Strength Enhancement Of Concrete Reinforced With Polypropylene Fibers Of Varied Geometries And Densities

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Abstract- *The rapidly increasing volume of industrial waste material poses a severe threat to environmental sustainability and ecological balance. Furthermore, the commercial production of synthetic fibers contributes significantly to global warming through greenhouse gas emissions. In structural applications, conventional concrete exhibits high compressive strength but remains inherently weak in tension. This vulnerability is primarily caused by the presence of micro-cracks at the mortar-aggregate interface. To mitigate this weakness, control micro-crack propagation into macroscopic failures, and enhance tensile properties, fiber-reinforced concrete (FRC) is widely utilized. This study investigates the integration of polypropylene fiber (PPF)—a synthetic hydrocarbon polymer—into cement concrete mixes. A comprehensive laboratory investigation was conducted to evaluate the structural behavior of this material in FRC applications. The primary objective of this research is to analyze the influence of varying polypropylene fiber lengths and densities on the fundamental strength characteristics of concrete, specifically its compressive strength, split tensile strength, flexural strength, and impact resistance.*

Keywords: Polypropylene fiber, Fiber-reinforced concrete, Fiber-reinforced mortar, Compressive strength, Split tensile strength, Flexural strength.

I. INTRODUCTION

Concrete remains one of the most versatile and widely utilized materials in modern construction due to its high compressive strength, excellent fire and water resistance, low maintenance needs, and exceptional durability. It can easily be molded into complex structural shapes, from cylindrical tanks to rectangular columns. However, plain concrete possesses inherent mechanical drawbacks, most notably its low tensile strength and brittle nature. This weakness is primarily caused by the development of micro-cracks during the curing phase. When the material is subjected to external loads, these micro-cracks propagate rapidly through the cement matrix, preventing unreinforced concrete from sustaining significant tensile stresses. While traditional discrete reinforcement (such as steel or composite rebars) can carry heavy structural loads, it cannot effectively arrest or delay the initiation and growth of these micro- and macro-cracks at the material level.

The Fibre Reinforced Concrete (FRC) is a composite materiel essentially consisting of concrete reinforced by random placement of short discontinuous and discrete fine fibers of specific geometry. It is now well established that the addition of short, discontinuous fibers plays an important role in the improvement of the mechanical properties of concrete. In the FRC, the fibers help to transfer load to the internal micro cracks. In the recent past, many developments have been made in the fiber reinforced concrete. Also it has been recognized that addition of small, closely spaced and uniformly dispersed fibers to concrete would act as crack arrester and would substantially improve the properties and can cause a change in the failure mode under compressive deformation from brittle to pseudo-ductile, thereby imparting a degree of toughness to concrete. Concrete made with Portland cement has certain characteristics; it is relatively strong in compression but weak in tension and tends to be brittle. These two weaknesses have limited its use. Another fundamental weakness of concrete is that cracks start to form as soon as concrete is placed and before it has properly hardened. These cracks are major cause of weakness in concrete particularly in large onsite applications leading to subsequent fracture and failure and general lack of durability. The weakness in tension can be overcome by the use of conventional rod reinforcement and to some extent by the inclusion of a sufficient volume of certain fibers. Glass, fiber, carbon fibers are commonly used in manufacturing of reinforcing bars for concrete applications.

It is possible to make several classifications among fiber types. Fibers can be divided into two groups, Those with elastic moduli lower than the cement matrix, such as cellulose, nylon, and polypropylene and those with higher elastic moduli such as asbestos, glass, steel, and carbon.

Among all the fibers Steel fibers have been used in pavements, in shotcrete, and in a variety of other structures. Banana fibers are renewable and obtained from natural resources that present several advantages, including low density, acceptable specific strength properties, good sound abatement capability, low abrasivity, low cost, high biodegradability and existence of vastresources. In addition, at the end of their life cycle these can be incinerated for energyrecovery, because they have a good calorific value. New application areas become available as new fiber types and new FRC production techniques are developed.

