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Experimental Investigation of RCC Beams Using a Layer of Ultra-High-Performance Reinforced Concrete with different Types of Steel Fibers for Beam Strengthening Applications

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Abstract: Concrete, one of the most widely used construction materials globally, offers versatility, strength, and cost-effectiveness. However, conventional concrete is inherently brittle, possesses low tensile strength, and is prone to cracking and environmental deterioration, which limits its long-term durability. To overcome these shortcomings, Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) has emerged as an advanced cementitious composite that exhibits superior mechanical performance, enhanced ductility, and exceptional durability. UHPFRC is characterized by its ultra-high compressive strength, typically exceeding 120 MPa. Its exceptional performance is achieved through optimized particle packing, a very low water-to-binder ratio (0.18–0.22), and the incorporation of high-strength steel or synthetic fibers (1–3% by volume). The design of UHPFRC eliminates coarse aggregates and relies on fine materials such as cement, silica fume, quartz sand, and high-range water-reducing admixtures to produce a dense, homogeneous microstructure.

The inclusion of fibers imparts crack-bridging capability and pseudo-ductile behavior to UHPFRC, allowing it to sustain significant tensile deformation after cracking. This leads to remarkable improvements in impact resistance, fatigue performance, and energy absorption capacity. Consequently, UHPFRC is ideal for structures subjected to dynamic loads, blast effects, or severe exposure environments. Its modulus of elasticity typically ranges from 45 to 55 GPa, and its fracture energy is several times greater than that of conventional or high-performance concrete. Applications of UHPFRC extend across various sectors including bridges, high-rise buildings, tunnels, and precast components. It is also widely used for strengthening and rehabilitation of existing structures, offering enhanced bond strength and durability without adding significant weight. Although UHPFRC involves higher initial costs and stringent mixing and curing requirements, its superior strength, durability, and low maintenance needs make it a sustainable solution. Representing a significant advancement in concrete technology, UHPFRC provides an integrated solution to strength, ductility, and durability challenges—ushering in a new era of resilient and long-lasting infrastructure.

Keywords: CompressiveStrength,FlexuralStrength,SplitTensileStrength,WaterAbsorption,Strength,AndDuctility.

I. INTRODUCTION

Concrete has long been the cornerstone of modern construction, valued for its versatility, strength, and cost-effectiveness. It is used extensively in infrastructure such as buildings, bridges, dams, tunnels, and pavements across the world. Despite its widespread use, conventional concrete suffers from several inherent limitations, including low tensile strength, brittleness, susceptibility to cracking, and reduced durability under harsh environmental conditions. These drawbacks often result in premature deterioration, increased maintenance costs, and reduced service life of concrete structures.

To address these challenges, significant advancements have been made in the development of high-performance materials, leading to the emergence of Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC). UHPFRC represents a new generation of cementitious composites that combine superior mechanical strength, exceptional durability, and enhanced ductility. With compressive strengths typically exceeding 120 MPa, UHPFRC outperforms both conventional and high-performance concretes.

The superior properties of UHPFRC are attributed to its optimized mix design, which eliminates coarse aggregates and utilizes fine materials such as cement, silica fume, quartz sand, and high-range water-reducing admixtures. This produces a dense, homogeneous microstructure with extremely low porosity and permeability.

The addition of steel or synthetic fibers, usually between 1% and 3% by volume, provides crack-bridging ability and transforms the material from brittle to pseudo-ductile, allowing it to sustain deformation even after cracking.

Due to these properties, UHPFRC has found extensive applications in structural and non-structural elements, including bridges, high-rise buildings, precast components, and repair works. Its high resistance to impact, abrasion, and chloride ingress makes it particularly suitable for marine and aggressive environments. Moreover, while the initial cost of UHPFRC is higher than that of traditional concrete, its superior longevity and reduced maintenance requirements make it an economically viable and sustainable material in the long term.

A. Aim

To investigate the mechanical and structural performance of Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) incorporating silica fume and Ground Granulated Blast Furnace Slag (GGBS) with different types and volume fractions of steel fibers and to evaluate its effectiveness as a strengthening layer for reinforced concrete beams. in short form.

B. Objective

- To compare performance of UHPFRC mixes using silica fume (SF), and GGBS, incorporating steel fiber types at 1.0% and 1.5% volume.
- To perform compression, flexural, and impact tests to quantify strength, toughness, residual post-crack capacity and impact resistance.
- To investigate the effectiveness of UHPFRC as a bottom strengthening layer in improving the flexural strength, stiffness, energy absorption, and crack resistance of RC beams.

