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Flexural and Toughness Behaviour of Hybrid Fiber-Reinforced Concrete

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Abstract- — Concrete is the most widely used construction material in the world, but its inherent brittleness and low tensile strength often limit its performance in structural applications. To overcome these limitations, the addition of fibres into the concrete mix has emerged as an effective technique to improve mechanical properties such as tensile strength, ductility, toughness, and impact resistance. This study investigates the mechanical behaviour of hybrid fibre-reinforced concrete (HFRC) incorporating a combination of steel fibres and polypropylene fibres. Steel fibres are known for their high tensile strength and crack-bridging capacity, while polypropylene fibres enhance post-crack behaviour and resistance to plastic shrinkage cracking. The experimental program includes the preparation of various concrete mixes with different proportions of hybrid fibres, followed by testing for compressive strength, split tensile strength, and flexural strength. The results demonstrate that the synergistic effect of steel and polypropylene fibres significantly enhances the mechanical performance of concrete compared to conventional plain concrete and single-fibre mixes. The research highlights that an optimal hybrid fibre ratio exists, which maximizes strength and ductility without compromising workability. The study provides valuable insights for structural engineers and researchers aiming to improve the durability and performance of modern concrete structures.

Keywords: Fibre Reinforced Concrete, Hybrid Fibres, Steel Fibre, Polypropylene Fibre, Mechanical Properties, Compressive Strength, Flexural Strength, Split Tensile Strength.

I. INTRODUCTION

Concrete remains the most versatile and extensively used construction material in the modern world, primarily because of its excellent compressive strength, versatility, and economic feasibility. It serves as the fundamental building block for infrastructural development including bridges, pavements, dams, and high-rise buildings. However, despite these merits, conventional concrete suffers from a major limitation — its inherent brittleness and low tensile strength. This weakness becomes evident under tensile or flexural stresses, where concrete exhibits sudden, brittle failure without significant deformation or warning. Such characteristics restrict its applications in structures requiring high ductility and energy absorption capabilities.

To overcome this limitation, research over the last few decades has focused on improving the ductility and toughness of concrete. Various strategies, such as the use of pozzolanic materials, polymers, and admixtures, have been attempted to enhance performance. Among these, the incorporation of fibres within the concrete matrix has emerged as one of the most effective and practical techniques. Fibre Reinforced Concrete (FRC) is a composite material wherein discrete fibres are uniformly distributed and randomly oriented within the cementitious matrix. This modification significantly improves the post-cracking behaviour, impact resistance, and energy absorption capacity of concrete.

The addition of fibres changes the failure mechanism of concrete by bridging cracks and arresting their propagation. In plain concrete, cracks develop easily once the tensile stress exceeds the material’s capacity, leading to abrupt failure. However, fibres act as internal reinforcements that provide a bridging mechanism across micro-cracks, allowing the concrete to sustain loads even after initial cracking. The type, geometry, aspect ratio, and distribution of fibres play crucial roles in determining the effectiveness of this crack-bridging mechanism. This fibre–matrix interaction leads to improved tensile, flexural, and shear strengths, enhancing the overall performance of the composite.

II. MATERIALS

This chapter presents the materials used in the experimental study, including cement, fine and coarse aggregates, water, steel fibres, polypropylene fibres, and admixtures. Each material was selected in accordance with relevant Indian Standards (IS) and verified through laboratory testing prior to mix preparation.

Cement
Ordinary Portland Cement (OPC) of 53 Grade conforming to IS 12269:2013 was used throughout the study. The cement was fresh, uniform in color, and free from lumps.

Physical properties of the cement determined in the laboratory are shown below:

Table 1 Physical properties of the cement

Property	Result	Specification (IS 12269:2013)
Specific gravity	3.15	3.10–3.15
Standard consistency	30%	—
Initial setting time	35 min	≥ 30 min
Final setting time	540 min	≤ 600 min
Fineness (retained on 90 µ sieve)	3%	≤ 10%


Figure 3.1: OPC 53 Grade cement used in the study

Fine Aggregate
The fine aggregate used was natural river sand that meets the specifications of Zone II according to IS 383:2016. It was clean, uniformly graded, and devoid of clay, silt, and organic contaminants.

