Sustainable Development of Fibre Reinforced Self-Compacting Concrete Using Recycled Coarse Aggregates

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Abstract - This study investigates the strength behaviour of fibre reinforced self-compacting concrete (FRSCC) incorporating recycled coarse aggregate (RCA) obtained from building demolition waste as a sustainable alternative to natural aggregates. The experimental program evaluates fresh and hardened properties of FRSCC mixes with RCA replacement levels ranging from 0% to 60%. Fresh concrete properties, including slump flow, T50, V-funnel, and L-box tests, were assessed in accordance with EFNARC guidelines to ensure adequate filling ability, passing ability, and segregation resistance. Hardened concrete performance was determined through compressive strength, split tensile strength, and flexural strength tests at 7 and 28 days. Results indicate that RCA replacement up to 35% provides optimum performance with minimal reduction in strength compared to conventional SCC. Beyond this level, workability and strength decreased gradually due to the higher water absorption and lower density of RCA. The addition of steel fibres improved post-cracking behaviour and ductility, contributing to enhanced structural efficiency. The findings highlight the potential of integrating self-compacting technology, fibre reinforcement, and recycled aggregates to develop environmentally sustainable and structurally reliable concrete.

Key Words: Fibre Reinforced Self-Compacting Concrete (FRSCC), Recycled Coarse Aggregate (RCA), slump flow, compressive strength, split tensile strength, EFNARC guidelines, sustainable concrete.

1. INTRODUCTION

Self-Compacting Concrete (SCC) is defined as a high-performance concrete capable of flowing under its own weight, filling formwork, and passing through reinforcement without external vibration. Initially developed to simplify casting in heavily reinforced or geometrically complex structures, SCC has since been recognized for its potential in enhancing productivity and quality in housing, precast, and large-scale construction projects. The introduction of steel fibres into concrete further advanced concrete technology by enhancing ductility and post-cracking behaviour. Meanwhile, the recycling of demolition waste into coarse aggregate promotes sustainability. This study focuses on evaluating the fresh and hardened properties of fibre reinforced SCC (FRSCC) containing varying proportions of RCA.

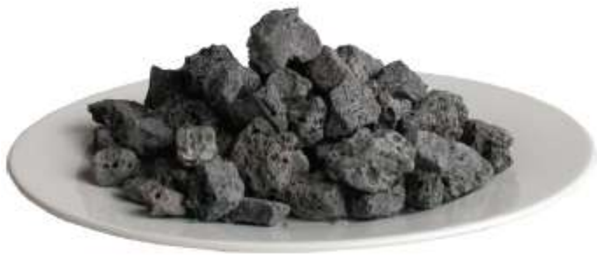

Fig -1: Blast Furnace Rock Slag

1.2 OBJECTIVES

The primary objective of this research is to investigate the flexural strength behaviour of FRSCC incorporating recycled coarse aggregate as a partial replacement for natural aggregates. The scope of the study includes:

- Evaluating fresh concrete properties of FRSCC with RCA replacement.
- Investigating hardened properties such as compressive, split tensile, and flexural strength.
- Assessing the influence of steel fibres on ductility and crack resistance.
- Exploring the feasibility of sustainable construction materials using building demolition waste.

2. LITERATURE REVIEW

Extensive research has been carried out worldwide to improve the performance of self-compacting concrete (SCC) using various materials, including fibres and recycled aggregates.

Sonebi et al. [6] reported the structural performance of full-scale beams cast with both ordinary concrete and SCC containing steel fibres. Their results indicated that the ultimate moment capacity of SCC beams was comparable to conventional reinforced concrete beams, with SCC beams exhibiting higher deflections.

Ganesan et al. [7] conducted experimental studies on eighteen steel fibre reinforced SCC (SFRSCC) flexural elements. The findings revealed that existing theoretical models underestimated the ultimate strength of SFRSCC members, suggesting the need for model modifications.

Nehdi and Ladanchuk [8] examined hybrid fibre combinations in SCC to evaluate their effects on workability, compressive and flexural strength, toughness, and post-crack behaviour. They concluded that hybrid fibres improved crack control due to better micromechanical resistance across multiple strain levels.

Hemanth et al. [9] developed self-compacting fibre reinforced concrete (SCFRC) mixes for prestressed concrete beams, reporting higher normalized tensile strengths than traditional fibrous concretes.

Studies have also investigated the role of recycled aggregates in SCC. Jiong [10] evaluated SCC made with recycled concrete aggregate (RCA) and demonstrated that, with suitable mix design, RCA can produce SCC with properties comparable to conventional mixes.

