aggregate is not only technically feasible at appropriate replacement levels but also economically and environmentally advantageous, reducing landfill waste and conserving natural stone resources.
6. Workability of fresh concrete mixes (slump: 35–70 mm; compaction factor: 0.85–0.92) remained acceptable across all replacement levels, with no significant reduction in workability up to 30% replacement.
7. Steel slag should not be used as a coarse aggregate replacement in excess of 30% in M30 grade concrete to prevent strength degradation below the characteristic value.

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