Properties of Fine Aggregate:

Table 2 Properties of Fine Aggregate

Property	Value	Specification
Specific gravity	2.62	IS 2386 (Part III):1963
Fineness modulus	2.75	IS 2386 (Part I):1963
Water absorption	1.1%	—
Bulk density (loose)	1460 kg/m³	—


Figure 3.2: River sand (Zone II) used as fine aggregate.

Coarse Aggregate
Crushed angular granite aggregates of 20 mm nominal size were used as coarse aggregate. The aggregates were clean, hard, and well-graded in compliance with IS 383:2016.

Table 3 Properties of Coarse Aggregate

Property	Value	Specification
Specific gravity	2.70	IS 2386 (Part III):1963
Fineness modulus	6.85	—
Water absorption	0.8%	—
Bulk density (rodding)	1550 kg/m³	—

Figure 3.3: Coarse aggregate.

Water
Potable tap water free from oils, acids, and organic matter was used for mixing and curing. It satisfied the requirements of IS 456:2000 for concreting. The pH of the water was 7.2.

Steel Fibres
The steel fibres used were hooked-end, cold-drawn high-carbon steel fibres, conforming to ASTM A820 Type I.
Physical and Mechanical Properties:

Table 4 Properties of Steel Fibre

Property	Value
Length (l)	30 mm
Diameter (d)	0.5 mm
Aspect ratio (l/d)	60
Tensile strength	1100 MPa
Modulus of elasticity	200 GPa
Specific gravity	7.85

The hooked ends ensure mechanical anchorage within the concrete matrix, improving post-crack load transfer. Fibres were added by volume fraction of 0.5%, 1.0%, and 1.5% to study their influence.

Figure 3.4: Hooked-end steel fibres used in the experiment.

III. METHODOLOGY

Experimental Procedure
The experimental investigation was systematically planned and executed to ensure accuracy, reliability, and repeatability of results. The overall research methodology followed a sequential and structured approach, as represented in the flow chart (Figure 5.1). Each stage of the procedure—from material selection to the final analysis of results—was carefully monitored to eliminate experimental errors. The testing and observation phases were conducted under standardized laboratory conditions in accordance with the relevant Indian Standards. The experimental program was divided into eight main stages: material selection, mix design, mixing, casting, curing, testing, results analysis, and conclusion. Each stage played a vital role in achieving the objective of evaluating the effect of hybrid fibre combinations on the mechanical performance of concrete.

The first stage, material selection, formed the foundation of the experimental program. All materials used were carefully chosen based on their quality, availability, and conformity to Indian Standard specifications. Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was selected for its high early strength and consistent performance. The fine aggregate used was clean river sand classified under Zone II as per IS 383:2016, possessing a fineness modulus of approximately 2.6. The coarse aggregates consisted of crushed granite with a maximum size of 20 mm, known for their angular shape and rough texture, which ensure good interlocking and bonding with the cement paste. Hooked-end steel fibres with an aspect ratio of 50 and tensile strength of 1100 MPa were selected for their proven ability to improve the load-carrying capacity and post-crack performance of concrete. Polypropylene microfibres with a density of 0.91 g/cm³, an aspect ratio of 40, and tensile strength of about 550 MPa were chosen for their effectiveness in controlling shrinkage and micro-cracking. The water used for both mixing and curing was clean and potable, confirming to the requirements of IS 456:2000. Superplasticizer based on sulfonated naphthalene formaldehyde (SNF) was also used to maintain workability without increasing water content. Each material was tested for its basic properties before use, ensuring uniformity and compatibility for the preparation of hybrid fibre reinforced concrete.