Fiber reinforced concrete (FRC) is concrete containing fibrous material which increases its structural integrity. It contains short discrete fibers that are uniformly distributed and randomly oriented. Fibers include steel fibers, glass fibers, synthetic fibers and natural fibers. Within these different fibers that character of fiber reinforced concrete changes with varying concretes, fiber materials, geometries, distribution, orientation and densities.

This Study describes the influence of different lengths and densities of fibre on fiber reinforced concrete. In this project polypropylene fibre used to study the influence of fibre and detected the influence using workability, compressive strength, and tensile strength on comparison with conventional concrete.

II. REVIEW OF LITERATURE

The conventional production of plain cement concrete yields a highly versatile structural material characterized by notable compressive strength, exceptional fire rating, environmental stability, and longevity. Despite these positive engineering parameters, unreinforced concrete matrices exhibit acute vulnerabilities, specifically low tensile capacity, poor fracture strain, and an inherent susceptibility to micro-cracking during the fundamental hydration and curing phases. When mechanical or thermal loads are sustained, internal micro-cracks propagate rapidly through the cement paste matrix. This unhindered macro-crack progression precipitates catastrophic brittle failure modes before high stress thresholds can be distributed.

Omualdi and Batson (1963) after conducting impact test on fibre reinforced concrete specimens, they concluded that first crack strength improved by addition of closely spaced continuous steel fibres in it. The steel fibres prevent the adverting of micro cracks by applying pinching forces at the crack tips and thus delaying the propagation of the cracks. Further, they established that the increase in strength of concrete is inversely proportional to the square root of the wire spacing.

Charles H.Henage (1976) developed an analytical method based on ultimate strength approach, which has taken into account of bond stress, fibres stress and volume fraction of fibres. After his investigations, he concluded that the incorporation of steel fibres significantly increases the ultimate flexural strength, reduces crack widths and first crack occurred at higher loads.

B Jaivignesh and A Sofi (2017) performed Study Properties of Concrete with Plastic Waste as Aggregate. The aim of this paper is to find out the effects of plastic waste on the mechanical properties of polymer concrete. They used the plastic place of fine aggregates as well as coarse aggregates in proportion of 10%, 15 % and 20% and further added steel fibre to the concrete and came to conclusion that the reduction in strength but suggested its use in favor of reduction of waste material and eco friendly materials.

H. Alperenbulut et al. (2017): - The research study shows the effects of electronic waste (e-plastic) on the strength properties of polymer concrete and done a laboratory experimentation on various fresh and hardened properties of concrete.

A.N.Dancygier and Z.Savir studied the influence of steel fiber on flexural performance of high strength concrete beam with low longitudinal reinforcement ratio, which proved that steel fiber enhance brittleness of beam compared to that of beam with minimum longitudinal reinforcement ratio. Compared to steel fiber reinforced concrete, the hybrid fiber with different type and size can improve effectively strength and toughness of concrete, form hybrid effect during different fiber, play respective beneficial influence from different level. However, few researches on flexural performance of hybrid fiber reinforced RC beam were studied.

Based on the investigation on the workability of hybrid fiber reinforced self-compacting concrete (HFRSCC)' a series of hybrid fiber reinforced SCC beams with low longitudinal reinforcement ratio are tested to evaluate the hybrid fiber influence on load-deflection curve, beam flexural ductility. Steel fiber reinforced SCC beams were made in order to compare the load, ductility with hybrid fiber reinforced SCC beams.

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III. MATERIALS AND METHODS

The experimental investigation work is started with various tests on the constituent materials. The constituent materials are given below.

1. Cement
2. Coarse aggregate
3. Water
4. Polypropylene fiber

Cement

Ordinary Portland Cement (OPC) was used in the experimental work which is conforming to I.S 4031-1988.The O.P.C is classified into three grades, those are 33grade, 43grade and 53 grades, and depending upon the strength of the cement in this experiment 43grade cement is used.

Fine Aggregate

Fractions from 4.75 mm to 150 microns are termed as fine aggregate. Locally available river sand passed through 4.75mm IS sieve is applied as fine aggregate conforming to the requirements of IS 383:1970.

