

An Experimental study on strength properties of Fiber Reinforced High Strength Concrete using Recycled Coarse Aggregates

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Abstract— The global construction industry is facing increasing challenges related to sustainability, resource depletion, and effective waste management. In response, the use of recycled coarse aggregates (RCA) and fiber reinforcement in high-strength concrete (HSC) has emerged as a viable solution to enhance material performance while minimizing environmental impact. This study investigates the behavior of steel fiber-reinforced high-strength concrete (SFRHSC) incorporating RCA at varying steel fiber content levels of 0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% by volume. A detailed experimental analysis was conducted to assess key properties, including workability, mechanical performance, and durability. Mechanical properties such as compressive strength, flexural strength, split tensile strength, and density were measured to evaluate the impact of steel fiber addition. Results demonstrated that increasing steel fiber content improved strength properties, with optimal fiber content achieving maximum compressive and tensile performance. Durability properties, including water absorption, water permeability, and resistance to acid attack, were also examined to determine the material's long-term performance. SFRHSC demonstrated enhanced durability with higher fiber content, indicating improved resistance to environmental degradation. Additionally, microstructural analysis using Scanning Electron Microscopy (SEM) provided insights into the bonding behavior between the RCA, cement matrix, and steel fibers, revealing a denser, more cohesive internal structure. This research highlights the potential of SFRHSC as a sustainable, high-performance construction material that offers improved workability, superior mechanical strength, enhanced durability, and optimized microstructural properties.

Index Terms— High-Strength Concrete (HSC), Recycled Coarse Aggregates (RCA), Mechanical Properties, Durability Properties, Scanning Electron Microscopy (SEM)

I. INTRODUCTION

The construction industry plays a fundamental role in shaping global infrastructure and driving economic development, providing essential support for urbanization, transportation, housing, and industrial growth. However, this vital sector is increasingly facing significant challenges related to environmental sustainability, resource depletion, and effective waste management. Concrete, a key material in the construction industry, is one of the most widely used materials worldwide due to its versatility, strength, and durability. Yet, the high demand for concrete has intensified environmental concerns. The production and consumption of concrete result in the extensive extraction of natural aggregates, contributing to land degradation, habitat destruction, and the depletion of non-renewable resources (Mehta & Monteiro, 2017). Additionally, the manufacture of cement, a crucial component of concrete, is responsible for a substantial share of global carbon dioxide (CO₂) emissions—approximately 7%—further exacerbating climate change. The environmental footprint of concrete is also compounded by the generation of large volumes of construction and demolition (C&D) waste, much of which ends up in landfills, contributing to waste management challenges (Thomas et al., 2018). As urbanization accelerates and global infrastructure needs continue to grow, addressing these sustainability issues has become an urgent priority for policymakers, researchers, and industry stakeholders. To mitigate the environmental impacts associated with conventional concrete production, researchers have been exploring the potential of sustainable materials and construction practices. One promising avenue is the use of recycled coarse aggregates (RCA), which are produced by crushing and processing C&D waste materials. RCA offers several environmental benefits, including reducing the reliance on virgin aggregates, minimizing the carbon

footprint of concrete production, and promoting the circular economy through the reuse of waste materials (Kou & Poon, 2012). However, RCA-incorporated concrete typically exhibits lower mechanical performance due to the porous nature and weaker bonding characteristics of recycled aggregates compared to natural aggregates (Poon & Chan, 2007). To overcome these performance limitations and enhance the properties of RCA-incorporated concrete, fiber reinforcement has emerged as an effective strategy. Among the various types of fibers, steel fibers have demonstrated significant potential in improving the mechanical and durability properties of concrete. Steel fibers enhance tensile strength, flexural strength, and crack resistance by bridging cracks and preventing their propagation under loading conditions (Naaman, 2018). The addition of steel fibers also improves concrete's toughness, impact resistance, and overall structural integrity, making it suitable for high-performance applications (ACI Committee 544, 2016). The combination of RCA and steel fiber reinforcement has the potential to create a new generation of steel fiber-reinforced high-strength concrete (SFRHSC) that is both environmentally sustainable and mechanically superior. High-strength concrete (HSC) itself is characterized by its high compressive strength, typically exceeding 50 MPa, and its ability to support large loads and withstand aggressive environmental conditions. When RCA and steel fibers are incorporated into HSC, the resulting composite material can offer improved sustainability, enhanced load-bearing capacity, and increased durability. This study aims to comprehensively evaluate the behavior of SFRHSC incorporating varying percentages of RCA and steel fibers, focusing on critical performance metrics such as workability, mechanical, durability, and microstructural properties. Workability, which affects the ease of handling and placing concrete, is a crucial factor that influences the quality and performance of the finished structure. Mechanical properties, including compressive strength, flexural strength, split tensile strength, and density, are essential for assessing the structural integrity of concrete. Durability properties, such as water absorption, permeability, and resistance to acid attack, are key indicators of long-term performance under adverse environmental conditions. Finally, microstructural analysis using techniques like scanning electron microscopy (SEM) provides insights into the internal structure of concrete,

helping to explain the observed improvements in mechanical and durability behavior.

