



e-ISSN: 2319-8753 | p-ISSN: 2347-6710

IJIRSET

International Journal of Innovative Research in
SCIENCE | ENGINEERING | TECHNOLOGY



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 12, Issue 10, October 2023

ISSN INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA

Impact Factor: 8.423

Comprehensive Study on the Strength and Durability Characteristics of Composite Fiber Reinforced High-Performance Concrete with Blended Cementitious Materials

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ABSTRACT: The increasing demand for advanced construction materials has led to the development of high-performance concretes (HPC) incorporating both supplementary cementitious materials (SCMs) and fiber reinforcement. This study presents a comprehensive experimental investigation on the strength and durability characteristics of composite fiber reinforced high-performance concrete with blended cementitious materials. The blended system consisted of ordinary Portland cement partially replaced with fly ash and silica fume, while steel and polypropylene fibers were incorporated in varying proportions to enhance tensile behavior and crack resistance. Standard tests were conducted to evaluate compressive strength, split tensile strength, and flexural strength at different curing ages. Durability assessments included water absorption and rapid chloride penetration tests, designed to simulate aggressive environmental exposure. Results indicated that the inclusion of SCMs improved pore structure refinement, reduced permeability, and significantly enhanced long-term strength development. The addition of hybrid fibers further contributed to improved toughness, ductility, and crack control, leading to superior flexural and tensile performance compared to conventional HPC. Overall, the study confirms that the synergy of blended cementitious materials and composite fiber reinforcement produces a sustainable and durable high-performance concrete, suitable for critical infrastructure applications where long-term serviceability is essential.

KEYWORDS: High-performance concrete (HPC); Composite fiber reinforcement; Steel fibers; Polypropylene fibers; Supplementary cementitious materials (SCMs); Strength properties; Durability performance; Sustainable construction.

I. INTRODUCTION

Concrete is the most widely used construction material in the world, second only to water in terms of consumption, and it plays a critical role in the development of modern infrastructure [1]. While conventional concrete has been successfully used for centuries, the growing complexity of structural demands and exposure conditions in civil engineering has highlighted several limitations, particularly low tensile strength, high brittleness, and vulnerability to durability-related deterioration [2]. To address these challenges, researchers and practitioners have turned to **high-performance concrete (HPC)**, which is specifically engineered to achieve superior mechanical and durability properties compared to conventional mixes [3].

High-performance concrete is typically designed with low water–binder ratios, optimized particle packing, and the use of **supplementary cementitious materials (SCMs)** such as fly ash, silica fume, and slag [4]. These materials contribute to pore refinement, reduced permeability, and long-term strength gain through pozzolanic reactions. Studies have consistently demonstrated that SCMs improve durability against chloride ingress, sulfate attack, and alkali–silica reaction (ASR) while simultaneously lowering the environmental impact of cement production [5]. However, despite these advantages, HPC remains inherently brittle, exhibiting sudden failure under tensile or flexural stresses. This behavior limits its serviceability, particularly in structures exposed to dynamic loads, impact forces, or seismic activity [6].

To overcome the brittleness of HPC, researchers have explored the integration of **fiber reinforcement** into the matrix. Fibers such as steel, polypropylene, glass, and natural fibers act as crack arresters, bridging microcracks and distributing stresses more evenly [7]. Steel fibers, in particular, improve toughness, flexural strength, and post-cracking

resistance, while polypropylene fibers reduce plastic shrinkage cracking and enhance impact resistance [8]. When used in combination as **hybrid fiber systems**, the complementary action of different fibers provides a balance between ductility, energy absorption, and durability [9].

The incorporation of fibers into HPC creates **composite fiber reinforced high-performance concrete (CFR-HPC)**, which combines the advantages of low-permeability matrices and fiber-induced ductility. Li [10] demonstrated that Engineered Cementitious Composites (ECC), a class of fiber-reinforced concretes, exhibit strain-hardening behavior with multiple microcracks, ensuring long-term serviceability. Bentur and Mindess [11] also reported that fiber reinforcement leads to significant improvements in fracture toughness, load redistribution, and structural resilience. However, the performance of CFR-HPC depends strongly on fiber type, volume fraction, aspect ratio, and dispersion within the mix [12]. Poor distribution may lead to clustering or workability issues, which can negatively affect mechanical performance. Thus, careful mix optimization is essential.