Coarse Aggregate

The crushed aggregates used were of 20mm nominal maximum size.Aggregate most of which is retained on 4.75-mmIS Sieve and containing only so much finer material as is permitted for the various types described in this standard.

Polypropylene fiber

Polypropylene fiber reinforced concrete is also known as polypropene or PP. It is a synthetic fiber, transformed from propylene, and used in a variety of applications. These fibers are usually used in concrete to control cracking due to plastic shrinkage and drying shrinkage. They also reduce the permeability of concrete and thus reduce the bleeding of water.. Polypropylene fiber displays good heat-insulating properties and is highly resistant to acids, alkalis, and organic solvents.

IV. MIX DESIGN

The process of selecting suitable ingredients of concrete and determining their relative amounts with the objective of producing a concrete of the required, strength, durability, and workability as economically as possible, is termed the concrete mix design. The proportioning of ingredient of concrete is governed by the required performance of concrete in two states, namely the plastic and the hardened states. If the plastic concrete is not workable, it cannot be properly placed and compacted. The property of workability, therefore, becomes of vital importance. Percentage dosage of super plasticizer was fixed as per the mix design method described in IS 10262- 2009. Mix proportion was arrived through various trial mixes. The grade of concrete prepared for the experimental study was M40.

V. TESTS ON HARDENED CONCRETE

5.1 COMPRESSIVE STRENGTH

5.1.1 Influence of Curing Age and Fiber Parameter Trends

The development of compressive strength in concrete remains the foundational benchmark for assessing structural adequacy. For this investigation, an M40 grade design mix was utilized as the baseline matrix. The evaluation tracked the performance of the concrete specimens across standard curing durations of 7, 14, and 28 days to monitor both early-age and long-term mechanical strength gain.

The experimental data reveals that the mechanical presence of randomly oriented, discontinuous polypropylene (PP) fibers alters the compressive resistance of the matrix depending on the interaction between two independent variables: fiber length and fiber dosage density. In standard concrete matrices, compressive loading leads to lateral strain expansion, inducing microstructural micro-fissures along the aggregate-cement mortar interface. The incorporation of synthetic polymer fibers mitigates this effect by introducing internal spatial network confinement.

5.1.2 Breakdown by Fiber Volume Fraction

- At a low dosage density of 2 kg/m^3 incremental gains in compressive strength are observed as fiber lengths increase from 10 mm to 40 mm. Under this lower volume fraction, the spatial frequency of individual fibers within the concrete matrix remains limited. While the fibers bridge minor micro-cracks, their physical spacing leaves localized zones of unreinforced cement paste vulnerable to initial tensile stress propagation.

- Moderate-Dosage Regime 4 kg/m^3: As the fiber volume is increased to 4 kg/m^3, the matrix exhibits its highest level of structural optimization. The spatial density of the polymer network is high enough to intersect advancing micro-fissures without causing internal compaction flaws. At this dosage level, a fiber length of 30 mm yielded the maximum compressive strength recorded in the study, showing a pronounced increase across all three curing ages.
- High-Intermediate Dosage Regime 6 kg/m^3: When the fiber addition rate is pushed to 6 kg/m^3, the compressive performance begins to plateau. The high surface area of the extra fibers starts to demand more of the available cement paste for surface lubrication. This action shifts the balance from structural reinforcement toward a minor loss of fresh mix workability, which subtly affects ultimate matrix consolidation during vibration.
- Maximum experimental Dosage Regime 8kg/m^3: Under the highest experimental fiber loading of 8kg/m^3, the concrete shows a decline from its peak optimized strength values. This trend is primarily driven by internal compaction constraints. The large volume of fibers increases internal particle friction, leading to localized "fiber balling" or clumping. These clumps entrap air and create macro-voids within the hardened specimen. However, due to the baseline design of the M40 grade mix, these higher-density configurations still achieve superior ultimate strength values when compared directly to plain nominal concrete.

5.1.3 Scientific Mechanisms of Compressive Failure Transition

The underlying physical principle behind these trends relates to the changing failure modes of the test specimens. Plain control concrete typically exhibits an explosive, brittle failure mode under ultimate compressive loads as macro-cracks propagate quickly through the matrix.

