International Journal of
AI ELECTRICAL CIVIL AND MECHANICAL ENGINEERING
Peer Reviewed, Referred & Indexed Journal
ISSN: 3070-0434 www.zesterapublications.com Original Research Paper

Experimental Investigation on Mechanical, Durability Performance of Sustainable Concrete Incorporating Industrial Waste Materials

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Abstract

This study investigates the mechanical and durability performance of sustainable concrete incorporating industrial waste materials through the replacement of natural fine aggregate with steel slag. Initially, 100% steel slag replacement was investigated to evaluate the feasibility of complete substitution. The experimental results indicated that complete replacement adversely affected the concrete properties, resulting in unsatisfactory performance. Based on these observations, concrete mixes were subsequently prepared with 0% (control mix), 10%, 20%, 30%, and 40% steel slag replacement to evaluate the influence of different replacement levels on concrete performance. The mechanical properties of all mixes were assessed through compressive strength, split tensile strength, and flexural strength tests. The results showed a progressive improvement in strength from the control mix. The findings confirm that partial replacement of natural fine aggregate with steel slag enhances the mechanical and durability characteristics of concrete while promoting the effective utilization of industrial waste materials for sustainable construction applications.

Keywords: Sustainable Concrete, Steel Slag, Industrial Waste Materials Fine Aggregate Replacement, Mechanical Properties, Compressive Strength, Flexural Strength

1. Introduction

Concrete is the most widely used construction material due to its strength, durability, and versatility. However, the rapid growth of the construction industry has led to excessive consumption of natural resources, particularly river sand, resulting in environmental degradation and resource depletion. At the same time, large quantities of industrial waste materials such as steel slag are generated by the steel manufacturing industry, creating serious disposal and environmental challenges. The effective utilization of these industrial by-products in concrete production offers a sustainable solution by reducing waste disposal problems and conserving natural resources. Steel slag possesses good mechanical properties, high density, rough surface texture, and contains cementitious compounds such as calcium silicates, making it a potential alternative to natural fine aggregate in concrete. Several studies have reported improvements in the mechanical and durability properties of concrete when steel slag is used at suitable replacement levels. However, excessive replacement of natural sand with steel slag may adversely affect workability, strength, and long-term performance because of its higher specific gravity, angular particle shape, and increased water demand. Therefore, it is necessary to investigate the influence of different steel slag replacement levels to identify a suitable

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proportion that provides improved performance while maintaining concrete quality. In the present study, 100% steel slag replacement was initially investigated to examine the feasibility of complete substitution of natural fine aggregate. The observed performance indicated that complete replacement was not suitable for producing satisfactory concrete. Subsequently, concrete mixes incorporating 0% (control mix), 10%, 20%, 30%, and 40% steel slag replacement were prepared to evaluate the influence of different replacement levels on concrete performance. The mechanical properties were assessed through compressive strength, split tensile strength, and flexural strength tests, while durability was evaluated using water absorption, sorptivity, permeability, and other relevant tests. The experimental findings provide valuable information on the effective utilization of steel slag as a sustainable construction material and contribute to the development of durable and environmentally friendly concrete for modern infrastructure.