II. LITERATUREREVIEW

The growing demand for high-strength and durable materials has driven extensive research on Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) and related advanced composites. Multiple international studies have demonstrated its superior mechanical, structural, and durability performance across various applications.

Li et al. [1] reported that UHPFRC significantly enhances the impact and flexural performance of reinforced concrete (RC) beams compared to conventional concrete. Chun et al. [2] examined the use of Ultra-Rapid-Hardening Fiber-Reinforced Mortar (URH-FRM) to improve the flexural behavior of RC beams, investigating the influence of fiber aspect ratio and strengthening layer thickness on overall structural performance. Xing et al. [3] explored Steel–Basalt Fiber Composite Bars (SBFCBs) combined with Ultra-High-Performance Concrete–Normal Concrete (UHPC–NC) layered beams, achieving enhanced flexural capacity, durability, and cost-effectiveness in bridge structures exposed to aggressive environments.

Abu Bakar et al. [4] conducted experimental studies on retrofitting short RC columns using UHPFRC jackets, resulting in improved axial load-carrying capacity and ductility. Ma et al. [5] analyzed the behavior of concrete-encased concrete-filled steel tube (CECFST) columns incorporating UHPFRC, demonstrating increased strength, ductility, and buckling resistance under axial loading through both experimental and numerical approaches. Zhou et al. [6] investigated the effect of strain rate on Type I fracture performance of UHPFRC, evaluating various loading rates (0.12–120 mm/min) and steel fiber contents (1.0–2.0% by volume) to determine their influence on fracture behavior. Yoo et al. [7] focused on hybrid reinforcement systems combining Carbon Fiber Reinforced Polymer (CFRP) and steel bars in UHPFRC, which enhanced strength, ductility, and thermal resistance. Ahn et al. [8] studied the superior impact resistance and residual load-carrying capacity of UHPFRC compared to Normal-Strength Concrete (NSC) in RC slabs under high-velocity bending loads, considering both static and dynamic conditions. Yu et al. [9] investigated Ultra-High-Performance Slag Concrete (UHPSC) and observed that incorporating Polyoxymethylene (POM) steel fibers, a novel plastic-derived fiber, improved both mechanical and fracture properties.

Overall, these studies confirm that UHPFRC and its derivatives represent a major advancement in cementitious materials, offering superior strength, ductility, and durability. Their proven effectiveness in new construction, retrofitting, and repair applications underscores UHPFRC's potential as a next-generation material for resilient and sustainable infrastructure.

III. METHODOLOGY

This study adopts a detailed experimental methodology to evaluate the mechanical and structural performance of Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) incorporating silica fume and Ground Granulated Blast Furnace Slag (GGBS) with varying types and volume fractions of steel fibers. The key phases of the research are as follows:

A. Material Selection and Preparation

- Cementitious Materials: Ordinary Portland Cement (OPC 53 grade) was used as the primary binder. Silica fume and GGBS were added as supplementary cementitious materials to enhance microstructure densification and strength development.
- Fine Aggregates: Clean, well-graded quartz sand passing through a 2.36 mm sieve was used to maintain the dense matrix. No coarse aggregates were included.
- Steel Fibers: Cold-drawn steel fibers of various types (straight, hooked, and crimped) were used in different volume fractions (0.5%, 1.0%, 1.5%, and 2.0%) to study their influence on strength and ductility.
- Water and Admixture: Potable water and a high-range water-reducing admixture (superplasticizer) were used to achieve a low water-to-binder ratio (0.18–0.22) and desired workability.

B. Mix Design

- Mix proportions were optimized through trial mixes targeting compressive strengths above 120 MPa.
- The mix eliminated coarse aggregates, relying on fine materials for uniform particle packing.
- Silica fume and GGBS were used in selected percentages to improve workability, durability.
- Steel fibers were incorporated in varying proportions to analyze their effect on mechanical properties.

C. SpecimenCasting

- Differenttypesofstructuralandnon-structuralspecimenswerecast,including:
- Cubesforcompressivestrengthtesting.
- Cylindersforsplittensilestrength.
- Reinforcedbeamsfor flexural and impact load test.
- Post-tensionedbeamsformomentcapacityevaluation.

D. Curing

- Allspecimenswerecuredunderstandardconditions(e.g.,28daysinwater)toensureconsistenthydrationandstrength development.