II. LITERATURE SURVEY

Concrete is one of the most widely used construction materials globally due to its strength, durability, and versatility. However, its production poses significant environmental challenges, primarily driven by the high carbon emissions from cement manufacturing and the extensive consumption of natural resources. The cement industry alone is responsible for approximately 7% of global carbon dioxide (CO₂) emissions, making it a major contributor to climate change (Naik, 2008). Cement production is an energy-intensive process, and a significant portion of its carbon footprint comes from the calcination process, which is essential for clinker production—the key component of cement. Thomas et al. (2018) emphasize that the removal of topsoil during aggregate extraction disrupts local ecosystems, reduces biodiversity, and can result in water pollution from sediment runoff. The overexploitation of natural aggregate resources has also led to a growing scarcity of high-quality aggregates in many regions, adding pressure to find alternative sources. Kou and Poon (2012) highlighted the multiple environmental benefits of using RCA. One of the most critical advantages is the reduction in demand for virgin materials, such as natural sand, gravel, and crushed stone. The extraction and processing of these materials often lead to extensive land degradation, deforestation, and biodiversity loss. Research has shown that steel fibers enhance the durability of RCA-based concrete by reducing water ingress and improving resistance to freeze-thaw cycles, chloride penetration, and acid attacks (Khaloo et al., 2015). The presence of steel fibers also improves the homogeneity of the concrete matrix and enhances the dispersion of RCA particles, further improving the overall performance of SFRHSC (Li et al., 2020). In conclusion, the integration of RCA and steel fibers into high-strength concrete offers a sustainable and high-performance solution for modern construction. By leveraging the complementary properties of RCA and steel fibers, the construction industry can address environmental sustainability challenges while ensuring structural durability and long-term reliability.

Despite extensive research on recycled coarse aggregates (RCA) in concrete, several key knowledge gaps remain:

1. Limited studies on RCA in high-strength concrete (HSC) – Most research focuses on RCA in normal-strength concrete, while its application in high-strength concrete (HSC) is relatively unexplored (Tam et al., 2018).
2. Scarcity of research on the synergistic effect of RCA and steel fibers – While RCA reduces mechanical strength, and steel fibers enhance it, limited studies have comprehensively investigated the combined impact of these materials (Xiao et al., 2012).
3. Lack of durability investigations – Previous studies have focused primarily on mechanical properties, but detailed durability studies (water absorption, permeability, acid attack) of RCA-based steel fiber-reinforced HSC are limited (Thomas et al., 2018).
4. Absence of microstructural analysis – The microstructural characteristics, including the effect of steel fibers on the interfacial transition zone (ITZ) of RCA concrete, remain insufficiently explored (Kou et al., 2011).
5. Unclear optimal fiber dosage – While fiber reinforcement enhances strength and durability, research on the ideal fiber content for balancing strength, durability, and workability in RCA-based HSC is still inconclusive (ACI Committee 544, 2016).

III. MATERIALS AND METHODOLOGY

This section outlines the materials used and the experimental procedures followed to study the behavior of steel fiber-reinforced high-strength concrete (SFRHSC) incorporating recycled coarse aggregates (RCA). The research focuses on evaluating the workability, mechanical properties (compressive strength, flexural strength, split tensile strength, and density), durability properties (water absorption, water permeability, and acid resistance), and microstructural properties (scanning electron microscopy) of SFRHSC. The materials selection, mix design, specimen preparation, curing process, and testing methods are described in detail to ensure the reproducibility of the results.

3.1 Cement

Ordinary Portland Cement (OPC) of grade 53, conforming to IS 12269:2013 standards, was used in all concrete mixes. This grade was chosen due to its high compressive strength and suitability for producing high-strength concrete (HSC). The

physical and chemical properties of the cement were tested to ensure compliance with industry standards.

3.2 Recycled Coarse Aggregates (RCA)

RCA was obtained from the crushing and processing of construction and demolition (C&D) waste, primarily consisting of old concrete, bricks, and tiles. The RCA was screened, cleaned, and graded to remove impurities such as dust, debris, and organic matter. The physical properties of RCA, including specific gravity, water absorption, and porosity, were tested according to IS 2386 (Part III): 1963 to evaluate its suitability for concrete production.

3.3 Natural Fine Aggregates

River sand, conforming to IS 383:2016 standards, was used as the fine aggregate. The sand was sieved to achieve a uniform particle size distribution and was tested for parameters such as specific gravity, fineness modulus, and silt content.

3.4 Steel Fibers

Hooked-end steel fibers with an aspect ratio (length to diameter) of 50 were used as fiber reinforcement in varying percentages (0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1.0% by volume). Steel fibers were chosen due to their superior tensile strength and crack-bridging capabilities, which help enhance the mechanical and durability properties of concrete.

3.5 Methodology

Since 100% RCA is used as a full replacement for natural aggregates, the mix design has been optimized to compensate for increased water absorption and reduced density of RCA. Additional water and superplasticizer adjustments were made accordingly.