Dabhade et al. [11] assessed mechanical properties of concrete mixes with 0–100% RCA replacement and found optimum compressive and tensile strengths at 20% replacement. Similarly, Reddy et al. [12] observed that RCA could replace up to 25% of natural aggregate in different grades of concrete without significant performance reduction.

Safiuddin et al. [13] studied the effects of RCA on fresh SCC properties and recommended up to 50% RCA replacement without major loss in filling, passing, or segregation resistance. Malesev et al. [14] reported higher shrinkage in concretes containing over 50% RCA compared to natural aggregate concretes.

Modani et al. [15] observed that SCC mixes with up to 40% RCA exhibited good resistance to acid attack and chloride penetration, though higher RCA content increased permeability due to greater water absorption. Vasam et al. [16] emphasized the ecological benefits of RCA in SCC, citing reductions in CO_2 emissions. Patil et al. [17] found that RCA could effectively be used up to 50% replacement in structural concrete.

A. Research Significance

The literature highlights increasing global interest in incorporating recycled aggregates into concrete, driven by environmental and economic factors. However, gaps remain in understanding the combined influence of steel fibres and RCA in SCC. This study attempts to address this gap by investigating the strength and flexural behaviour of fibre reinforced SCC using recycled aggregates from building demolition waste.

3. MATERIALS AND METHODOLOGY

3.1. General

The materials used for Fibre Reinforced Self-Compacting Concrete (FRSCC) were selected from conventional concrete industry practices. Typical constituents included cement, fine and coarse aggregates, mineral admixtures, fibres, chemical admixtures, and recycled coarse aggregates (RCA).

3.2. Materials

1. **Cement:** Ordinary Portland Cement (OPC) conforming to IS:12269–1987 was used. Its physical and chemical properties were verified in accordance with IS:4031–1988.
2. **Aggregates:**
    - *Fine Aggregate:* Natural river sand conforming to IS:383 was used.
    - *Coarse Aggregate:* Crushed stone of 12.5 mm maximum size was obtained from a local source.
    - *Recycled Coarse Aggregate (RCA):* Derived from building demolition waste, RCA was washed and heated to remove adhered mortar and improve quality.
3. **Water:** Clean potable water, free from impurities, was used for mixing and curing.
4. **Superplasticizer (SP):** A high-range water-reducing admixture (Conplast SP 430) was used to enhance workability and flow.
5. **Mineral Admixtures:** Fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume were incorporated to improve workability and durability.
6. **Fibres:** Steel fibres with diameters of 0.92 mm and varying aspect ratios (15, 25, 35) were used. The corresponding fibre lengths were 13.8 mm, 23 mm, and 32.2 mm. Fibre dosages ranged from 0.5% to 1.5% by volume.

3.3. Properties of Recycled Coarse Aggregate

RCA exhibited increased water absorption, reduced bulk density, and lower specific gravity compared to natural aggregates. The treatment process included:

- *Washing:* High-pressure water jetting to remove adhered mortar.
- *Heating:* Oven heating at 150 °C for one hour to improve surface quality and reduce porosity.

3.4. Methodology

The study involved preparation of SCC mixes incorporating RCA at varying replacement levels (0–60%). Steel fibres were added to selected mixes to study their effect on mechanical and flexural performance.

3.5. Testing Program

1. **Fresh Properties:**
    - Slump Flow
    - T50
    - V-Funnel
    - L-Box

    These tests were conducted in accordance with EFNARC guidelines [3] to assess filling ability, passing ability, and segregation resistance.
2. **Hardened Properties:**
    - *Compressive Strength:* Cubes (150 × 150 × 150 mm) tested at 7 and 28 days.
    - *Split Tensile Strength:* Cylinders (150 mm dia × 200 mm height).
    - *Flexural Strength:* Beams (100 × 100 × 500 mm) tested under two-point loading.

4. MODELLING ON ETABS

A. General

The mix design of self-compacting concrete (SCC) requires careful proportioning of constituents to achieve high fluidity, passing ability, and resistance to segregation. Unlike conventional concrete, SCC is proportioned based on paste volume, fines content, and admixture dosage to ensure self-compactability.

B. Mix Design Guidelines

Several guidelines for SCC mix design exist, including those proposed by Okamura and Ozawa [18], EFNARC [3], and JRMCA [19]. General recommendations include:

- Coarse aggregate content limited to 28–35% of total volume.
- Paste volume maintained at 40–45% of total mix.
- High fines content (cement + mineral admixtures) to ensure flowability.
- Use of superplasticizer to achieve workability without excessive water.
- Water–binder ratio maintained between 0.28 and 0.45 depending on required strength and durability.