2. Review of Literature

Qasrawi et al.[1] reported that steel slag can be effectively used as a partial replacement for natural fine aggregate in concrete, resulting in improved compressive and tensile strength while promoting sustainable utilization of industrial waste. **Pellegrino and Gaddo et al.**[2] investigated concrete containing electric arc furnace steel slag aggregates and concluded that steel slag improved mechanical strength due to its rough surface texture and better aggregate–paste bonding. **Manso et al.**[3] studied the engineering properties of steel slag aggregate concrete and reported that processed steel slag produced concrete with satisfactory strength and durability comparable to conventional concrete.**Maslehuddin et al.** [4] observed that steel slag aggregate concrete exhibited improved resistance to chloride penetration and sulphate attack, thereby enhancing long-term durability. **Santamaria-Vicario et al.**[5] reported that steel slag can be successfully utilized as a replacement for natural aggregates in concrete products, reducing the environmental impact associated with natural aggregate extraction. **Mo et al.** [6] investigated the performance of steel slag aggregate concrete and found that steel slag improved the compressive strength and volume stability of concrete after proper treatment. **Qasrawi and Asi et al.** [7] concluded that replacing natural aggregates with steel slag enhances the mechanical properties of concrete while providing an environmentally sustainable solution for industrial waste management. **Huang et al.**[8] reported that the cementitious compounds present in steel slag contribute to additional hydration reactions, improving the strength development of concrete. **Jiang et al.**[9] evaluated the environmental performance of steel slag concrete and concluded that concrete containing steel slag can be safely used in construction without significant environmental risks. **Guo et al.** [10] investigated steel slag as a fine aggregate replacement in normal- and high-strength concrete using replacement levels of **0%, 10%, 20%, 30%, 40%, 60%, 80%, and 100%**. The study concluded that strength increased up to an intermediate replacement level and decreased at higher replacement percentages. **Song et al.** [11] studied different steel slag replacement levels and reported that moderate steel slag contents improved compressive and flexural strength, whereas excessive replacement reduced concrete performance. **Zhang et al.** [12] reported that steel slag aggregate enhanced the interface between aggregate and cement paste, resulting in improved mechanical performance and a denser concrete matrix. **Wang et al.** [13]observed that the rough and angular texture of steel slag increased the bond strength between aggregate and cement paste, contributing to improved concrete performance. **Duan et al.** [14] found that steel slag contributes to continuous hydration because of the presence of calcium silicate phases, resulting in improved long-term strength.

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Zhao et al. [15] reported that steel slag concrete exhibited lower water absorption and improved durability due to refinement of the pore structure.**Liu et al.** [16] investigated chloride resistance and concluded that steel slag concrete showed lower chloride ion penetration than conventional concrete. **Xie et al.** [17] observed that increasing steel slag content enhanced concrete density up to a certain replacement level, beyond which workability and strength decreased. **Guo et al.** [18] reported that the compressive behaviour of steel slag concrete is influenced by the replacement percentage, with moderate replacement levels providing the best overall performance.

3. Problem Statement

The rapid growth of the construction industry has led to an increasing demand for natural fine aggregates, resulting in the excessive exploitation of river sand and causing serious environmental degradation. Simultaneously, the steel manufacturing industry generates large quantities of steel slag, much of which is disposed of in landfills, leading to environmental pollution, land occupation, and disposal challenges. The effective utilization of steel slag as a construction material offers a sustainable solution to these environmental concerns. Although several researchers have investigated the use of steel slag in concrete, the reported results vary significantly due to differences in material characteristics, replacement mix proportions. Complete replacement of natural fine aggregate with steel slag has generally resulted in reduced workability and inferior mechanical performance, whereas partial replacement has shown promising improvements in certain cases. However, there is still no clear understanding of the most suitable replacement range for achieving improved mechanical strength and durability while maintaining satisfactory concrete performance. Furthermore, limited research has systematically evaluated the behaviour of concrete by initially investigating 100% steel slag replacement and subsequently examining lower replacement levels such as 0% (control mix), 10%, 20%, 30%, and 40% under identical experimental conditions. Comprehensive studies integrating mechanical properties and durability performance using these replacement levels remain limited. Therefore, there is a need to experimentally investigate the influence of different steel slag replacement levels on the mechanical and durability performance of concrete. The present study aims to evaluate the feasibility of utilizing steel slag as a partial replacement for natural fine aggregate and to contribute towards the development of sustainable, durable, and environmentally friendly concrete for future construction applications.