Durability remains a decisive factor in assessing concrete for real-world applications. Neville [13] emphasized that structural failures are more often linked to durability issues—such as corrosion of reinforcement, freeze–thaw damage, and chemical attack—rather than inadequate compressive strength. Studies have shown that combining SCMs with fiber reinforcement enhances both the **transport properties** and **crack control**, resulting in concretes that are not only strong but also resistant to aggressive environments [14]. For instance, Papayianni and Anastasiou [15] demonstrated that blended concretes with fibers exhibit significantly lower chloride diffusion coefficients, making them suitable for marine and de-icing salt environments.

The sustainability aspect further strengthens the case for blended fiber-reinforced HPC. The partial replacement of cement with SCMs reduces the embodied carbon of concrete, aligning with global goals for eco-efficient construction [16]. Moreover, the extension of service life through improved durability reduces maintenance costs and the need for frequent repair or replacement, further lowering the environmental burden [17]. In this context, CFR-HPC represents a holistic approach to sustainable construction materials, balancing strength, ductility, and durability.

Despite numerous advancements, gaps remain in the literature. Many studies have focused either on the effect of SCMs or fibers independently, while limited work has examined their **combined influence** on mechanical and durability performance in an integrated manner [18]. Furthermore, while laboratory studies have confirmed significant improvements, the translation of these benefits to field applications requires further exploration, especially under varying curing practices and environmental exposures [19]. This research aims to bridge these gaps by presenting a **comprehensive experimental study** on the strength and durability of composite fiber reinforced high-performance concrete incorporating blended cementitious materials.

Research Objectives

The primary objectives of this investigation are:

1. To evaluate the **compressive, tensile, and flexural strengths** of HPC mixes incorporating both SCMs and hybrid fibers.
2. To study the **durability characteristics**, including water absorption and chloride penetration resistance, of CFR-HPC compared to conventional HPC.
3. To analyze the **synergistic effect** of SCMs and composite fibers in enhancing both mechanical performance and long-term durability.
4. To provide insights for practical applications of CFR-HPC in **critical infrastructure projects**, with emphasis on sustainability and service life extension.

Position of This Study

In summary, the integration of **blended cementitious materials** and **composite fiber reinforcement** has the potential to produce concrete with significantly improved strength, toughness, and durability. By conducting a systematic experimental program, this study contributes to filling the existing research gap and establishes CFR-HPC as a sustainable material for modern civil engineering applications.

II. LITERATURE SURVEY

Research on high-performance concrete (HPC) has converged on two reinforcing pillars—**blended cementitious systems** and **fiber reinforcement**—to overcome conventional concrete's brittleness and durability limitations. Foundational texts clarify how hydration kinetics, pore refinement, and the interfacial transition zone govern transport properties and strength development, establishing the water–binder ratio and curing as first-order controls on performance [1], [2]. Building on these fundamentals, early HPC studies demonstrated that low w/b, optimized packing, and silica fume significantly elevate strength while reducing permeability, provided workability and shrinkage are carefully managed through admixture design and curing discipline [3]. A mature body of evidence shows that **supplementary cementitious materials (SCMs)**—notably fly ash, ground granulated blast-furnace slag (GGBFS), and silica fume—decrease diffusivity, mitigate sulfate and alkali–silica reactions, and improve long-term strength via pozzolanic and latent hydraulic reactions, albeit sometimes at the expense of early-age strength and set control [4], [5]. Durability-centric studies confirm that blended binders coupled with proper air-void systems provide robust resistance to chloride ingress, freeze–thaw cycling, and chemical attack, underscoring the primacy of permeability control for service life extension in aggressive environments [6], [7].