C. Adopted Mix Proportion
The present study designed M30 grade SCC using BIS method, modified to meet EFNARC requirements. The target mean strength was calculated as:

$$f'_{ck} = f_{ck} + K \cdot S = 30 + (1.65 \times 6) = 39.9 \text{ N/mm}^2$$

where $K = 1.65$ (tolerance factor) and $S = 6.0$ (standard deviation).

The adopted mix proportion included cement, fly ash, GGBS, and silica fume as binders. Fine aggregate constituted 56% of total aggregate volume, while coarse aggregate was restricted to 44%. Water–cementitious ratio was fixed at 0.41.

D. Final Mix Proportions
For 1 m³ of FRSCC, the optimized mix consisted of:

- Cement: 240 kg
- Fly ash: 132 kg
- GGBS: 96 kg
- Micro silica: 2.4 kg
- Fine aggregate: 915.7 kg
- Coarse aggregate: 719.5 kg
- Water: 191.9 liters
- Superplasticizer (SP 430): 11.7 liters
- Viscosity Modifying Agent (VMA): 1.6 liters
- Steel fibres: 0.1% of binder content

E. RCA Replacement Levels
Natural coarse aggregate (NCA) was progressively replaced with RCA at increments of 25%, 30%, 35%, 40%, 45%, 50%, 55%, and 60%. Each mix was proportioned to maintain EFNARC-recommended flow characteristics.

Table-1: Limits on SCC material proportions

	High fines	VMA	Combination
Cementations (kg/m3)	450-600	385-450	385-450
Water/Cementations material	0.28-0.45	0.28-0.45	0.28-0.45
Fine aggregate/Mortar (%)	35-45	40	40
Fine aggregate/Total Aggregate (%)	50-58	--	--
Coarse aggregate / Total mix (%)	28-48	45-48	28-48

5. TESTS ON FRSCC

A. General
The performance of Fibre Reinforced Self-Compacting Concrete (FRSCC) in both fresh and hardened states was assessed through standardized test methods. Since no universal standard for FRSCC exists, the procedures followed were primarily based on EFNARC guidelines [3] and modified as necessary for experimental evaluation. The primary focus was on assessing three fresh concrete properties—filling ability, passing ability, and segregation resistance—and corresponding hardened strength characteristics.

B. Fresh Concrete Tests

1. Slump Flow and T50 Time:
   - The slump flow test measured the horizontal spread of concrete after lifting the slump cone, while T50 time recorded the time taken to reach a 50 cm spread.
   - A slump flow value ≥650 mm was considered satisfactory for SCC. Lower T50 times indicated better flowability, with acceptable ranges between 2–5 seconds.
2. L-Box Test:
   - The L-box test evaluated the passing ability of SCC through reinforcement. The blocking ratio (H_2/H_1) was measured, with values ranging from 0.8 to 1.0 considered acceptable.
3. V-Funnel Test and V-Funnel at T5 Minutes:
   - This test measured the flow time of SCC through a narrow funnel to assess filling ability and viscosity.
   - A typical flow time of 6–12 seconds indicated adequate flowability.
   - Repeating the test after 5 minutes provided insights into segregation and stability of the mix.

C. Preparation of Test Specimens

- Mixing: Concrete was mixed using a mechanical mixer. Approximately 25% of the mixing water was added first, followed by aggregates, cement, admixtures, and remaining water.
- Casting: Concrete was poured into cube moulds (150 × 150 × 150 mm), cylinder moulds (150 mm × 200 mm), and prism/beam moulds (100 × 100 × 500 mm) without compaction.
- Curing: Specimens were demoulded after 24 hours and cured in water until testing ages of 7 and 28 days.

D. Hardened Concrete Tests

1. Compressive Strength:
   - Conducted on cubes at 7 and 28 days as per IS 516.
   - Load was applied at a uniform rate of 140 kg/cm²/min until failure.

2. **Split Tensile Strength:**
   - Cylindrical specimens were tested under diametral compression according to IS 5816–1999.
   - The tensile strength was calculated using:

$$f_t = \frac{2P}{\pi DL}$$

where P = applied load, D = diameter, L = length.

3. **Flexural Strength (Modulus of Rupture):**
   - Beams were tested under two-point loading at third spans.
   - The flexural strength was determined using:

$$f_{cr} = \frac{PL}{bd^2}$$

where P = applied load, L = span length, b = width, d = depth of specimen.