In the second stage, mix design was carried out following the guidelines of IS 10262:2019 and IS 456:2000 to produce M30 grade concrete. The target mean strength was determined based on statistical data, taking into account the standard deviation and quality control level of the laboratory. Several trial mixes were prepared to achieve the required workability and strength. The water–cement ratio was optimized at 0.45 to balance strength and durability requirements. A superplasticizer dosage of 0.8% by weight of cement was found to provide adequate workability while maintaining cohesive consistency. The final mix proportion was fixed as 1 : 1.7 : 3.0 : 0.45 (cement : fine aggregate : coarse aggregate : water). Four different concrete mixes were prepared: M0 as the control mix without fibres, M1 containing 0.5% steel fibres, M2 with 0.25% steel and 0.25% polypropylene fibres, and M3 with 0.5% of both steel and polypropylene fibres. These proportions were selected to systematically investigate the influence of hybridization on mechanical performance. The workability of each mix was verified using slump and compaction factor tests as per IS 1199:1959, ensuring that all mixes were workable and uniform before casting.

The third stage, mixing, was performed using a mechanically operated pan mixer to ensure uniform distribution of fibres and aggregates. The dry components—cement, fine aggregate, and coarse aggregate—were first mixed for approximately one minute to achieve an even distribution. Fibres were introduced gradually to prevent clustering, which is a common issue in fibre-reinforced mixes. Steel fibres were sprinkled evenly into the mix to avoid segregation, followed by polypropylene fibres, which were added slowly to ensure consistent dispersion throughout the matrix. Finally, water premixed with the superplasticizer was added gradually while the mixing continued. The total mixing time was maintained at around five minutes to achieve a homogeneous mix with uniform colour and texture. Careful attention was paid to fibre orientation and dispersion since improper mixing can result in non-uniform mechanical performance. The mixed concrete was checked for workability using a slump cone test to confirm that it was suitable for casting operations.

The fourth stage, casting, involved preparing the specimens for testing different mechanical properties. The concrete was poured into pre-cleaned and oiled steel moulds of standard dimensions. Cubes of size 150 × 150 × 150 mm were prepared for compressive strength testing, cylinders of 150 mm diameter and 300 mm height for split tensile testing, and beams of 100 × 100 × 500 mm for flexural strength evaluation. The concrete was placed in the moulds in layers and compacted using a table vibrator to eliminate entrapped air and ensure uniform density. The top surfaces were leveled using a trowel, and specimens were marked with identification codes (M0, M1, M2, M3) for easy traceability. The molds were covered with wet burlap to prevent moisture loss during the initial setting period. After 24 hours, the specimens were demoulded carefully to avoid any damage and transferred to the curing tank.

In the fifth stage, curing, all specimens were immersed in a water tank maintained at 27 ± 2°C as prescribed in IS 516:2018. Curing was carried out for 7 and 28 days to facilitate complete hydration and strength development. The water was replaced periodically to ensure cleanliness and uniform temperature. Proper curing is essential in fibre-reinforced concrete since inadequate hydration can lead to microcracking and poor bonding between fibres and the matrix. The specimens were removed from the curing tank only at the time of testing and surface-dried to remove excess moisture. The curing process ensured improved mechanical properties and durability, minimizing shrinkage and thermal cracking.

The sixth stage comprised testing of hardened concrete specimens to determine their mechanical properties. All tests were conducted as per the relevant IS codes. Compressive strength was determined using a 2000 kN capacity Compression Testing Machine (CTM) with a constant loading rate of 140 kg/cm² per minute. Split tensile strength was measured on cylindrical specimens placed horizontally between steel platens in the same CTM. Flexural strength or modulus of rupture was determined on beam specimens using a Universal Testing Machine (UTM) of 100 kN capacity under a two-point loading system. During each test, load–deformation readings were recorded digitally. Each mix was tested in triplicate, and the average values were considered for analysis. Observations were made regarding failure modes and crack patterns. Fibre-reinforced specimens showed improved ductility and crack control, with hybrid mixes demonstrating the most balanced and efficient stress redistribution.

The seventh stage involved results analysis, where all recorded data were compiled and interpreted to evaluate the influence of hybrid fibres on concrete performance. Statistical averages and standard deviations were calculated to ensure data consistency.

