Evaluation of Compressive & Fluxural Strength of Concrete mixes with Steel & Polypropylene Fibers

Nikhil A. Maske
Research Scholar, Civil Engineering,
Shri Venkateshwara University,
Amroha, Uttar Pradesh, India.
nikhilmaske@gmail.com

Dr. Gopal Krishna Mehta
Professor, Civil Engineering,
Shri Venkateshwara University,
Amroha, Uttar Pradesh, India.
mehtaconsultants_gkm@yahoo.com

Dr. Snehal Abhyankar
Dean, Skill Development Cell
Tulsiramji Gaikwad-Patil College of Engineering
Nagpur, Maharashtra, India.
snehal.abhyankar@gmail.com

***Abstract* — Cement concrete remains the most commonly utilized construction material in civil engineering due to its numerous established advantages. Nevertheless, its inherently low tensile strength presents a significant limitation. To address this issue, extensive research has been conducted. Findings from these studies indicate that fiber reinforcement is among the most effective and versatile strategies for enhancing post-cracking strength in tension and ability to sustain load and deform without immediate failure, significantly improving the toughness and durability of concrete. The incorporation of fibers improves the post-peak ductility of concrete, enhances its fatigue and tensile strength before cracking, and effectively reduces cracking induced by temperature fluctuations and shrinkage. In concrete applications, hybrid fiber composites enhance the overall performance by leveraging the complementary properties of the individual fibers.**

Index Terms— Fluxural strength, workability, Fibre reinforced concrete etc.

I. Introduction

A range of fiber types are employed as reinforcement within the concrete matrix, including polymer-based, metallic, and natural fibers. Natural fibers commonly used include those derived from palm, straw, and coir. Metallic fibers typically consist of steel or stainless steel, while polymer fibers are generally composed of materials such as polyester, polypropylene, and aramid. These fibers can vary in form being either long or short, straight or hooked, and may be used individually or in hybrid combinations.

Conventional concrete consists of cement, aggregates, water, and optionally admixtures, which together form a composite material through proper mixing. It is the primary construction material in most structural applications due to its excellent compressive strength. However, it exhibits poor tensile performance. A key limitation of even high-quality conventional concrete is the inherent presence of micro-cracks, capillaries, and micro-capillaries. Concrete behaves as a quasi-brittle material, meaning that once cracking initiates, it rapidly loses its load-bearing capacity. To address these deficiencies, SF's are commonly taken into consideration to improvise the mechanical performance of concrete. Polypropylene fiber, a more recent addition to construction materials, has been introduced to mitigate several of concrete's weaknesses, particularly its low tensile strength and susceptibility to cracking caused by drying or plastic shrinkage.

The term *hybrid* commonly refers to a composite system composed of multiple materials with distinct properties. Incorporating more than one type of fiber into concrete addresses its inherent deficiencies more effectively than using a single fiber type. This approach, known as hybridization, involves combining fibers with varying mechanical characteristics to form a composite material, generally referred to as a hybrid. HyFRC i.e. Hybrid fiber-reinforced concrete is a specialized form of FRC characterized by the inclusion of two or more types of fibers differing in size, shape, or origin. This composite material consists of hydraulic cement, sand, coarse aggregates, water, and a combination of distinct fiber types. In recent years, HyFRC has gained prominence as an effective form of secondary reinforcement due to its ability to control and resist the propagation of microcracks. Specifically, combining polypropylene fibers (PPF) and steel fibers enables the optimization of both mechanical and durability-related properties.

The integration of fibers with different physical and chemical characteristics including blends of organic (e.g., polypropylene, nylon) and inorganic (e.g., steel) fibers enhances the performance of cement-based composites by leveraging the advantages of each component. Organic fibers such as polypropylene and nylon contribute to increased impact resistance and long-term stability. Additionally, improved flexural performance can be achieved through the use of higher fiber volume fractions, which enhance stress transfer mechanisms within the matrix. By leveraging the concept of hybridization the incorporation of two distinct fiber types within a single cementitious matrix the resulting hybrid fiber-reinforced composite can exhibit superior engineering properties compared to systems with individual fibers alone. This enhancement arises from the synergistic interaction between the fibers, where the presence of one fiber type can activate or complement the latent performance characteristics of the other, leading to improved crack control, ductility, and energy dissipation.