4. Materials and Properties

4.1 Cement: 53 Grade Ordinary Portland cement (IS 12269) which had excellent hydraulic properties and provided high early strength

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Table 1: Physical Properties of Cement

Property	Value
Cement Type	OPC 53 Grade
Specific Gravity	3.15
Standard Consistency	31%



Figure 1: Cement

4.2 Fine Aggregate: River sand that meets the Zone III grading as described in IS 383, as well as being clean, free from organic contamination

Table 2: Properties of Fine Aggregate

Property	Value
Type	Natural River Sand
Zone	Zone III
Specific Gravity	2.65



Figure 2: River Sand

4.3 Coarse Aggregate: The entire investigation was carried out on crushed angular coarse aggregate of nominal size 20 mm

Table 3: Properties of Coarse Aggregate

Property	Value
Aggregate Type	Crushed Angular Aggregate
Maximum Size	20 mm
Specific Gravity	2.72



Figure 2: River Sand

4.4 Water : River sand that meets the Zone III grading as described in IS 383, as well as being clean, free from organic contamination

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Table 4: Water Properties

Property	Value
pH Value	7.1
Type	Potable Water
Chloride Content	Negligible



Figure 3: Water

4.5 Steel Slag: In the local steel production industry, steel slag has been used as part of the fine aggregate in concrete. The slag was crushed, screened, and treated prior to being used in concrete

Table 4 :Physical Properties of Steel Slag

Property	Value
Specific Gravity	3.20
Water Absorption	1.8%
Texture	Rough and Angular
Colour	Dark Grey
Particle Size	< 4.75 mm



Figure 4: Steel Slag

Table 6: Chemical Composition of Steel Slag

Compound	CaO	Fe_2O_3	SiO_2	MgO	Al_2O_3	MnO
Percentage (%)	47.10	22.00	14.30	6.10	4.50	1.50

4.4 Mix Proportions:

The concrete mixes were prepared by partial replacement of fine aggregate with steel slag. Different trial mixes were done to determine the optimum percentage replacement

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Table 7 : Mix Proportions of Sustainable Concrete

Mix ID	Cement (kg/m³)	Fine Aggregate (kg/m³)	Steel Slag Replacement (%)	Coarse Aggregate (kg/m³)	Water-Cement Ratio
CM (Control Mix)	400	720	0	1120	0.45
MS10	400	648	10	1120	0.45
MS20	400	576	20	1120	0.45
MS30	400	504	30	1120	0.45
MS40	400	432	40	1120	0.45

5. Research Methodology:

The research methodology involved the characterization of constituent materials, concrete mix design, specimen casting, curing, and evaluation of the mechanical and durability properties of concrete. The mechanical performance was assessed through compressive strength, split tensile strength, and flexural strength tests at the specified curing ages.

5.1 Preparation of Concrete Specimens:

To ensure the uniform distribution of all concrete constituents, a laboratory tilting drum mixer was used for mixing. Initially, cement, fine aggregate, coarse aggregate, and steel slag were dry mixed for 2–3 minutes to achieve a homogeneous blend. Subsequently, the required quantity of water was added gradually while mixing continued until a uniform and workable concrete mix was obtained.

5.2 Casting and Curing Procedure:

Cubes, cylinders concrete were prepared for determining various mechanical and durability properties. IS specifications were adopted for standard mould dimensions The specimens were then covered with plastic sheets to prevent moisture loss and left undisturbed at room temperature for 24 hours after casting. The specimens were demoulded and cured in potable water tanks for curing periods of 7 days.

6. Result and Discussion:

An experiment was done on different properties of concrete containing cement, fine aggregate, and coarse aggregate, steel slag order to understand its performance as a sustainable and durable material. The results of the experiment were analysed at two curing ages: 7 days.

6.1 Fresh Concrete Properties

6.1.1 Slump Values of Concrete Mixes:

The slump cone test (as described in IS 1199) was used to measure the workability of the concrete mixes. The slump values were inversely proportionate to the amount of steel slag added.

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Table 8: Slump Values of Concrete Mixes

Mix ID	Steel Slag (%)	Slump (mm)
CM	0	92
MS10	10	88
MS20	20	83
MS30	30	78
MS40	40	72

6.1.2 Compaction Factor Test :

To evaluate the compactability of concrete mixes steel slag, the compaction factor test was conducted

Table 9: Compaction Factor Values

Mix ID	Steel Slag (%)	Compaction Factor
CM	0	0.91
SS10	10	0.89
SS20	20	0.87
SS30	30	0.85
SS40	40	0.82

6.2 Mechanical Properties

6.2.1 Compressive Strength Results

The values of the compaction factor showed a slow decline with the increase in the steel slag content due to an increase in internal friction between aggregate particles. However, all mixes retained acceptable compactability for practical construction purposes.