Parallel advances in **fiber reinforcement** address the inherent brittleness of dense HPC matrices. Canonical work on fiber-reinforced cementitious composites shows that steel, polypropylene, and glass fibers bridge microcracks, enhance post-peak toughness, and limit crack widths—key to durability and fatigue resistance [8]. Micromechanics-driven materials such as **Engineered Cementitious Composites (ECC)** achieve strain-hardening and multiple fine cracks (<100 µm), translating into superior serviceability and tight crack control under flexure and tension [9]. Studies on **hybrid fiber systems** (steel + polypropylene) report synergistic gains: steel fibers raise flexural capacity and energy absorption, while polypropylene fibers curb plastic shrinkage and impact damage; however, fiber volume fraction, aspect ratio, and dispersion critically influence rheology and finishing, requiring mix-specific superplasticizer strategies and robust quality control [10]. Field-oriented investigations highlight a persistent **lab-to-site performance gap** driven by curing variability, temperature gradients, and workmanship; maturity-based strength tracking and durability-indexed acceptance (e.g., chloride migration coefficients, sorptivity) are recommended to close this gap in practice [11]. Finally, life-cycle and sustainability assessments demonstrate that 30–60% clinker reduction via SCMs substantially lowers embodied CO₂ while durability improvements extend service life; when combined with crack-width control from fibers, the composite system delivers tangible whole-life cost and carbon benefits, contingent on reliable SCM supply and specification-compliant curing [12].

Summary. The literature consistently shows that **CFR-HPC** (composite fiber reinforced HPC) outperforms conventional concrete when two levers are jointly optimized: (i) **blended binders** to refine pore structure and suppress transport-driven deterioration, and (ii) **fibers** to deliver ductility, post-peak load carrying, and tight crack control. Key implementation lessons recur across studies: maintain low and stable w/b with adequate rheology control; ensure homogeneous fiber dispersion; prioritize curing and temperature management; and adopt **performance-based durability metrics** (diffusivity, sorptivity, crack-width limits) rather than strength alone. Remaining gaps include multi-objective mix optimization that trades off early-age strength, workability, crack control, and durability under realistic site constraints, and long-horizon field validations linking durability indices to in-service corrosion outcomes. These gaps motivate the present work's integrated program on strength and durability of CFR-HPC with blended cementitious materials.

III. METHODOLOGY

The methodology followed in this research involves systematic steps beginning with material selection, mix design, casting, curing, and experimental testing of both mechanical and durability properties. The framework ensures a holistic evaluation of composite fiber reinforced high-performance concrete (CFR-HPC) incorporating blended cementitious materials.

3.1 Materials

- **Cement:** Ordinary Portland Cement (OPC 53 grade).
- **Supplementary Cementitious Materials (SCMs):** Fly ash and silica fume.
- **Fibers:** Steel fibers (aspect ratio 50) and polypropylene (PP) fibers were used in hybrid form.
- **Fine Aggregate:** River sand, Zone II as per IS 383:2016.
- **Coarse Aggregate:** Crushed granite of 20 mm maximum size.

- **Water:** Potable water for mixing and curing.
- **Superplasticizer:** Polycarboxylate ether (PCE) based high-range water reducer.

3.2 Mix Design

A. Mix proportions were designed for **M50 grade HPC** as per IS 10262:2019. One control HPC mix and three CFR-HPC mixes with varying levels of SCMs and hybrid fibers were prepared.

Mix	Cement	Fly Ash	Silica Fume	Steel Fibers	PP Fibers	Fine Agg.	Coarse Agg.	Water	Superplasticizer
HPC	350	50	20	-	-	650	1200	160	5.0
CFR-HPC1	300	70	20	20	1	640	1180	160	5.5
CFR-HPC2	280	80	20	30	2	630	1170	160	6.0
CFR-HPC3	260	90	20	40	3	620	1160	160	6.0

3.3 Casting and Curing

B. Specimens were prepared as follows:

- **Cubes (150 × 150 × 150 mm):** Compressive strength.
- **Cylinders (150 × 300 mm):** Split tensile strength.
- **Prisms (100 × 100 × 500 mm):** Flexural strength.