Fiber reinforcement contributes to crack bridging, which can enhance aggregate interlock mobilization, leading to improved shear capacity. To develop design guidelines that account for the role of fibers in shear resistance, it is essential to understand how fibers affect post-cracking shear stress transfer across rough crack surfaces and their overall impact on the strength in shear for RC structures. Construction and demolition (C&D) activities worldwide generate substantial amounts of waste.

For instance, in 2018 alone, the United States produced approximately 600 million tons of C&D debris, more than double the volume of municipal solid waste (MSW) generated in the same period (U.S. Environmental Protection Agency, 2015). In the European Union, C&D waste accounts for roughly 33.5% of total waste mass (World Cement, 2016), and by 2026, China is projected to dispose of around 4 billion tons of such materials. Given that conventional concrete comprises approximately 70% aggregate by volume, substituting natural aggregates with recycled materials presents an opportunity to mitigate environmental impacts.

However, while the use of recycled aggregates can reduce the need for virgin aggregate extraction, it may negatively influence properties such as compressive strength, workability, segregation resistance, and chemical stability. As a result, the incorporation of recycled aggregates in concrete is typically restricted to a maximum of 20%. To overcome the inherent brittleness of concrete, the incorporation of fibers can effectively address issues such as plastic settlement, shrinkage, and bleeding in its fresh state. Additionally, fibers enhance the material's deformation capacity, improve fatigue resistance, and promote the formation of finer, more uniformly distributed cracks.

II. CHARACTERIZATION OF A FIBROUS MATERIAL

Fiber reinforcement is extensively employed to enhance the toughness and ductility of inherently brittle cement-based materials. Traditionally, fiber-reinforced composites incorporate a single type of fiber, which can lead to only limited improvements in performance characteristics. However, when different fiber types are combined, they can interact synergistically—producing a combined effect that exceeds the sum of their individual contributions. This synergistic behavior is observed in hybrid composites, which are formed by the intentional blending of two or more fiber types to capitalize on the unique advantages of each. The term "hybrid" denotes this process of fiber integration.

Hybrid fiber-reinforced composites exhibit enhanced performance due to this synergistic interaction. Hybridization can be achieved through various approaches, including varied aspect ratios among various types of fibers (i.e., variations in length and diameter) or differing mechanical properties such as modulus of elasticity E or improving tensile strength T etc. Combinations based on fiber aspect ratio tend to improve both the strength and fracture resistance of the material, helping to manage both microcrack initiation and macrocrack propagation.

Alternatively, hybrids based on distinct fiber mechanical properties leverage complementary behavior where a stiffer fiber enhances load-bearing capacity (including first-crack and post-crack strength), and a more resilient fiber contributes to improved capacity in strain as well as firmness . The study determines the optimal volume fraction of hybrid fibers that yields the highest level of synergy in terms of allied properties of SPHFRC.

The persuasion of both polypropylene fibers (PPF) and steel fibers (SF) on concrete performance varies depending on their respective volume fractions. A synergistic effect was observed in SPHFRC, where the combined use of both fiber types resulted in superior flexural and tensile performance compared to concrete reinforced with only a single type of fiber.

High Performance Concrete (HPC) is specifically engineered to deliver enhanced performance tailored to the available materials, intended application, and environmental exposure, while meeting requirements for cost-efficiency, service life, and durability. Technological advancements over the past two decades have significantly influenced the concrete construction industry—some enhancing its practical application, while others have focused on improving concrete's engineering properties. Key advancements in concrete technology include the development of high-strength concrete through the use of superplasticizers, fiber-reinforced concrete incorporating steel, glass, polymer, carbon, or natural fibers, as well as innovations such as latex-modified concrete, chemically bonded ceramics, macro-defect-free (MDF) cement products, and various forms of polymer-based concrete.

Modern construction industries increasingly demand advanced materials that meet specific criteria such as sturdy, longevity, and value-driven. Concrete, one of the most widely used construction materials, is composed of a cement paste matrix and aggregates, with its overall performance being significantly influenced by the strength and quality of the interfacial transition zone (ITZ) between these two phases. Presently in recent years, high-strength concrete has gained significant popularity among civil engineers and contractors due to its ease of production and favorable mechanical properties.