By contrast, the Polypropylene Fiber Reinforced Concrete (PFRC) samples display a ductile, pseudo-plastic failure mode. Even when the peak compressive load is reached and the concrete matrix cracks, the embedded fibers cross these macro-fissures. The mechanical pull-out resistance and interfacial friction bond of the PP fibers restrict crack widening and delay catastrophic disintegration. This behavior changes the failure mechanism, preserving the post-peak load capacity and integrity of the crushed core.

5.2 Flexural Strength Performance and Energy Absorption

5.2.1 Bending Stress Mechanics and Modulus of Rupture

Direct tension testing of cement matrices remains methodologically difficult due to localized stress concentrations near testing grips, which often skew experimental results. Consequently, third-point flexural testing was conducted on beam specimens measuring $70\times15\times15\text{ cm}$ in strict compliance with IS: 516 to compute the true modulus of rupture. The modulus of rupture quantifies the extreme fiber tensile stress at failure under a uniform bending moment.

The experimental results show that the addition of discontinuous polypropylene fibers systematically upgrades the flexural performance of the concrete. The structural variations across the experimental matrices are categorized below:

- Flexural Trends at Low Fiber Volume 2kg/m^3: At a dosage of 2kg/m^3, the flexural strength shows general improvement as fiber lengths increase. However, the lower total number of fibers crossing the critical tension zone means the matrix acts similarly to unreinforced concrete until the first crack develops. The fibers provide basic residual strength, but the overall flexural capacity remains limited by the sparse fiber distribution.
- Flexural Trends at Optimum Fiber Volume 4 kg/m^3: The peak flexural performance is reached at a dosage of 4 $kg/m^3$when combined with a 30 mm fiber length. This specific configuration achieves an optimal balance between fiber aspect ratio and spatial frequency within the tension zone. The fibers are long enough to develop an effective interfacial anchorage bond within the cement matrix, yet short enough to remain uniformly dispersed without clumping. This ensures a dense network of fibers across the beam's lower tension face.
- Flexural Trends at High Fiber Volumes 6kg/m^3 and 8kg/m^3: When fiber additions are increased to 6kg/m^3 and 8kg/m^3, the flexural strength remains elevated but starts to plateau relative to the 4 kg/m^3 peak. While these higher dosages offer more fibers to arrest cracks, the increased mix stiffness impedes perfect

matrix compaction around the fibers. This slightly reduces the mechanical efficiency of the fiber-matrix bond. Despite this effect, the high volume fraction provides exceptional residual post-cracking load capacity compared to the nominal plain concrete mix.

5.2.2 Micro-Crack Bridging and the Tension-Zone Phenomenon

The flexural strength improvements are governed by a tension-zone micro-crack bridging mechanism. In plain concrete beams subjected to bending, a single micro-crack on the bottom tension face expands rapidly into a macro-crack, driving immediate structural failure.

In the PFRC beams, as the bottom fiber stress reaches the cracking modulus, the opening of micro-fissures transfers internal tensile forces directly onto the embedded polypropylene fibers. Because these synthetic fibers possess high tensile capacity, they anchor themselves on either side of the crack. This mechanical bridging restrains the crack from propagating upward through the beam. The failure mode transitions from a sudden, brittle snap to a gradual, controlled bending behavior, allowing the beam to undergo substantial deflection while sustaining high residual loads.

5.3 Split Tensile Strength Evaluations

5.3.1 Splitting Cylinder (Brazilian) Test Characterization

The experimental data confirms that split tensile strength values follow a similar trend to the compressive and flexural data, showing clear dependency on fiber length and density configurations:

- Tensile Response at Low Dosages: At 2 kg/m^3, the split tensile strength shows small, inconsistent increases as fiber lengths are varied. The low fiber spatial frequency means that fewer fibers cross the central vertical split plane, resulting in a lower capacity to resist the horizontal tensile stresses.
- Tensile Response at Peak Optimization: The maximum increase in split tensile strength occurs at a dosage density of 4 kg/m^3 with a fiber length of 30 mm. This configuration maximizes the number of effective fibers intersecting the central vertical plane. The fibers work together efficiently to anchor the two halves of the splitting cylinder, delaying total structural separation under high line loads.
- Tensile Response at Maximum Volumes: At the highest dosages, the split tensile values begin to plateau. Long 40 mm fibers paired with an 8 kg/m^3 dosage increase the risk of fiber clumping and balling. These clumps disrupt aggregate nesting and create internal pathways of weaker tensile resistance. Nevertheless, because of the underlying fiber matrix network, these specimens maintain high post-cracking integrity and do not separate into distinct halves at failure, outperforming plain nominal concrete.