Table-2: Acceptance criteria for SCC

S. No.	Method	Unit	Typical range of values	
			Minimum	Maximum
1.	Slump flow test	mm	650	800
2.	T50cm slump flow	Sec	2	5
3.	V-funnel test	Sec	6	12
4.	V-funnel at T_5 minutes	Sec	6	15
5.	L-Box test	H2/H1	.8	1.0

6. PROPERTIES OF MATERIALS

A. Cement

Ordinary Portland Cement (OPC) of 53 grade was used in this study. The cement was tested in accordance with IS:4031–1988 and satisfied the requirements of IS:12269–1987. The key properties were:

- Normal consistency: 30%
- Initial setting time: 35 minutes
- Compressive strength: 37 N/mm² (7 days), 53 N/mm² (28 days)
- Specific gravity: 3.01

B. Fine Aggregate

Natural river sand conforming to IS:383 was used. The properties of fine aggregate were determined as per IS:2386.

- Fineness modulus: 2.72
- Specific gravity: 2.61
- Bulk density: 1585 kg/m³ (loose), 1690 kg/m³ (compacted)

C. Coarse Aggregate

Locally available crushed stone of 12.5 mm maximum size was used. Properties were as follows:

- Fineness modulus: 6.15
- Specific gravity: 2.63
- Bulk density: 1475 kg/m³ (loose), 1696 kg/m³ (compacted)

D. Fly Ash

Fly ash was obtained from the Vijayawada Thermal Power Station, Andhra Pradesh. Its properties included:

- Specific surface area: 4250 cm²/g
- Specific gravity: 2.3
- Major chemical constituents:
  - SiO_2: 49–67%
  - Al_2O_3: 26–28%
  - Fe_2O_3: 4–10%
  - CaO: 0.7–3.6%

E. Ground Granulated Blast Furnace Slag (GGBS)

The GGBS used conformed to BS:6699 standards.

- Specific gravity: 2.91
- Fineness: 330 m²/kg
- Bulk density: 1100 kg/m³
- Glass content: 93%

Chemical composition included: SiO_2 (33.1%), Al_2O_3 (18.3%), CaO (41%), MgO (11.6%).

F. Silica Fume

Silica fume, obtained from Elkem Metallurgy Pvt. Ltd., Navi Mumbai, was used as a supplementary cementitious material. It served to enhance strength, reduce permeability, and improve durability.

G. Superplasticizer

Conplast SP430, a high-range water-reducing admixture from Fosroc, was used. It had a specific gravity of 1.22. The optimum dosage was approximately 2.5% of binder content.

H. Water

Potable water, free from harmful impurities such as oils, acids, and alkalis, was used for both mixing and curing.

7. MIX DESIGN

A. General

Mix design is the process of selecting suitable ingredients for concrete and determining their proportions to achieve the desired strength, workability, and durability at the most economical cost. For Fibre Reinforced Self-Compacting Concrete (FRSCC), the conventional BIS method of mix design was adopted and modified in accordance with EFNARC specifications.

B. Target Mean Strength

For M30 grade concrete, the target mean compressive strength was determined as:

$$f_{ck}^{*} = f_{ck} + K \cdot S = 30 + (1.65 \times 6) = 39.9\ \mathrm{N/mm^2}$$

where fck is the characteristic compressive strength, K=1.65 is the tolerance factor, and S=6.0 is the standard deviation.

C. Water–Cement Ratio

Based on strength requirements and durability considerations, the adopted water–cement ratio was 0.41.

D. Binder Content

The cementitious content was designed to include:

- Cement: 240 kg/m³
- Fly ash: 132 kg/m³ (55% of supplementary cementitious material)
- GGBS: 96 kg/m³ (40%)
- Silica fume: 2.4 kg/m³ (1%)

E. Aggregates

- Fine aggregate constituted 56% of total aggregate volume.

- Coarse aggregate content was restricted to 44% of total aggregate volume.

F. Water and Admixtures

- Water content: 191.9 liters/m³
- Superplasticizer (SP430): 11.7 liters/m³
- Viscosity Modifying Agent (VMA): 1.6 liters/m³

G. Fibre Reinforcement

Steel fibres were added at 0.1% of binder content to improve ductility and crack resistance.

H. RCA Replacement Levels

Natural Coarse Aggregate (NCA) was progressively replaced with Recycled Coarse Aggregate (RCA) at levels of 25%, 30%, 35%, 40%, 45%, 50%, 55%, and 60%. Each mix was proportioned to ensure fresh and hardened properties satisfied EFNARC recommendations.