Despite its widespread application in both new construction and repair works, concrete possesses inherent weaknesses—particularly in tension—and exhibits a brittle nature. The brittleness of concrete tends to increase as compressive strength rises, which can limit the practical use of high-strength concrete. This brittleness is further exacerbated by the low water-to-cement ratio typically used in high-strength concrete, which reduces porosity but increases susceptibility to cracking.

High Performance Concrete (HPC) is characterized by the enhancement of one or more of the following properties:

- Improved workability for ease of placement
- Superior long-term mechanical performance
- Increased early-age strength
- Enhanced toughness
- Greater volume stability
- Extended service life under harsh environmental conditions

III. TENSILE STRENGTH FOR CONVENTIONAL CONCRETE COMPOSITE

Concrete's brittle behavior often results in early formation of microcracks, even prior to the application of external loads or exposure to environmental factors, due to intrinsic volumetric and microstructural changes. Additionally, concrete has low strain capacity and limited toughness, as microcracks propagate rapidly under applied stresses. Environmental factors and service loads further aggravate this condition by promoting the growth and coalescence of microcracks, particularly at the interface matrix in aggregate layer and the cement paste. Over time, these very tiny cracks can develop into macrocracks, ultimately compromising the integrity of structural elements.

Therefore, there is a critical need for effective strategies to enhance the tensile strength of concrete and mitigate its brittle failure mechanisms. Previous research has demonstrated that the inclusion of short, randomly distributed discontinuous fibers can significantly enhance the overall integrity of concrete, particularly by evaluating the strength in tension, crack resistance alongwith toughness. The concept of fiber addition to cementitious materials is not new historical evidence shows the use of straw in bricks and animal hair in cement mortars long before the modernization in FRC Composites.

AS per (ACI) Committee i.e. American Concrete Institute, FRC is defined as *"hydraulic cement containing fine or fine and coarse aggregates and discontinuous discrete fibers."* FRC composites incorporate a wide variety of fiber types, which can be broadly categorized as metallic or non-metallic, natural or synthetic, and low-modulus or high-modulus fibers. Commonly used fibers include steel, glass, asbestos, carbon, and various synthetic or organic fibers such as polypropylene, polyethylene, and polyester.

The evolution of FRC technology began with the adoption of steel fibers in the early 1960s, followed by the introduction of polymeric fibers in the 1970s, glass fibers in the 1980s, and carbon fibers in the 1990s. Plain, unreinforced cementitious composites are inherently brittle due to their low tensile strength and limited stress-carrying capacity. While conventional reinforcement bars placed at strategic locations can improve tensile and shear performance, fiber-reinforced composites modify the behavior of concrete through effective crack control mechanisms rather than by directly increasing load-bearing capacity. It is crucial to recognize that fibers are not intended to replace traditional reinforcement bars.

The dense microstructure and enhanced rheological characteristics of materials enable them to have or provide supplementary reinforcement, particularly in areas where conventional reinforcement may be impractical. The mechanical performance of FRC is largely governed by the interaction between the surrounding matrix alongwith composition of fibres in variations, specifically ability to bridge cracks and limit their propagation.

The orientation of fibers relative to the direction of applied loads significantly influences key mechanical parameters such as the elastic modulus and capability in both cracked and uncracked states. In a properly engineered FRC system, fibers contribute to one of two primary functions within the cracked matrix: enabling strain hardening or facilitating controlled strain softening, depending on the design intent and material composition.

HPC is an intricate material characterized by superior strength, workability, and durability. It is specifically engineered to fulfill stringent performance and consistency standards, typically achieved by reducing the water content compared to conventional concrete and incorporating supplementary cementitious materials. Attaining the desired strength in HPC depends heavily on the quality and specific properties of each constituent. Appropriate material selection is essential for producing a cost-effective and efficient high-performance mix. High Performance Fiber Reinforced Concrete (HPFRC) involves reinforcing a cementitious matrix either cement or a cement-based mixture with discrete fibers. In this research, the development of HPFRC is accomplished using an amalgamation of cement, FA, CA, water, chemical or mineral admixtures & reinforcing fibers.

IV. LITERATURE REVIEW

Jing Zhu

- The experimental findings, supported by anchorage analysis, demonstrate that AASC exhibits bonding and reinforcement capabilities
- Additionally, the results confirm the superior thermal resistance and reliable bonding performance of AASC.
- These outcomes offer valuable insights for the structural design and practical implementation of inorganic matrices in FRP strengthened concrete systems.
- Overall, this review aims to serve as a valuable reference for researchers and engineers focused on advancing the surface engineering of NFRCs for improved performance in diverse application domains.