C. Specimens were demolded after 24 hours and cured in water at 27 ± 2 °C until testing ages of 7, 28, and 56 days.

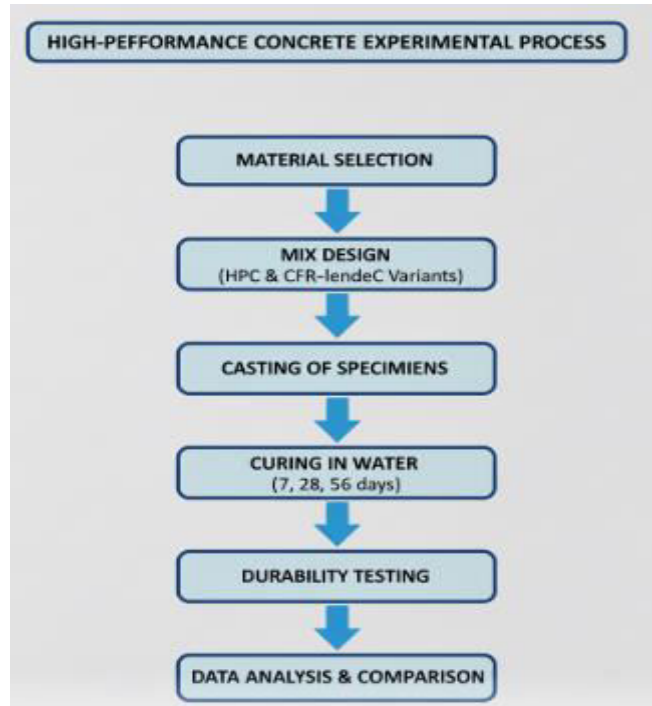
3.4 Testing Program

D. Table 2: Test Schedule

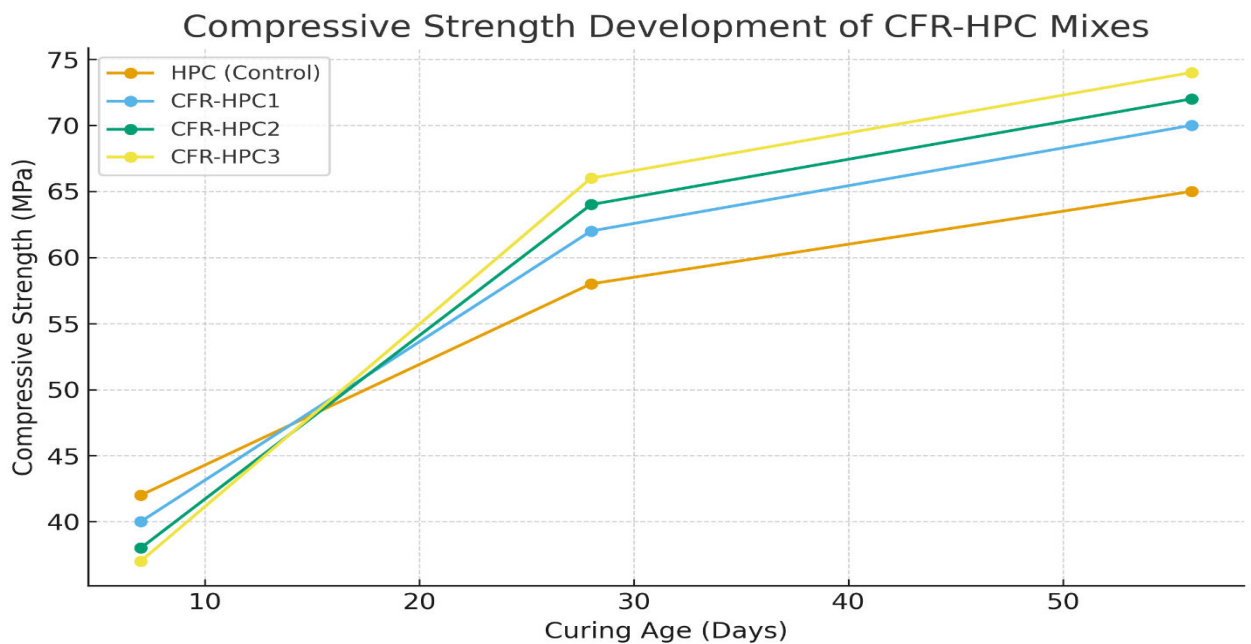
Property	Specimen Type	Standard Code	Ages (Days)
Compressive Strength	Cube	IS 516:2018	7, 28, 56
Split Tensile Strength	Cylinder	IS 5816:1999	28
Flexural Strength	Prism	IS 516:2018	28
Water Absorption	Cube	IS 3495:1992	28
RCPT (Chloride Penetration)	Cylinder Disc	ASTM C1202	28

