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Fibre-reinforced Concrete: Review on Bridging Mechanism, Mechanical Properties, Durability, and Eco-economic Analysis

Fibre Reinforcement

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***Abstract*— Fibre-reinforced concrete (FRC) has significantly enhanced the mechanical performance and durability of concrete structures. The influences of various physical and mechanical properties of fibres on FRC are complex, requiring a systematic review to clarify their roles and interactions. Unlike previous reviews that classify fibres based on type or size, this study introduces a different approach based on fibre Young's modulus, providing deeper insights into fibre functionality and its influence on the bridging mechanism. By shifting the focus to modulus, this review assesses the role of fibre stiffness in governing the mechanical behaviour, durability, and eco-economic aspects of FRC. The study comprehensively examines FRC properties, including bridging mechanisms, workability, mechanical performance, and durability under environmental conditions such as freeze-thaw cycles and chloride ingress. Findings indicate that high-modulus fibres, such as steel and carbon, enhance tensile strength and crack control, while low-modulus fibres, such as polypropylene and polyethylene, improve impact resistance and energy absorption. Hybrid fibre systems offer synergistic benefits by optimising toughness, ductility, and strain-hardening behaviour. Additionally, an eco-economic analysis highlights the potential of fibre selection strategies to balance sustainability, cost-efficiency, and performance. By synthesising extensive previous research results, this review offers practical guidelines/suggestions for fibre selection to enhance ductility, maximise efficiency, and minimise embodied carbon, considering cost efficiency**

***Keywords*—** Benefits of FR in Concerete for Strength increment and protection against the propogation of further cracks and its strength.

I. Introduction

Fibre-reinforced concrete (FRC) has improved concrete structures by significantly enhancing their mechanical properties and durability. Recent studies have demonstrated that the incorporation of micro steel fibres can increase the compressive strength of ultra-high performance concrete (UHPC) by up to 30 % and the compressive strength by 16.79 % compared to hooked-end steel fibres . Furthermore, the addition of just 0.5 % fibrillated polypropylene (PP) fibres improved the fracture energy of concrete under impact loading by 100 % . FRC not only enhances mechanical performance but also greatly extends the service life of structures. Previous studies indicated that the use of micro fibres, such as polypropylene and polyvinyl alcohol (PVA) fibres, can reduce the permeability and porosity of concrete more effectively than macro fibres , thereby increasing durability. The use of hybrid fibre reinforcement, combining steel and PVA fibres, enhances the resistance of UHPC to electrochemical corrosion These remarkable improvements in strength and longevity have made FRC an indispensable material in the construction of bridges, tunnels, pavements, and high-rise buildings, where superior performance and extended service life are paramount.

FRC integrates various types of fibres, such as PP, steel, synthetic, and natural fibres, into the concrete mix. These fibres act as a bridge across cracks, distributing stresses more evenly and preventing the propagation of cracks, which significantly improves the concrete's tensile and flexural strength. For instance, PP fibres are particularly effective in enhancing the durability of concrete under freeze-thaw cycles and chloride ion penetration, making it suitable for structures exposed to harsh environmental conditions. Steel fibres, with their high tensile strength, are known to improve the impact resistance and overall toughness of concrete

II. Research Significance

This study takes a different approach by classifying fibres based on their modulus rather than type, providing new insights into how fibre stiffness influences the bridging mechanism, mechanical behaviour, and overall durability of FRC. In addition to those aspects, this manuscript reviews the use of fibres and their functionalities in both FRC and UHPC. While FRC and UHPC are distinct in their formulations and overall performance characteristics, they both rely on the fibre bridging mechanism to enhance crack resistance and improve durability. By examining these two types of concrete together, this review emphasizes the critical role of fibres in bridging mechanisms, which is fundamental to improving the mechanical properties and extending the service life of concrete structures.

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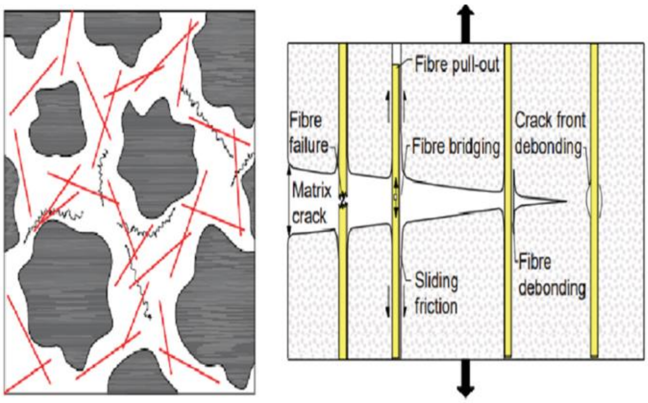
To address these knowledge gaps, this comprehensive review aims to provide an in-depth analysis of state-of-the-art research on FRC, focusing on fundamental bridging mechanisms, fibre properties, mechanical performance, durability under various environmental conditions, and eco-economic aspects.