Mohammed Mohammed

- Advantages of NFRC—such as low cost, low density, wide availability, and biodegradability—have spurred significant research interest across various industrial sectors. However, several inherent limitations hinder their broader application.
- As a result, surface modification of NFRC has become a critical area of study to address these challenges. This review article provides a comprehensive overview of NFRCs, their material characterization, and the complications associated with their integration into polymer matrices.
- Surface treatment techniques for NFRC—such as alkali treatment, silanization, acetylation, and benzoylation—aimed at mitigating moisture uptake and fiber degradation. These treatments are explored in terms of their impact on fiber hydrophilicity, surface chemistry, interfacial adhesion, mechanical performance, and thermal stability.
- Furthermore, the review includes an in-depth assessment of nanoparticle (NP)-based surface modification approaches. These methods have shown promise in enhancing hydrophobicity and interfacial bonding between NFRC and polymer matrices, thereby potentially improving their mechanical integrity and dimensional stability.

Ferit Cakir

- Advanced and widely adopted materials in the construction industry today. Unlike traditional Portland Cement Mortars (PCMs), PMs are produced using distinct formulation and processing techniques, making them increasingly favorable for constructions.
- Mechanical characteristics of PMs were examined. Three distinct mix designs were evaluated: M1 (0.5% CGFs, 0% CBFs by weight of pure polymer cement), M2 (0% CGFs, 0.5% CBFs), and M3 (0.25% CGFs, 0.25% CBFs).
- The mechanical properties of these mixtures were assessed to observe phenomena such as fiber pullout, fiber fracture, debonding, and matrix cracking.
- Fiber types, chopped basalt fibers (CBFs) demonstrated superior performance compared to chopped glass fibers (CGFs). The M2 mixture, containing only CBFs, exhibited the most favorable mechanical characteristics and fracture resistance.

Adil R. Al-Alawi

- The broader aim of constructing environmentally sustainable cities by promoting structural materials that are lightweight, highly durable, require minimal maintenance, and support long service life—all of which are critical in mitigating the effects of climate change.
- Combining macro-synthetic fibers (at Vf = 0.69%, 0.52%, and 0.34%) with steel fibers enabled a reduction in steel fiber usage by 56%, 42%, and 28%, respectively—while still maintaining 75%, 86%, and 90% of the shear capacity associated with 1.25% steel fiber-reinforced UHPC beams.
- Values corresponding gains in shear capacity of 17%, 53%, and 74%. While the initial cracking load showed minimal sensitivity to lower fiber volumes, it increased by 27% for the 0.69% macro-synthetic fiber mix and by 56% when combined with steel fibers, highlighting the synergistic effect on early crack resistance.

Krzysztof Ostrowski

- A typical CFT column consists of an inner concrete core encased within a steel tube, which provides both formwork and passive confinement to the concrete, effectively delaying or mitigating buckling of the steel shell.
- The steel tube yields, local buckling and the resulting non-uniform confinement stress pose serious concerns for the structural integrity of these columns.
- Experimental findings confirm that the external CFRP confinement is effective in suppressing bucklings.
- Stress–strain response of these systems is strongly influenced by the level of confinement pressure induced by the CFRP layers.
- The results provide valuable insight into the structural behavior and optimization of hybrid confinement systems for concrete filled steel tubes.

P.L. Ng

- FRP materials typically possess a lower elastic modulus than steel, serviceability considerations such as deflection and crack control become particularly critical in the design and analysis
- Among these, the tensile stress block method offers a practical and less computationally intensive approach suitable for routine structural design. To support this, the study introduces a parameterized tensile stress block, derived from finite element simulations of the tensile stress field, as a tool for deflection prediction in FRP-RC members.
- Several methods are discussed for predicting the flexural response and deformation of these members, including:
  ➢ Analytical or empirical models for estimating effective flexural stiffness,
  ➢ Finite element analysis (FEA) incorporating nonlinear constitutive models, and
  ➢ Simplified member analysis based on tensile stress block concepts.

Rostami Rohollah

- This study investigates the role of superabsorbent polymers (SAPs) in mitigating shrinkage and reducing cracking tendencies in fiber-reinforced mortars (FRMs).