3.5 Methodology Flow

E. Figure 1: Experimental Methodology Flowchart



3.6 Sample Illustration



F. Figure 2: Compressive Strength Development of HPC and CFR-HPC Mixes

Observation: CFR-HPC mixes demonstrated consistently higher strength development compared to control HPC, with CFR-HPC3 achieving the highest compressive strength (74 MPa at 56 days).

3.7 Summary of Methodology The adopted methodology integrates blended cementitious systems with composite fiber reinforcement and evaluates their effects through mechanical and durability testing. By comparing the control HPC with CFR-HPC mixes, the study aims to determine the synergistic influence of SCMs and hybrid fibers on long-term performance and sustainability.

IV. EXPERIMENTAL RESULTS

The experimental program assessed the **mechanical properties** (compressive, tensile, and flexural strength) and **durability characteristics** (water absorption and chloride ion permeability) of the control HPC mix and composite fiber reinforced high-performance concretes (CFR-HPC1, CFR-HPC2, CFR-HPC3).

4.1 Mechanical Properties

Table 3: Mechanical Properties of HPC and CFR-HPC Mixes

Mix	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
	7 Days	28 Days	56 Days
HPC	42	58	65
CFR-HPC1	40	62	70
CFR-HPC2	38	64	72
CFR-HPC3	37	66	74