Mix ID	RCA (%)	Steel Fiber (%)	Cement (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (kg/m ³)	Superplasticizer (%)
M1	100%	0%	450	750	1100	160	1.0%
M2	100%	0.2%	450	750	1100	160	1.0%
M3	100%	0.4%	450	750	1100	160	1.1%
M4	100%	0.6%	450	750	1100	160	1.1%
M5	100%	0.8%	450	750	1100	160	1.2%
M6	100%	1.0%	450	750	1100	160	1.2%

The final mix proportions were determined based on trial mixes, and adjustments were made to optimize workability, strength, and durability.

Testing Methods

Workability Test

The slump test was performed on fresh concrete to evaluate its workability, in accordance with IS 1199:1959.

Mechanical Property Tests

Compressive Strength: Tested on cube specimens at 7, 14, and 28 days using a compression testing machine (IS 516:1959).

Flexural Strength: Evaluated using a two-point loading method on beam specimens (IS 516:1959).

Split Tensile Strength: Measured on cylindrical specimens using a compression testing machine (IS 5816:1999).

Density: The density of hardened concrete was calculated by dividing the mass of the specimen by its volume.

Durability Property Tests

Water Absorption: The percentage of water absorbed by concrete specimens was determined using ASTM C642-06.

Water Permeability: The permeability of concrete was assessed using the water penetration method specified in DIN 1048.

Acid Attack: Concrete specimens were immersed in a 5% sulfuric acid solution for 28 days, and the loss in mass and strength was measured to evaluate resistance to acid attack.

Microstructural Analysis

Scanning Electron Microscopy (SEM) was used to study the microstructural characteristics of the concrete, including the distribution of steel fibers, the bond between RCA particles and the cement matrix, and the presence of microcracks and voids. SEM analysis helped provide insights into the concrete's performance at the microscopic level.

Data Collection and Analysis

All experimental data were recorded and statistically analyzed to identify trends and correlations between steel fiber content, RCA incorporation, and concrete properties. The results were compared to control mixes (0% steel fiber) to evaluate improvements in mechanical and durability properties.

IV. RESULTS AND DISCUSSIONS

This section presents the experimental results obtained from various tests conducted on steel fiber-

reinforced high-strength concrete (SFRHSC) incorporating recycled coarse aggregates (RCA). The results are analyzed and discussed to assess the impact of steel fiber dosage on the workability, mechanical properties, durability properties, and microstructural characteristics of concrete. The findings are supported by tables and figures for clarity.

4.1 Fresh Concrete Properties

4.1.1 Workability of Concrete

The workability of fresh concrete was assessed using the slump test. The results indicate that increasing steel fiber content led to a reduction in slump values, which can be attributed to the increased surface area and interlocking effect of the fibers. The slump decreased as steel fiber content increased due to the increased resistance to flow caused by fiber entanglement. The addition of a superplasticizer helped maintain workability within an acceptable range. For higher fiber dosages ($\geq 0.8\%$), additional water-reducing admixtures may be required to achieve desired workability.

4.2 Mechanical Properties

4.2.1 Compressive Strength

Steel Fiber Content (%)	7-Day Strength (MPa)	28-Day Strength (MPa)
0.0%	48.3	64.2
0.2%	49.8	66.5
0.4%	52.1	69.8
0.6%	55.3	73.5
0.8%	53.5	71.0
1.0%	51.2	68.4

4.2.2 Split Tensile Strength & Flexural Strength

Steel Fiber Content (%)	Split Tensile Strength (MPa)	Steel Fiber Content (%)	Flexural Strength (MPa)
0.0%	4.8	0.0%	6.8
0.2%	5.2	0.2%	7.3
0.4%	5.7	0.4%	8.1
0.6%	6.3	0.6%	9.0
0.8%	6.0	0.8%	8.6
1.0%	5.5	1.0%	8.0

4.2.3 Microstructural Analysis

Parameter	Observation from SEM Analysis	Impact on Concrete Properties
ITZ Microstructure	Weak bonding in RCA, improved with steel fibers	Enhanced strength and durability
Fiber-Matrix Interface	Strong bonding, reduced fiber pullout	Increased tensile and flexural strength
Porosity	RCA increases porosity, steel fibers reduce it	Improved durability and reduced permeability
Crack Behavior	More micro-cracks in RCA, reduced with fibers	Increased toughness and ductility

V. CONCLUSION

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The incorporation of RCA led to a reduction in compressive strength compared to conventional natural aggregate concrete due to the presence of residual mortar and increased porosity (Poon & Chan, 2007). The addition of steel fibers significantly improved compressive strength, particularly at an optimal fiber content of 0.6%, beyond which the strength gains plateaued or slightly declined due to fiber clustering. Steel fibers enhanced crack arresting mechanisms and improved the load-carrying capacity of RCA concrete, making it more resilient under compressive loads (Naaman, 2018).

SEM analysis confirmed that RCA led to an increase in micro-cracks and weak bonding at the ITZ, resulting in compromised mechanical strength. The addition of steel fibers significantly improved fiber-matrix interaction and enhanced crack resistance by bridging micro-cracks and improving ITZ properties. The presence of well-distributed steel fibers reduced pore connectivity, leading to improved durability properties such as lower permeability and higher resistance to environmental attacks.

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