- The study emphasized SAP's dual role:
  ➢ First, in promoting internal curing by releasing absorbed water to sustain ongoing hydration of FA and GGBS.
  ➢ Second, in providing microstructural space especially in pores <20 nm for the precipitation of hydration products.
- The findings revealed that SAPs enhance hydration kinetics and microstructural uniformity, particularly by depositing hydration products on fiber surfaces and within capillary pores. SAPs with finer particle sizes (~80 µm) were especially effective, demonstrating up to 50% strength recovery.
- Furthermore, the strength gain beyond the second week of curing was significantly improved in samples containing CEM III/A, indicating that SAP-induced internal curing becomes more prominent in FRMs incorporating slag based cements. The study provides evidence that the synergistic use of SAPs with SCMs results in enhanced long-term durability and reduced cracking potential in advanced cementitious composites.

Mathias Hammerl

- HPC & CFRP exhibit advantageous material properties, making them promising candidates for advanced structural applications.
- The approach adopted by the authors involves integrating these two materials to develop lightweight concrete structures with slender wall sections.
- However, a notable limitation of such filigree constructions lies in the reduced flexural stiffness of the cross section, primarily due to CFRP's relatively low Young's modulus despite its high tensile strength.
- In conventional steel-reinforced systems, prestressing is commonly employed to enhance deflection performance.

Krzysztof Adam Ostrowski

- Three types of concrete surface conditions ground, sanded, and unprepared were analyzed.
- The surface morphology of each condition was clearly characterized, and the Abbott-Firestone bearing area curve was used to quantitatively evaluate surface roughness profiles.
- Among treatments on the surfaces he went through, ground surfaces yielded the most effective bond characteristics and thus the highest reinforcement performance.

V. METHODOLOGY

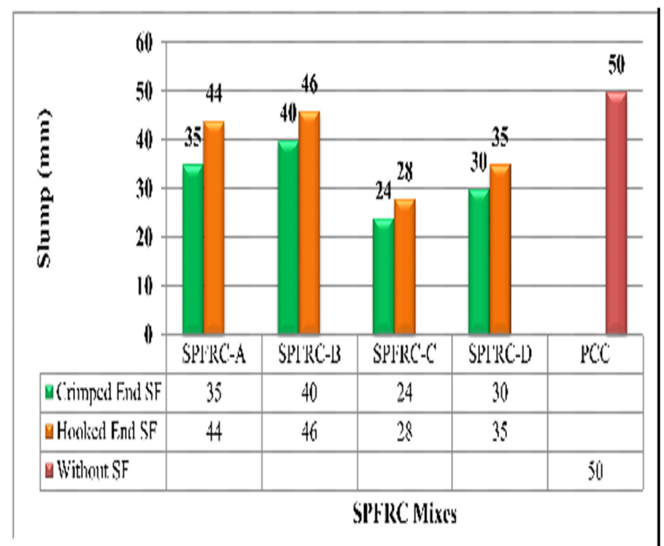
Ingredients taken into consideration are -

a. PPC Cement by Ultratech Cements Ltd.
b. Sand confirming to all the specifications of Indian Standard specifications (Specific Gravity test, bulking of sand test etc.) are performed.
c. Course aggregates with nominal size aggregates of 20 mm are used confirming to IS 383 by performing (Specific Gravity test, impact test, crushing strength test, flakiness index, elongation index, abrasion value etc.)
d. Super plasticizer taken to be 0.5 % weight of cement
e. Mix Design calculations confirming IS 10262.

Sampling Method -

A. Sample I is taken 0.5% of total fibre content including sf as .35% part & ppf as 0.15% part
B. Sample II is taken 0.5% of total fibre content including sf & ppf as .25% part each
C. Sample III is taken 1% of total fibre content including sf as .85% part & ppf as 0.15% part
D. Sample IV is taken 01% of total fibre content including sf as .75% part & ppf as 0.25% part

Workability by Slump Cone



The SPFRC–C mix, containing 0.85% crimped steel fibers, exhibited the maximum slump loss of approximately 52%, highlighting the significant impact of higher fiber content on workability. When hooked-end steel fibers were used in the same mix, the slump loss was comparatively lower at 44%. In the SPFRC–D mix, slightly improved workability was observed, with slump reductions of 40% for crimped steel fibers and 30% for hooked-end steel fibers.