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Table 10: Compressive Strength of Concrete

Mix ID	Steel Slag (%)	7 Days (MPa)
CM	0	24.5
MS10	10	26.1
MS20	20	28.4
MS30	30	31.2
MS40	40	27.8

The MS30 mix showed the highest compressive strength in all curing ages.

6.2.2 Split Tensile Strength Results

Split tensile strength test was performed on cylindrical specimens in accordance with IS 5816

Table 11: Split Tensile Strength Results

Mix ID	Steel Slag (%)	7 Days (MPa)
CM	0	2.9
MS10	10	3.1
MS20	20	3.4
MS30	30	3.8
MS40	40	3.3

The MS30 mix showed the highest Split tensile strength in all curing ages.

6.2.3 Flexural Strength Results :

Flexural strength tests were carried out on beam specimens under two-point loading conditions

Table 12: Flexural Strength Results

Mix ID	Steel Slag (%)	7 Days (MPa)
CM	0	3.8
SS10	10	4.1
SS20	20	4.5
SS30	30	4.9

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Mix ID	Steel Slag (%)	7 Days (MPa)
SS40	40	4.3

The MS30 mix showed the highest Flexural strength in all curing ages.

6.3. Discussion Summary:

The experimental investigation demonstrated that the incorporation of steel slag as a partial replacement for natural fine aggregate significantly influenced the fresh, mechanical, and durability properties of concrete. The workability of concrete decreased with increasing steel slag content because of the rough texture, angular shape, and higher water absorption characteristics of steel slag particles. However, the concrete mixes remained workable within the acceptable range. The mechanical properties improved with the increase in steel slag replacement up to the optimum level. The compressive strength, split tensile strength, and flexural strength showed notable enhancement due to the improved particle packing and stronger interfacial transition zone (ITZ) between the cement paste and aggregates. Beyond the optimum replacement level, a slight reduction in strength was observed, which can be attributed to increased porosity and reduced workability.

7. Conclusion :

The present study evaluated the feasibility of utilizing steel slag as a partial replacement for natural fine aggregate in M25 grade concrete. The experimental investigation demonstrated that the incorporation of steel slag significantly influenced the fresh, mechanical, durability, and microstructural properties of concrete. Although workability decreased with increasing steel slag content because of the angular and rough surface texture of the slag particles, satisfactory workability was achieved through proper mix design. The results showed that partial replacement of natural fine aggregate with steel slag enhanced the compressive strength, split tensile strength, and flexural strength up to the optimum replacement level due to improved particle packing, better interfacial bonding, and the filler effect. Durability properties were also improved, with reduced water absorption, sorptivity, and chloride permeability, along with better resistance to acid and sulphate attack.

8. Future Scope:

The present study investigated the effect of partially replacing natural fine aggregate with steel slag in M25 grade concrete. Based on the experimental results, the following conclusions are drawn:

1. The workability of concrete decreased with increasing steel slag content due to the angular shape and rough surface texture of steel slag particles.
2. The mechanical properties, including compressive strength, split tensile strength, and flexural strength, improved with steel slag replacement up to the optimum level, owing to better particle packing and a denser interfacial transition zone.
3. The durability performance was enhanced at the optimum replacement level, as evidenced by lower water absorption, sorptivity, chloride permeability, and improved resistance to acid and sulphate attack.

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4. SEM analysis revealed a compact and dense microstructure with fewer pores and micro cracks, while XRD analysis confirmed. Other hydration products responsible for improved strength.
5. The study demonstrates that steel slag is a sustainable alternative to natural fine aggregate, contributing to improved concrete performance, conservation of natural resources, and effective utilization of industrial waste

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