A. BRIDGING MECHANISM

The bridging mechanism is fundamental to the performance of FRC. It involves fibres bridging across cracks in the concrete matrix, resisting crack propagation and enhancing tensile and flexural properties, thus improving toughness, ductility, and post-cracking behaviour. Fibres and concrete matrix are subjected to multiple failure modes, e.g., matrix cracking, fibre rupture, fibre pulling- out, sliding friction, and fibre bridging.



When concrete resists tensile or flexural stresses, micro cracks form due to inherent weaknesses. In plain concrete, these cracks can merge and propagate, leading to brittle failure. In FRC, fibres bridge these micro-cracks, transferring stresses from the matrix to the fibres, preventing further crack growth.

B. MICRO FIBRES

Micro fibres, typically 10–100 micrometres in diameter and a few millimetres long, have a high length-to-diameter ratio. When dispersed throughout the mix in small quantities (typically 0.1–0.5 % by volume), micro fibres can effectively enhance crack control, mechanical properties, and durability. Micro fibres, with their high aspect ratio and uniform distribution, effectively bridge micro cracks and enhance the crack resistance of FRC . The addition of micro fibres, e.g., PP and carbon, can increase the splitting tensile strength by 14–26 %. Micro fibre also can improve compressive strength in interaction with other factors like cement type, water-cement ratio, and mix design.

MACRO FIBRES

Macro fibres, larger (0.3–1.0 mm diameter) and longer (20–60 mm) than micro fibres, have high tensile strength and play a crucial role in the bridging mechanism. They bridge cracks, distributing tensile stresses and resisting crack opening. Macro fibres effectively control crack widths and prevent further propagation, while micro fibres provide more uniform stress distribution and manage vapor and thermal pressures at elevated temperatures.

EFFECT OF FIBRE SHAPE

The fibre shape significantly influences the interaction and bond between the fibres and the concrete matrix, thus affecting the bridging mechanism. Hooked-end steel fibres provide mechanical anchorage within the concrete matrix, preventing fibre pullout and enhancing the bridging effect. Similarly, crimped steel fibres increase surface area and create a better mechanical bond with the concrete, improving load transfer efficiency and crack bridging capacity. In another way, roughing fibres surface also improves their bonding, e.g., silane-treated jute fibres have shown improved tensile, flexural, and compressive shear strength by approximately 40%, 35%, and 55%, respectively, compared to untreated samples. The optimal volumes of long twisted fibre and medium-length straight fibre to effectively improve UHPC's flexural strength are less than 1% and 1.5%, respectively. Corrugated and hooked-end steel fibres can increase UHPC's compressive strength by 48% and 59%, respectively, while decreasing flowability by 45% and 51%.

III. STEEL FIBRES

PROPERTIES AND CHARACTERISTICS

Steel fibres are the most commonly used in FRC and UHPC due to their commercial viability and superior mechanical properties. With high tensile strength ranging from 0.69 to 2.94 GPa and modulus of elasticity around 200–210 GPa, steel fibres significantly enhance the tensile strength, ductility, toughness, and post-cracking behaviour of concrete. Fibres with hooked ends, spiral shapes, and deformed geometries provide better anchorage, resulting in improved compressive strength and tensile strength under both static and dynamic loads.

EFFECTS OF FIBRES ON MECHANICAL PROPERTIES

The mechanical properties of FRC are significantly influenced by the properties of fibres, particularly their modulus of elasticity. The modulus of fibres directly affects the stress transfer and crack bridging efficiency within the concrete matrix, which in turn governs the overall mechanical

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performance of FRC . To better understand the impact of fibre modulus on the mechanical properties of FRC, this section classifies fibres into two main categories: high modulus fibres (e.g., steel and carbon) and low modulus fibres (e.g., PP, nylon and PE). By comparing the effects of high vs low modulus fibres on various mechanical properties such as compressive strength, tensile behaviour, flexural performance, and energy absorption, this review aims to provide valuable insights into the selection of appropriate fibre types for specific FRC applications.