Compressive Strength Test

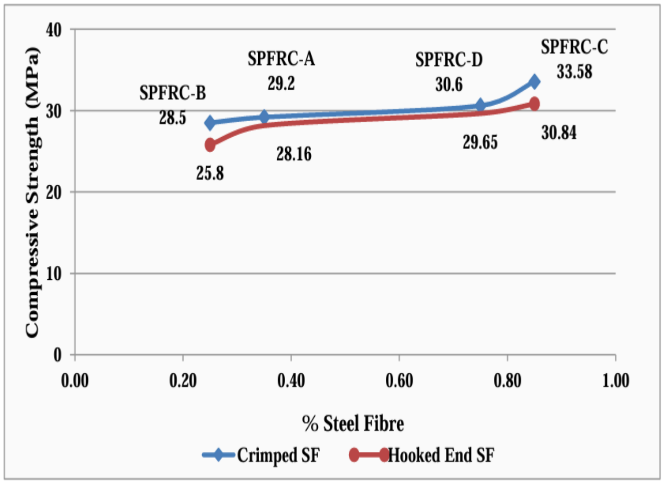


Figure 3 Variation of Compressive Strength with the % Steel Fibres at 7 Days

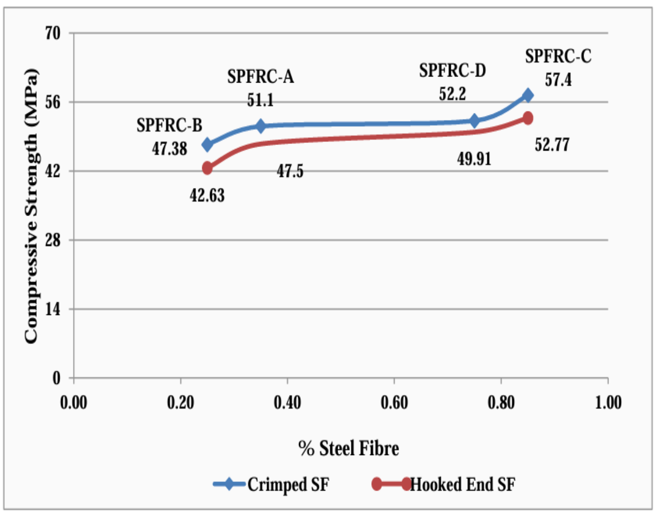


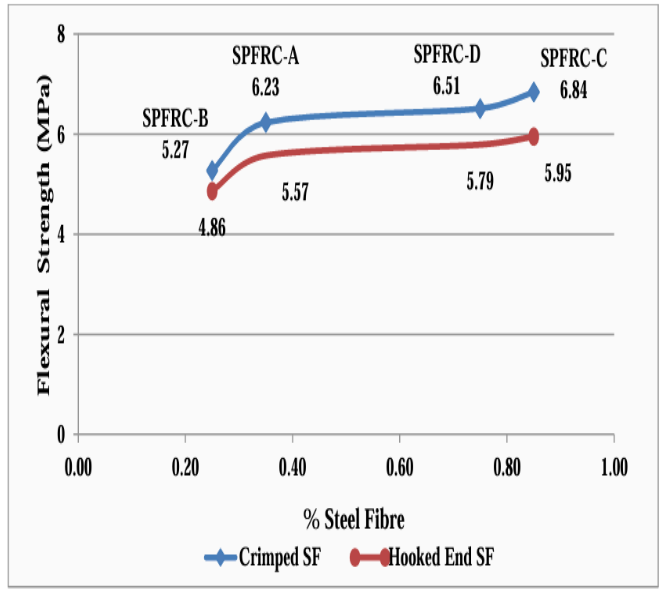
Figure 4 Variation of Compressive Strength with % Steel Fibres at 28 Days

Flexural Strength

The test results demonstrate the variation in flexural strength as a function of steel fiber content at both 7-day and 28-day curing periods. In the SPFRC–C mix incorporating crimped steel fibers, the 7-day flexural strength increased by 45.9% over the control concrete, while at 28 days, the increase reached 120%. For the same mix using hooked-end steel fibers, flexural strength gains were 21.42% at 7 days and 92% at 28 days.