E. TestingProcedures

- MechanicalTests:
  - Compressivestrength(IS:516/ASTMC39).
  - Flexuralstrength(IS:516/ASTMC78).
  - Split tensilestrength.
  - Impact Load Test
- DurabilityandWorkability:
  - Slumptestforworkability.

F. Analysisof Results

- Experimental results were compared with control specimens (conventional M40 concrete).
- Statistical and graphical analyses were conducted to evaluate the effect of fiber type and volume fraction.
- Parameters such as ductility, energy absorption, and deformation behavior were assessed to determine the structural performance.
- The optimal mix composition and fiber content were identified based on mechanical performance and economic consideration.

IV. RESULTSANDDISCUSSION

The experimental investigation demonstrates that the incorporation of steel fibers into Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) significantly enhances the mechanical and structural behavior of reinforced concrete (RC) beams. Three types of fibers—short straight (SS), long straight (LS), and long twisted (LT)—were evaluated at two volume fractions (1% and 1.5%) to analyze their effect on compressive, tensile, flexural, and impact performance.

The workability tests indicated satisfactory performance for all mixes, with slump values ranging between 124–130 mm. The use of a polycarboxylate-based superplasticizer effectively maintained self-compacting behavior despite the very low water-to-binder ratio, ensuring uniform fiber dispersion and homogeneity.

The compressive strength results revealed remarkable improvements with fiber inclusion. All UHPFRC mixes exhibited more than a 200% increase in strength compared to the control specimen (49.4 MPa). The highest value was obtained for LT1 (1% long twisted fiber) at 159.8 MPa, confirming that the twisted geometry provides superior mechanical anchorage and crack-bridging ability. However, increasing the fiber volume to 1.5% did not yield further benefits, as slight reductions were observed due to fiber clustering and reduced workability. The optimum fiber dosage was found to be around 1% for maximum compressive performance.

The split tensile strength results also confirmed the positive influence of steel fibers, with all fiber-reinforced mixes showing higher values than the control (3.72 MPa). The maximum tensile strength of 8.21 MPa was achieved with LT1.5 (1.5% long twisted fiber), representing an improvement of over 120%. The LT fibers provided the best results due to their twisted geometry, which enhances stress transfer and pull-out resistance. The LS series also showed significant improvement, while SS fibers provided moderate gains.

In terms of flexural performance, the inclusion of a 40 mm UHPFRC overlay layer significantly improved the load-carrying capacity and ductility of RC beams. The control beam (HSC1) had a flexural strength of 6.2 MPa, while the LT1 specimen reached a peak value of 37.4 MPa, showing a six-fold increase. The LT series demonstrated superior post-cracking behavior, with multiple fine cracks and gradual load reduction, indicating excellent energy absorption and ductile response. The LS fibers followed closely, while SS fibers, though effective, exhibited limited post-crack toughness. Increasing the fiber volume from 1% to 1.5% benefited the SS and LS series but slightly reduced performance in LT mixes due to fiber balling.

The impact test results further highlighted the effectiveness of UHPFRC strengthening. The control beam recorded a peak load of 310.8 kN, whereas LT1.5 achieved 332.4 kN, the highest among all specimens. Despite higher load capacities, the maximum deflections (31–34 mm) remained nearly constant, indicating that UHPFRC layers enhanced strength without compromising ductility. This demonstrates improved energy absorption and crack resistance under dynamic loading.

Overall, the results confirm that the integration of a 40 mm UHPFRC layer significantly enhances the strength, ductility, and impact resistance of RC beams. Among all fiber types, the long-twisted fibers (LT) provided the best mechanical performance, owing to superior bonding, anchorage, and stress redistribution. However, an optimum fiber content of 1% was found to balance strength gain, workability, and fiber dispersion. The study establishes UHPFRC as an effective material for structural strengthening and retrofitting applications, combining ultra-high strength with excellent crack control and energy dissipation capabilities.

V. CONCLUSIONS

The experimental study evaluated the mechanical behavior of reinforced concrete beams strengthened with a 40 mm UHPFRC layer incorporating different steel fiber types (short straight, long straight, and long twisted) and volume fractions (1% and 1.5%). Tests on compressive, split tensile, flexural strength, and impact performance revealed that the inclusion of steel fibers significantly enhanced strength, ductility, and post-cracking behavior.The long twisted fibers (LT) achieved the best overall performance due to superior anchorage and crack-bridging ability. Optimum results were obtained at 1% fiber content, as higher volumes slightly reduced workability and caused fiber clustering. The LT1.5 mix recorded the highest peak load (332.4 kN) with stable deflection, confirming improved load capacity without loss of ductility. Overall, the UHPFRC layer effectively improved the flexural and impact resistance of RC beams, demonstrating its suitability for structural strengthening and retrofitting applications.