EFFECTS OF FIBRES ON DURABILITY CHARACTERISTICS

The incorporation of fibres can significantly improve the resistance of concrete to various environmental and mechanical attacks, such as shrinkage, permeability, chloride diffusion, carbonation, freeze-thaw cycles, and exposure to elevated temperatures or aggressive environments. This section explores the influence of fibre characteristics, including size (micro vs. macro), length, shape, dosage, and modulus, on the durability properties of FRC.

MATERIALS AND METHODOLOGY CEMENT:

In the present experimental investigation, 53 Grade Ordinary Portland cement (OPC) was used. The physical properties of cement are shown in Table

S. No	Properties	Values	IS Specification
1	Fineness	4	IS:4031(part1)-1996
2	Specific Gravity	3.11	IS:4031(part11)
3	Normal Consistency	30%	IS:4031(part4) & IS269
4	Initial Setting Time	50 min	> 30 Min. IS:4031(part5) & IS269
5	Final Setting Time	335 min	< 600 Min. IS:4031(part5) & IS269

FINE AGGREGATE

Aggregate is also an important constituent of concrete, in the present experimental investigation, locally available sand confirming to Zone II of IS 383-2016.

COARSE AGGREGATE

The coarse aggregates are irregular broken stones or naturally available gravels that are used in making concrete. Aggregates that have a size more than 4.75 mm are considered as coarse aggregates. They are usually found in stone quarries and stone crushers with sizes of 4.75mm to 80 mm. The graded mixture of 20 mm and 12 mm coarse aggregates was adopted in the current experimental study to attain higher compaction and improve the mechanical properties of the concrete.

WATER

Casting and curing of the specimens were carried out using potable water. The quality of water plays a crucial role in determining the strength and durability of concrete. Therefore, it must be free from substances that are harmful to both concrete and reinforcement. Parameters such as pH, chloride content, sulphate content, alkalinity, acidity, and hardness are typically evaluated to assess the suitability of water for construction purposes. In this experimental study, water samples were analyzed, and the results are compared with the permissible limits specified in IS: 456–2000 to verify compliance with standard requirements.

CONCRETE MIX

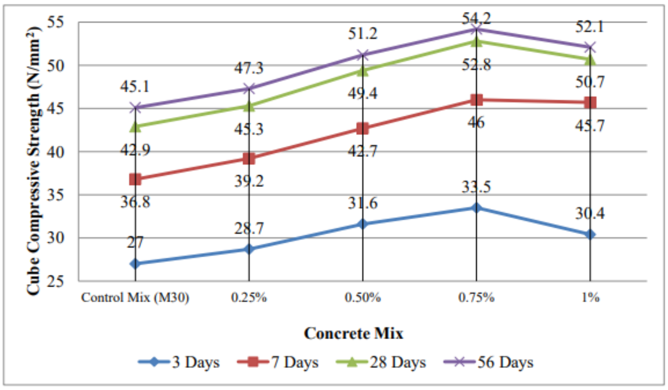
In compliance with IS 10262:2019 [20] and IS 456:2000 [21], concrete mix design is a procedure of determining the proportions of the constituents of concrete in order to achieve the required strength and workability. The proportions of design mix of grade of M30 concrete are 1:1.9:3.68 water-cement ratio = 0.5, and cement content = 340kg/m3.

TESTING PROCEDURE

Test specimens of concrete are in the shape of cubes (150 mm × 150 mm × 150 mm), cylinders (150mm × 300mm) and prisms (100mm × 100mm × 500mm). Concrete cubes were casted to test 3,7,28, and 56 days compressive strength though cylindrical and prism specimens were dried to test 28 days. Hardened concrete was cast after which tests were carried out on hardened concrete to establish the cube compressive strength of concrete, split tensile strength (on cylinders), flexural strength (on prisms) and drop weight impact strength. The outcomes of the test were compared with the control mix concrete (devoid of fibre) to identify the impact of fibre reinforcement on different strength characteristics, and the conclusions were made.

EXPERIMENTAL RESULTS

Compressive Strength: Initially, a Compression strength test was conducted on cured conventional M30 grade concrete cubes, in accordance with IS 516:2021 [23]. The cubes were tested at the ages of 3, 7, 28, and 56 days to determine the compressive strength. The results of the compressive strength test of concrete are shown



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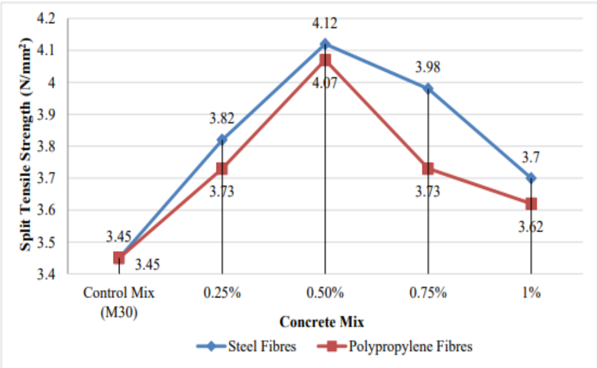
SPLIT TENSILE STRENGTH:

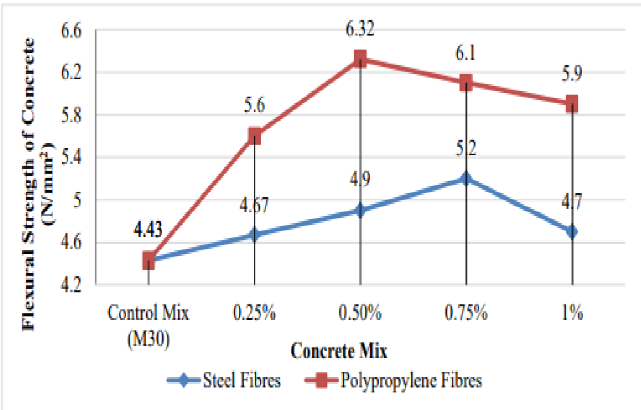
The split tensile strength test in the current experimental study was conducted on cylindrical specimens that were cast in conventional M30 grade concrete of 150 mm and 300 mm diameter and height respectively. It was the test conducted in IS 5816:1999.The specimens were also cured in water after casting and allowed to cure in a period of 28 days. The specimens were put in the machine lying horizontally, and compressive load was applied upon its vertical diametric plane until failure.



Variation of Split Tensile strength of concrete with Different Percentages of Steel and Polypropylene Fibres

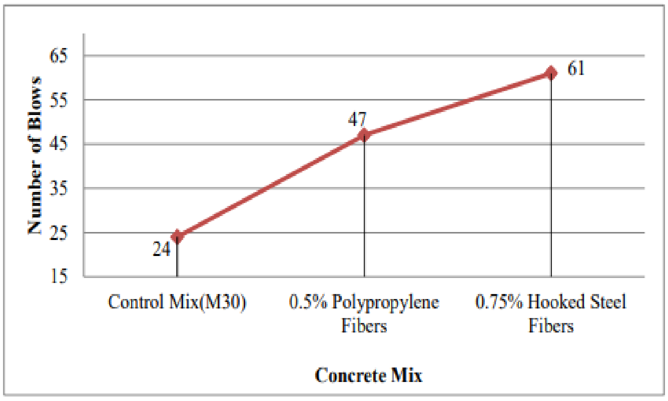
Flexural Strength:

The flexural strength test is conducted to evaluate the ability of concrete to resist bending or flexural stresses. In this study, the test was carried out on M30-grade conventional concrete prisms of size 100 mm × 100 mm × 500 mm, in accordance with IS 516:2021 [23]. After casting, the specimens were cured in water for 28 days.



Impact Strength of Fibre Reinforced Concrete:

A drop weight impact strength test is conducted to determine the strength of concrete. The impact strength test determines the number of blows that are required to cause particular magnitudes of distress to concrete specimens. The casting is done in cylindrically shaped moulds (diameter 150 mm and thickness 64 mm). It will be tested based on ACI 544.2R-89[24]. Fig. 6, indicates the comparison of impact strength of the control concrete and the fibre reinforced concrete. According to the test findings the impact strength of fibre reinforced concrete is higher than the controlled concrete.



CONCLUSIONS:

1. The compressive strength of 0.75% hooked steel fibre reinforced concrete exhibits 20% to 25% and Polypropylene fibre reinforced concrete exhibits 10 % to 23% more strength than the control concrete at 3, 7, 28, and 56 days of curing.

2. 2. The maximum split tensile strength of concrete is obtained at 0.5% for steel and Polypropylene fibre reinforced concretes. The split tensile strength of fibre reinforced concrete (steel and Polypropylene fibres) is approximately 18 % more than the control concrete.

3. Based on the test results, improved flexural strength of fibre reinforced concrete at the optimum content of fibres can be observed. The increase in flexural strength of concrete is 21.5 % in case of Steel fibres and 42% for Polypropylene fibres. The improved flexural strength properties can be attributed to the delayed crack formation due to the presence of fibres. Finally, based on the results of the experimental investigation, it can be concluded that the presence of steel fibres or Polypropylene fibres improves the strength properties of concrete. The optimum percentage of fibres depends on the type of fibres used. Hence, the use of fibre reinforced concrete is recommended for various structural applications and the durability of concrete can be enhanced.

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