In comparison, the SPFRC–B mix, containing a lower dosage of steel fibers, exhibited relatively lower strength improvements. When reinforced with crimped steel fibers, the 28-day flexural strength increased by 63.22%, whereas the mix with hooked-end fibers showed a 48.21% improvement over the control.

Overall, all SPFRC mixes demonstrated superior flexural performance compared to conventional concrete. The findings confirm that flexural strength is significantly influenced by both the fiber type and dosage, with higher fiber content and the use of crimped steel fibers leading to greater strength enhancements.



VI. Discussion & Conclusion

The workability of SPFRC mixes was significantly affected by both the type and dosage of steel fibers. An increase in steel fiber content consistently resulted in reduced workability. The highest slump loss was observed in the SPFRC–C mix, containing 0.85% crimped steel fibers and 0.15% polypropylene fibers.

Regarding mechanical performance, the SPFRC–C mix demonstrated a 37% increase in compressive strength compared to the control mix. Furthermore, the maximum enhancement in flexural strength was also recorded for this mix, showing a 120% increase, primarily due to the crack-bridging capability of the crimped steel fibers.

References

[1] Bassam A. Tayeh, Mahmoud H. Akeed, Shaker Qaidi, B.H. Abu Bakar, (2022), “Ultra-high-performance concrete: Impacts of steel fibre shape and content on flowability, compressive strength and modulus of rupture” Journal of Case Studies in Construction Materials, Volume – 17, Palestine.

[2] Lynda Kheddache, Chouaib Aribi, Kahina Chahour, Brahim Safi (2022) “Highlighting of the distribution effect of steel hook fibers at low and high dosage on the flexural strength of self-compacting mortars” Journal of Materials Today Proceeding, Volume – 52, Algeria.

[3] Daudi Salezi Augustino, Charles Kabubo, Christopher Kanali, Richard Ocharo Onchiri (2022) “The orientation effect of opening and internal strengthening on shear performance of deep concrete beam using recycled tyre steel fibres” Journal of Results in Engineering, Volume – 15, Kenya.

[4] Dorys C. Gonzalez, Alvaro Mena, Gonzalo Ruiz, Jose J. Ortega, Elisa Poveda, Jesús Mínguez, Rena Yu, Angel De La Rosa, Miguel A. Vicente (2022), "Size effect of steel fiber–reinforced concrete cylinders under compressive fatigue loading: Influence of the mesostructure" International Journal Fatigue, Volume – 107353, Spain.

[5] Chang Gao, Liang Huang, Libo Yan, Bohumil Kasal, Wengui Li, Ruoyu Jin, Yutong Wang, Yin Li, Peng Deng (2021), "Compressive performance of fiber reinforced polymer encased recycled concrete with Nanoparticles" Journal of Material Research & Technology, Volume – 14, China.

[6] Adil R. Al-Alawi, M.A. Mashrei (2022), " Shear capacity of sustainable ultra-high performance concrete beam reinforced with macro synthetic fiber as a sustainable alternative for stirrups and steel fiber" Journal of Case Studies in Construction Materials, Volume – 17, Iraq.

[7] Krzysztof Ostrowskia, Mateusz Dudekb, Łukasz Sadowskic (2020) "Compressive behaviour of concrete-filled carbon fiber-reinforced polymer steel composite tube columns made of high performance concrete" Journal of Composite Structures, Volume – 234, Poland.

[8] P.L. Ng, J.A.O. Barros, G. Kaklauskas, J.Y.K. Lam (2022), "Deformation analysis of fibre-reinforced polymer reinforced concrete beams by tension-stiffening approach" Journal of Composite Structures, Volume – 234, China.

[9] Rostami Rohollah, Klemm Agnieszka J., Fernando C.R. Almeida (2022), " Effect of superabsorbent polymers on microstructure and strength of blended cements mortars reinforced by polymeric fibre" Journal of Cement, Volume – 9, UK.

[10] Mathias Hammerl, Benjamin Kromoser (2021), "The influence of pretensioning on the load-bearing behaviour of concrete beams reinforced with carbon fibre reinforced polymers" Journal of Composite Structures, Volume – 273,Austria.

[11] Krzysztof Adam Ostrowski, Kazimierz Furtak (2021), "Influence of high temperatures on the bond between carbon Fibre-Reinforced polymer bars and concrete" Journal of Composite Structures, Volume – 276, Poland.