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To Enhance The Properties Of Concrete By Partial Replacement Of Coarse Aggregate With Steel Slag

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Abstract: Steel slag, an industrial by-product from steel manufacturing, has emerged as a potential alternative to natural coarse aggregates in concrete. This project investigates the mechanical, physical, and durability properties of concrete when coarse aggregates are partially replaced with steel slag in varying proportions (0%, 10%, 20%, 30%, 40%, and 50%). Extensive laboratory testing—including slump value, compressive strength, split-tensile strength, flexural strength, water absorption, density, and microstructural analysis (SEM)—was conducted. Results indicate that steel slag enhances concrete's density, compressive strength, and durability up to an optimum replacement level, after which workability issues and increased water demand negatively impact performance. This study concludes that steel slag is a sustainable, cost-effective, and mechanical performance-enhancing material for concrete production.

Index Terms **-** Steel slag, durability, compressive strength, split-tensile strength, flexural strength, water absorption, density, microstructural analysis (SEM).

I. INTRODUCTION

Concrete is the backbone of modern infrastructure development. It is used in buildings, roads, bridges, dams, and numerous civil engineering structures. Globally, more than **25 billion tons** of concrete are produced annually, making it the most consumed man-made material on Earth. A standard concrete mix contains **cement, fine aggregate, coarse aggregate, and water**, where **coarse aggregates** occupy nearly **60–70% of the total volume**. Because of this large proportion, the properties of coarse aggregates directly influence concrete performance.

However, rapid industrialization, urban expansion, and infrastructure development have led to a **huge surge in the demand for natural aggregates**. This excessive dependency on riverbed stones and crushed rock has resulted in severe environmental issues such as:

- Depletion of riverbeds
- Collapse of aquatic ecosystems
- Uncontrolled mining activities
- Land degradation
- Rise in construction material cost

Simultaneously, the steel manufacturing industry generates massive quantities of **solid waste**, one of which is **steel slag**. India is currently the **2nd largest steel producer in the world**, generating nearly **18–20 million tons of steel slag annually**. Unfortunately, only **25–30%** of this slag is utilized; the rest is dumped near steel plants, causing land pollution, groundwater contamination, and respiratory hazards due to dust.

Steel slag, however, has notable engineering properties: high crushing strength, excellent durability, high resistance to abrasion, and angular particle shape. These characteristics make it a potential substitute for natural coarse aggregates in concrete.

The importance of utilizing steel slag in concrete arises from the following considerations:

1. **Environmental Conservation**
   The extraction of natural aggregates from rivers and hills leads to environmental degradation. Replacing these aggregates with steel slag can reduce ecological pressure and promote sustainable construction.
2. **Waste Reduction and Sustainable Industrial Practices**
   Steel plants struggle with waste management. Dumping slag requires large landfills. By integrating steel slag into construction materials, we convert industrial waste into a valuable resource.
3. **Improved Engineering Properties of Concrete**
   Steel slag is harder, denser, and more durable than many natural aggregates. Incorporating it in concrete may enhance compressive strength, abrasion resistance, and long term durability.
4. **Economic Advantages**
   Steel slag is often available at very low cost or even free from steel industries. Using it reduces the overall cost of construction, particularly in bulk concrete applications.
5. **Alignment with Sustainable Development Goals (SDGs)**
   The use of recycled industrial waste supports SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production).

II. PHYSICAL AND CHEMICAL PROPERTIES OF STEEL SLAG

1. Physical Properties

Numerous studies have reported:

- **Specific gravity**: 3.0–3.6 (higher than 2.6–2.7 for natural aggregate)
- **Water absorption**: Higher due to rough surface
- **Angular shape**: Enhances interlocking
- **High crushing & abrasion resistance**

2. Chemical Properties

Steel slag contains:

- Calcium oxide (CaO)
- Iron oxides (FeO/Fe_2O_3)
- Silicon dioxide (SiO_2)
- Magnesium oxide (MgO)

Presence of free CaO and MgO may cause expansion, hence weathering is recommended

Almost all studies report **reduced workability** with slag due to:

- High water absorption
- Angular particle texture
- Increased surface roughness

Recommended solutions:

- Superplasticizers
- Pre-wetting / soaking of slag

III. MECHANICAL PROPERTIES OF SLAG CONCRETE

1. **Compressive Strength**
   Many studies show 10–20% improvement at 30–40% slag replacement.
2. **Split Tensile Strength**
   Improved by 5–15% due to aggregate interlocking.
3. **Flexural Strength**
   Enhanced because of better load transfer at the ITZ

IV. DURABILITY PERFORMANCE

1. **Water Absorption**

Decreases beyond 20–30% replacement due to denser matrix.

2. **Sulphate Resistance**

Slag concrete exhibits higher resistance due to reduced permeability.

3. **Acid Resistance**

Studies show significant improvement under H_2SO_4 and HCl exposure.

4. **Freeze–Thaw Resistance**

European studies prove excellent performance in freezing conditions.

5. **Microstructural Findings (SEM Studies)**

SEM analysis reveals:

- Reduced micro-cracking
- Dense interfacial transition zone (ITZ)
- Uniform distribution of C-S-H gel
- Enhanced bond between paste and aggregates

6. **Sustainability Advantages (From Global Literature)**

Steel slag usage contributes to:

- Reduced mining of natural aggregates
- Reduced landfill burden
- Lower construction costs
- Alignment with SDG goals for sustainable construction.

V. MATERIALS AND METHODOLOGY

. The methodology strictly follows:

- **IS 10262:2019** – Concrete Mix Proportioning
- **IS 456:2000** – Concrete Code of Practice
- **IS 2386 (Parts I–VIII)** – Testing of Aggregates
- **IS 516:1959** – Strength Tests

A systematic experimental plan was developed to evaluate performance at **0%, 10%, 20%, 30%, 40%, and 50%** slag replacement.