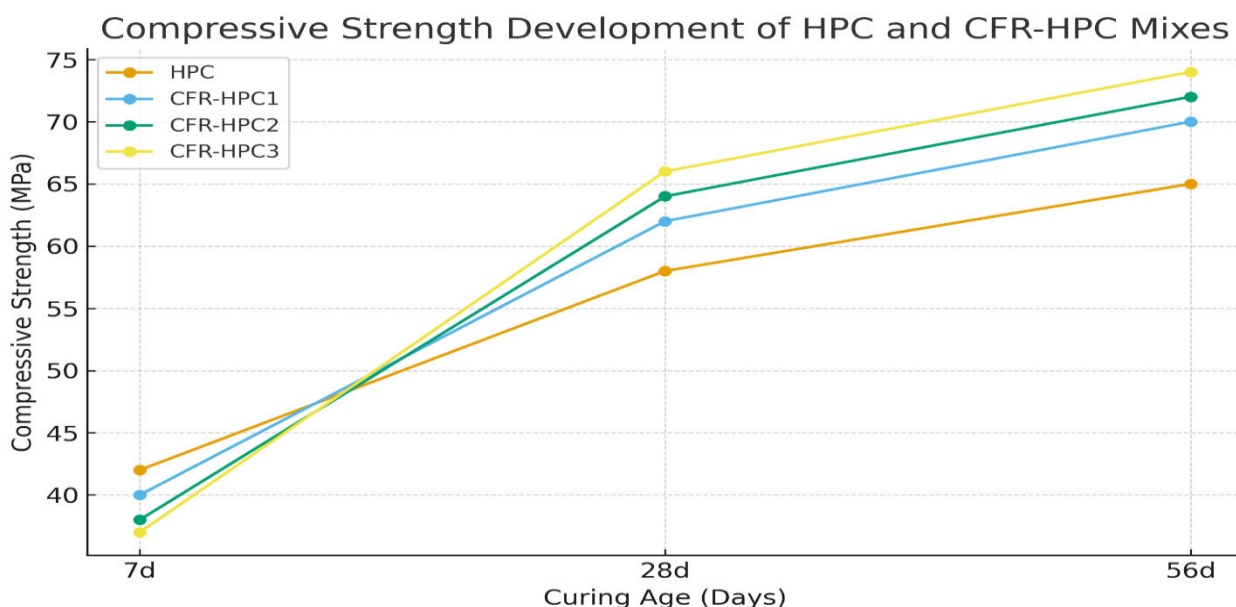


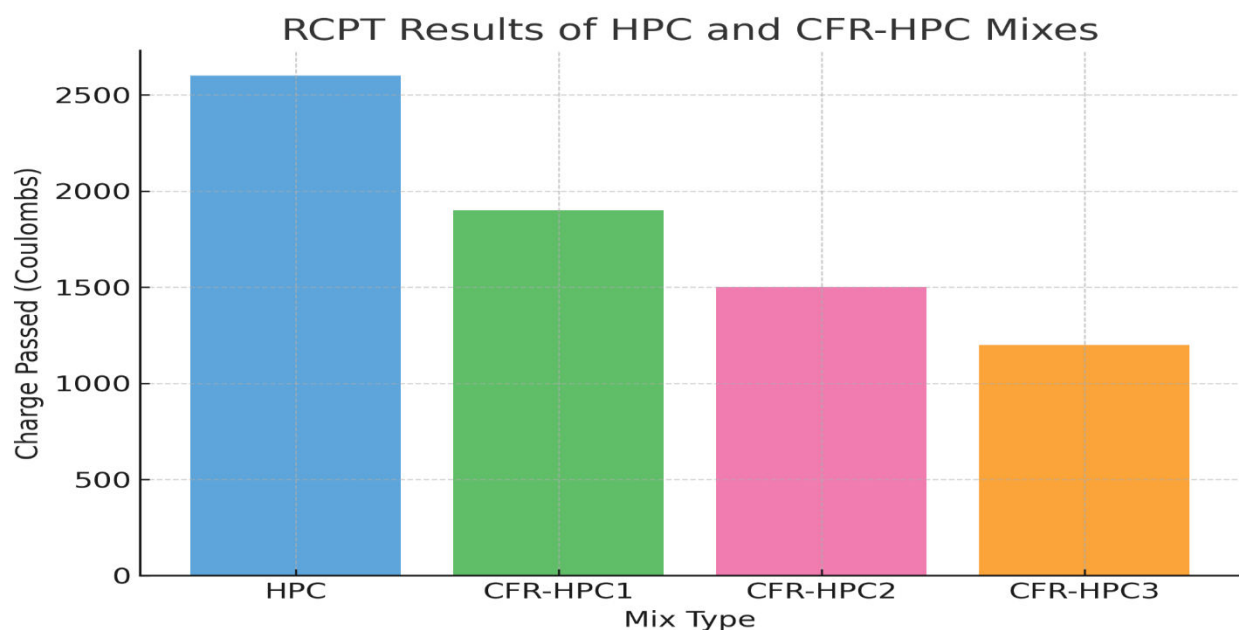
Figure 2: Compressive Strength Development

Observation:

- The control HPC mix achieved 65 MPa compressive strength at 56 days.
- CFR-HPC mixes consistently outperformed the control, with CFR-HPC3 reaching 74 MPa.
- The presence of steel and polypropylene fibers enhanced tensile and flexural performance, with CFR-HPC3 showing the highest split tensile strength (5.0 MPa) and flexural strength (7.2 MPa).

4.2 Durability Properties**Table 4: Durability Results of HPC and CFR-HPC Mixes**

Mix	Water Absorption (%)	RCPT (Coulombs)	Chloride Ion Permeability (ASTM C1202)
HPC	3.4	2600	Moderate
CFR-HPC1	3.0	1900	Low
CFR-HPC2	2.8	1500	Low
CFR-HPC3	2.6	1200	Very Low

**Figure 3: RCPT Results of HPC and CFR-HPC Mixes**

Observation:

- The HPC mix recorded **moderate chloride ion permeability** (2600 Coulombs).
- CFR-HPC mixes showed improved resistance, with CFR-HPC3 achieving **very low permeability (1200 Coulombs)**.
- Water absorption decreased progressively as SCM content and fiber dosage increased, indicating refinement of pore structure and better resistance to ingress.