8. RESULTS AND DISCUSSIONS

A. Fresh Concrete Properties

1. **Slump Flow and T50 Time:** The slump flow values for all mixes satisfied EFNARC requirements at RCA replacement levels up to 35%. Flow decreased with higher RCA content due to increased water absorption and angularity of RCA. T50 times increased correspondingly, indicating reduced flowability.
2. **L-Box Ratio:** Passing ability remained within acceptable ranges (0.8–1.0) up to 35% RCA. At higher replacement levels, blocking effects were observed due to the rougher surface texture and reduced workability.
3. **V-Funnel Flow Time**: Mixes with RCA up to 35% exhibited flow times between 6–12 seconds, indicating adequate viscosity. Beyond 40% RCA, flow times exceeded acceptable limits, suggesting higher resistance to flow and potential risk of segregation.

Summary of Fresh Properties: RCA replacement up to 35% did not adversely affect filling ability, passing ability, or segregation resistance. Beyond this level, fresh concrete workability reduced significantly.

B. Hardened Concrete Properties

1. **Compressive Strength:**
   - At 7 days, mixes with RCA up to 35% showed compressive strengths comparable to control SCC.
   - At 28 days, optimum performance was observed at 35% RCA, with a marginal reduction (about 5%) compared to natural aggregate mixes.
   - Strength decreased progressively beyond 40% RCA, attributed to weaker interfacial transition zones and higher porosity of RCA.
2. **Split Tensile Strength:** The addition of steel fibres enhanced tensile performance by bridging micro-cracks. Optimum tensile strength was achieved at 35% RCA with fibres. At higher RCA levels, the tensile strength decreased but remained superior to plain SCC due to fibre reinforcement.
3. **Flexural Strength:** Fibre inclusion significantly improved post-cracking behaviour and ductility. At 35% RCA replacement, flexural strength values were close to control SCC mixes, demonstrating effective crack resistance. At 50% and above, strength declined but fibre addition mitigated the reduction.

C. Influence of Steel Fibres: Steel fibres improved ductility, toughness, and post-cracking behaviour across all mixes. Their role was particularly significant at higher RCA levels, where they compensated for the loss of strength and contributed to improved structural performance.

D. Optimum RCA Replacement: The study confirmed that RCA replacement up to 35% provided the best balance between sustainability, workability, and strength. Beyond this threshold, performance declined due to the lower quality and higher absorption of recycled aggregates.

E. Discussion: The findings align with earlier studies [11], [12], [15], which reported satisfactory concrete performance up to 30–40% RCA replacement. The addition of fibres distinguishes this work by demonstrating enhanced ductility and crack resistance, making FRSCC with RCA a viable material for structural applications where sustainability and performance are equally critical.

9. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Based on the experimental investigation of Fibre Reinforced Self-Compacting Concrete (FRSCC) incorporating Recycled Coarse Aggregate (RCA), the following conclusions were drawn:

1. **Fresh Properties:**
   - FRSCC mixes with RCA replacement up to 35% satisfied EFNARC guidelines for slump flow, T50 time, V-funnel, and L-box tests.
   - Workability decreased gradually with higher RCA content due to increased water absorption and rough surface texture.
2. **Compressive Strength:**
   - RCA replacement up to 35% exhibited compressive strengths comparable to conventional SCC.
   - Beyond this level, strength declined due to weaker interfacial bonding and higher porosity of RCA.
3. **Split Tensile and Flexural Strength:**
   - Steel fibres enhanced ductility, crack resistance, and post-cracking behaviour.
   - Optimum tensile and flexural performance was observed at 35% RCA replacement.
4. **Overall Performance:**
   - The combination of self-compacting technology, fibre reinforcement, and RCA demonstrated that sustainable concrete can be produced without compromising structural efficiency.

- RCA replacement levels above 35% may be adopted only with additional measures such as pre-soaking, surface treatment, or admixture optimization.

B. Recommendations

1. **Practical Applications:**
   - FRSCC with up to 35% RCA can be recommended for structural applications such as beams, slabs, and precast elements.
   - It is suitable for projects emphasizing sustainability and reduction of natural resource consumption.
2. **Future Research:**
   - Long-term durability studies, including chloride penetration, carbonation, and freeze–thaw resistance, should be carried out.
   - The effect of alternative fibres (synthetic, glass, or hybrid fibres) in RCA-based SCC should be explored.
   - Life-cycle cost analysis and carbon footprint studies are recommended to strengthen the case for large-scale adoption.

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