1. **Materials**

Cement

- Type: Ordinary Portland Cement (OPC), 43 Grade
- Standard: IS 8112:2013

Fine Aggregate

- Source: River Sand
- Zone: Zone II (as per IS: 383–2016)

Coarse Aggregate

- Size: 20 mm
- Shape: Angular crushed aggregate

Steel Slag

Steel slag was procured from a steel plant and subjected to:

- 6 months weathering (to reduce free lime)
- Screening into 20 mm size
- Removal of metallic particles
- Slag particles were dark grey, angular, rough, and denser than natural aggregates.

2. **Methodology**

- Mix Design **(M30 Grade)**
- Replacement Levels

  Steel slag replaces coarse aggregate by:
  - **0%**
  - **10%**
  - **20%**
  - **30%**
  - **40%**
  - **50%**
- Mixing
- Casting &
- Curing

  Specimens cured for:
  - **7 days**
  - **14 days**
  - **28 days**
  - **56 days**
  - **90 days (for durability)**

- Testing Procedures
  - Slump Test
  - Compressive Strength Test
  - Split Tensile Strength Test
  - Flexural Strength Test
  - Sorptivity Test
  - SEM Analysis (Microstructural Study)

IV. RESULTS AND DISCUSSION

1. **Slump**

Steel slag has:

- Higher water absorption
- Angular & rough surface texture
- Higher density

These factors reduce the workability of fresh concrete

Table 1: **Slump Values for Different Replacement Levels**

Slag %	0%	10%	20%	30%	40%	50%
Slump (mm)	92	86	79	72	63	55

Observation

- Slump decreases continuously as slag content increases.
- At 50% replacement, slump is reduced by ~40% compared to control concrete.

Reason

- Slag particles absorb water quickly.
- Angularity increases internal friction.

2. **Compressive Strength**

Compressive strength was measured at **7, 14, 28, 56, and 90 days.**

Table 2: Compressive Strength (MPa)

Slag %	7 days	14 days	28 days	56 days	90 days
0%	22.8	28.4	35.6	37.2	38.5
10%	24.6	30.1	38.2	40.5	42.8
20%	26.1	32.6	41.0	43.3	45.6
30%	27.4	34.2	43.9	46.7	48.9
40%	26.8	33.1	42.1	44.8	47.2
50%	24.5	30.2	38.5	41.0	43.0

Observation

- Maximum compressive strength at 30% replacement.
- Improvement over control mix (at 28 days):
  Strength
  - At 0% ; 35.6 MPa
  - At 30% ; 43.9 MPa
- Percentage increase = (43.9 – 35.6)/35.56 X 100 = 23.3%
  Strength begins to decline after 30% due to reduced workability.

Interpretation

- Angular slag particles improve interlocking.
- Higher density results in stronger concrete.
- Excessive slag causes poor compaction → lowers strength.

3. **Split Tensile Strength**

Table 3: Split Tensile Strength (MPa)

Slag %	0%	10%	20%	30%	40%	50%
Split Tensile strength (MPa) in 28 days	2.82	2.95	3.12	3.28	3.19	2.98

Observation

- Tensile strength increases up to 30% and decreases thereafter.
- Maximum improvement: ~16% at 30% slag.

Reason

- Higher interlocking due to rough texture

4. **Flexural Strength**

Table 4: Split Tensile Strength (MPa)

Slag %	0%	10%	20%	30%	40%	50%
Flexural strength (MPa) in 28 days	4.52	4.66	4.87	5.14	5.01	4.68

Observation

- Flexural strength maximum at 30% slag (+13.7%).
- Strength drops slightly at higher replacements.

Interpretation

- Better aggregate–paste bonding at ITZ enhances bending strength

5. **Sorptivity**

Table 5: Sorptivity (mm/√min)

Slag %	0%	10%	20%	30%	40%	50%
Sorptivity (mm/ √ min)	0.264	0.248	0.229	0.215	0.223	0.241

6. **SEM Analysis (Microstructural Study)**

SEM images show:

Control Concrete (0% Slag)

- Porous ITZ
- Micro-cracks visible
- Uneven C-S-H gel distribution

30% Slag Replacement

- Highly dense microstructure
- Very strong ITZ bonding
- Crystal-like slag particles tightly embedded
- Reduced air voids
- Uniform hydration products

50% Slag Replacement

- Slight micro-cracks
- Compaction reduced due to low workability

Interpretation

- The microstructure validates the mechanical and durability trends.

7. **Final Results Summary**

Mechanical Properties Improvement at 30% Slag

Table 6: Final Results Summary

Property	Compressive Strength	Split Tensile Strength	Flexural Strength	Sorptivity
% Increase	+23%	+16%	+14%	-18%

V. CONCLUSION

The literature establishes the high potential of steel slag for replacing natural coarse aggregates. However, variations in slag properties and lack of standardized guidelines necessitate detailed experimental evaluation. The present research attempts to fill these gaps by conducting comprehensive mechanical, durability, and microstructural analysis for M30 grade concrete.

- Steel slag concretes are denser and more durable.
- Slag helps create denser, less permeable concrete
- Workability decreases, but remains manageable up to 30–40% replacement with proper mixing.
- The experimental results clearly indicate that steel slag significantly enhances the performance of concrete, with 30% replacement emerging as the optimum proportion

- Durability Improved Significantly

VI. Acknowledgment

We acknowledge the contributions of researchers worldwide in developing sustainable concrete using different materials as partial replacement of ingredients of concrete.

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