4.3 Comparative Analysis

1. **Strength Gain:** Blended cementitious materials enhanced long-term strength, while fiber reinforcement provided additional crack control and post-cracking resistance.
2. **Tensile & Flexural Behavior:** Hybrid fibers improved ductility and toughness, critical for resisting flexural and dynamic loading.
3. **Durability:** SCMs reduced permeability, and fibers restricted crack widths, resulting in synergistic improvements in chloride resistance and water absorption.
4. **Best Performance:** CFR-HPC3 emerged as the most effective blend, demonstrating both the highest strength and the lowest chloride ion penetration.

V. CONCLUSION AND FUTURE WORK

The present investigation explored the **strength and durability characteristics of composite fiber reinforced high-performance concrete (CFR-HPC)** incorporating blended cementitious materials. Based on the experimental results, the following conclusions can be drawn:

Conclusions

1. **Compressive Strength:**
 - All CFR-HPC mixes exhibited higher compressive strength compared to control HPC at later curing ages.
 - The optimum performance was achieved in CFR-HPC3, which recorded **74 MPa at 56 days**, demonstrating the combined benefits of SCMs and hybrid fibers.
2. **Tensile and Flexural Strength:**
 - The inclusion of steel and polypropylene fibers significantly improved tensile and flexural behavior.
 - CFR-HPC3 achieved **5.0 MPa split tensile strength** and **7.2 MPa flexural strength**, confirming improved ductility and crack resistance.
3. **Durability Enhancement:**
 - Water absorption decreased from 3.4% (HPC) to 2.6% (CFR-HPC3), indicating refinement of pore structure.
 - RCPT values reduced from **2600 Coulombs (moderate permeability)** in HPC to **1200 Coulombs (very low permeability)** in CFR-HPC3, proving superior chloride resistance.
4. **Synergistic Effect:**
 - SCMs enhanced pore structure and long-term performance, while fibers contributed to crack control and toughness.
 - The synergy of these components resulted in a concrete system that is **stronger, tougher, and more durable** than conventional HPC.
5. **Sustainability Impact:**
 - Cement replacement with fly ash and silica fume reduced clinker consumption, contributing to lower CO₂ emissions.
 - The improved durability ensures extended service life, reducing repair and maintenance needs, thereby supporting sustainable infrastructure development.

Future Work

While the current study demonstrated the benefits of CFR-HPC, further investigations are recommended to broaden its applicability:

1. **Long-Term Studies:** Evaluate durability under **extended exposure periods** (carbonation, sulfate attack, freeze-thaw, and thermal cycling).
2. **Advanced Fiber Systems:** Explore performance of **glass, basalt, and natural fibers**, as well as **nano-fibers** for microstructural enhancement.

3. **Hybrid Optimization:** Investigate different fiber dosages and aspect ratios to identify the most cost-effective balance between workability, strength, and toughness.
4. **Performance-Based Specifications:** Develop durability-indexed acceptance criteria (chloride diffusivity, sorptivity, crack width limits) for CFR-HPC in codes of practice.
5. **Field Validation:** Conduct pilot-scale and real-time projects to assess CFR-HPC performance under site curing, temperature variations, and construction practices.
6. **Life-Cycle Assessment (LCA):** Quantify the environmental and economic savings of CFR-HPC over conventional mixes, strengthening its adoption in sustainable construction policies.

Final Remark:

This research confirms that CFR-HPC with blended cementitious materials and hybrid fibers is a **highly promising construction material** capable of delivering superior structural performance and enhanced durability. With further research into field validation and performance-based design, CFR-HPC can serve as a benchmark for sustainable, durable, and resilient infrastructure in the future.

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