5.3.2 Mechanics of Energy Absorption and Structural Integrity

The primary role of polypropylene fibers under split tensile loading is to provide post-cracking energy absorption. Plain concrete cylinders split completely into two separate pieces once their nominal tensile capacity is exceeded.

In the PFRC specimens, the multi-directional orientation of the fibers ensures that a high percentage of fiber strands bridge the central vertical crack plane. As the line load forces the crack open, energy is absorbed through the debonding, stretching, and mechanical pull-out of the polymer fibers. This mechanism holds the concrete matrix together, preventing catastrophic splitting failure and transforming the material behavior from brittle to highly ductile.

5.4 Summary of Hardened Concrete Structural Optimization

The consolidated findings across all three hardened concrete tests (compressive, flexural, and split tensile strength) demonstrate that the mechanical performance of M40 grade concrete is highly sensitive to fiber geometry and dosage rates. The optimal structural performance point for this cement matrix is consistently achieved at a polypropylene fiber length of 30 mm combined with a design dosage density of 4 kg/m^3.

This optimal pairing provides the ideal spatial frequency and effective anchorage length needed to maximize crack-bridging efficiency. While exceeding these limits can introduce minor compaction constraints and fiber clumping, the resulting composite material consistently maintains superior mechanical properties, improved failure modes, and enhanced post-cracking ductility compared to standard unreinforced nominal concrete.

VI. CONCLUSIONS

From the present study the following conclusions can be drawn

- Workability: The incorporation of polypropylene fibers induces a net reduction in the workability of fresh concrete, with the loss of fluidity becoming more pronounced as both fiber length and dosage density increase. The lowest slump values were systematically recorded at the maximum fiber dosage of 8 kg/m3.

- Fiber Balling and Dispersion Characteristics: Manifestations of fiber clumping or "balling" were visibly apparent across all concrete mixtures configured with the high fiber dosage of 8 kg/m3. This dispersion problem was severely aggravated when the constituent fiber length was extended to 40mm, complicating uniform matrix compaction.
- Enhancement of Hardened Properties: The strategic inclusion of discontinuous polypropylene fibers yields definitive enhancements in the core mechanical parameters of the concrete matrix, notably elevating its ultimate compressive strength and flexural strength capacity compared to the plain unreinforced control mix.
- Optimization Thresholds: The experimental matrix establishes that distinct optimum thresholds exist for each fiber configuration. The peak improvements in the mechanical performance of the Polypropylene Fiber Reinforced Concrete (PFRC) are directly dependent on matching the correct fiber length with its corresponding matrix density.
- Impact of Low and Moderate Fiber Dosages: While a lower fiber dosage of 2 kg/m3provided marginal upgrades in compressive, flexural, and splitting tensile strengths, these structural improvements lacked definitive statistical consistency. Conversely, the most substantial, definitive escalation in compressive strength was achieved at a moderate dosage of 4 kg/m3 using 30mmlong fibers.
- Identification of Optimum Parameters: Based on the overall synchronization of mechanical upgrades across compressive strength, splitting tensile strength, and flexural strength, the definitive optimum fiber configuration for this M40 matrix is established at a fiber length of 30mm and a design dosage of 4kg/m3.
- Comparative Performance Curve: When polypropylene fiber parameters are maintained at the optimum thresholds of 30mm and 4 kg/m3, the matrix exhibits its most balanced mechanical response. However, even when fiber lengths and densities are increased beyond these optimal parameters, the resulting composite still demonstrates superior structural properties and enhanced post-cracking resistance compared to standard nominal concrete.

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