VI. FUTURE SCOPE

Further studies can explore long-term durability under aggressive environments, optimization of fiber dosage (0.5–2%), and hybrid fiber combinations for improved crack control. Dynamic and fatigue load tests are also recommended to evaluate UHPFRC performance under impact and cyclic conditions for use in high-performance and protective structures.

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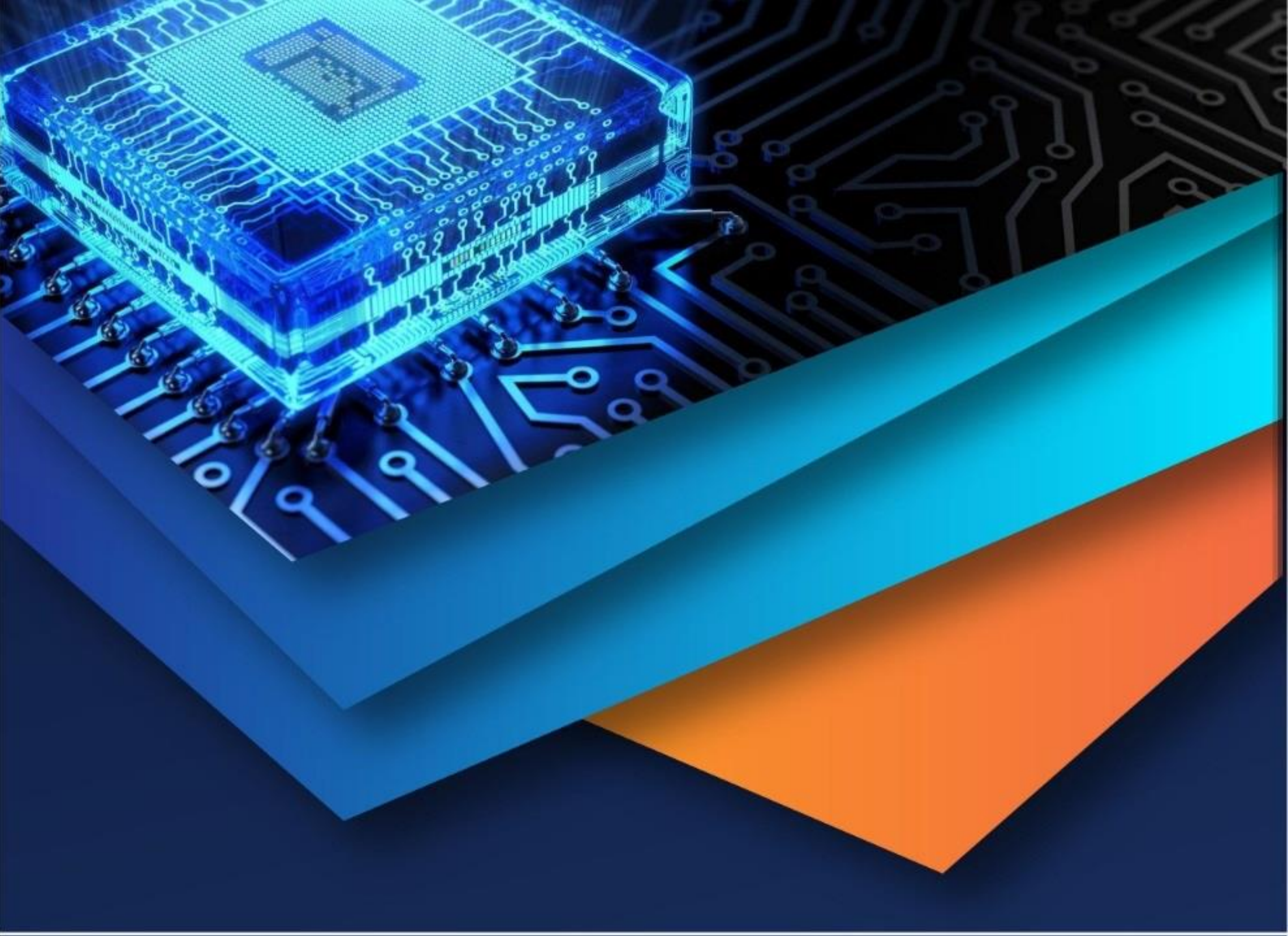

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