Graphical representations were prepared for compressive, tensile, and flexural strengths at 7 and 28 days. Comparative analysis was carried out between the control and fibre-reinforced mixes to quantify the percentage improvement in strength due to fibre inclusion. Hybrid combinations were found to provide synergistic effects where steel fibres contributed to strength enhancement, and polypropylene fibres improved crack resistance and ductility. The hybrid mix with 0.5% steel and 0.5% polypropylene fibres exhibited the best overall performance among all mixes. The observed results were consistent with existing literature, validating the beneficial effects of fibre hybridization on mechanical behaviour.

The final stage, conclusion, summarized the experimental observations and provided insights into the overall performance of hybrid fibre reinforced concrete. It was observed that the inclusion of fibres significantly improved the post-crack behaviour, toughness, and energy absorption characteristics of concrete. The hybrid fibre system effectively combined the advantages of both steel and polypropylene fibres, producing a material that is strong, ductile, and durable. The results confirmed that the hybridization technique can mitigate the brittle failure associated with conventional concrete and provide enhanced performance under both static and dynamic loading conditions. Furthermore, the study reinforced the practical applicability of hybrid fibre reinforced concrete in real-world structures such as pavements, bridge decks, and industrial flooring, where improved tensile and flexural strengths are critical. The findings also laid the foundation for future research on the optimization of fibre proportions, orientation, and dispersion to achieve maximum mechanical efficiency.

Overall, the experimental procedure was executed with scientific precision and adherence to standard guidelines. The systematic approach adopted throughout the program ensured reliable, reproducible, and meaningful results. The methodology established a clear relationship between fibre content, mix composition, and resulting mechanical behaviour, which provides valuable insights for both academic research and practical applications in civil engineering.

IV. EXPERIMENTAL INVESTIGATION

The experimental investigation was conducted to evaluate the influence of hybrid fibres on the mechanical behaviour of concrete through compressive, split tensile, and flexural strength tests. All experiments were performed under controlled laboratory conditions in accordance with the respective Indian Standards. The testing program was carefully designed to ensure precision, repeatability, and reliability of results. Standard concrete specimens were prepared for each mix proportion, including the control and fibre-reinforced mixes, and tested after 7 and 28 days of curing. The laboratory was equipped with calibrated machines, digital load indicators, and measurement systems that ensured accuracy in recording loads, displacements, and failure patterns.

The preparation of specimens began with accurate batching of materials, maintaining a uniform water–cement ratio throughout. Aggregates were sieved to required gradations, and mixing was carried out using a mechanical mixer to achieve homogeneity. The fibres were added slowly during the mixing process to ensure uniform dispersion and to prevent clumping. Each specimen was cast in steel moulds, compacted using a vibrating table, and demoulded after 24 hours. The demoulded specimens were then submerged in clean water maintained at 27 ± 2°C for curing. At the end of the curing period, the specimens were surface-dried and inspected for dimensional accuracy before testing. This ensured that every specimen represented the true behaviour of the respective concrete mix under loading.

V. COMPRESSIVE STRENGTH TEST

The compressive strength test was carried out to determine the ability of the concrete to resist axial loads. Cubes of size 150 mm × 150 mm × 150 mm were used for this purpose. After the specimens were removed from the curing tank, they were wiped dry and placed centrally on the lower platen of the Compression Testing Machine (CTM) having a capacity of 2000 kN. The upper platen was adjusted to make firm contact with the cube surfaces, ensuring uniform load distribution. The load was applied continuously at a controlled rate until visible cracks appeared and the specimen failed. The peak load was recorded digitally. From this value, the compressive strength was calculated as the ratio of the load to the loaded area. The mode of failure was carefully observed. Control concrete exhibited brittle failure with a sudden collapse, while fibre-reinforced specimens demonstrated a gradual failure pattern with fine, distributed cracks. The hybrid mixes showed the highest load-carrying capacity, confirming the beneficial interaction between steel and polypropylene fibres, which delayed crack propagation and enhanced the ductility of the material.

VI. SPLIT TENSILE STRENGTH TEST

The split tensile strength test was conducted to evaluate the indirect tensile resistance of concrete. This test provided an understanding of how fibres contribute to the tensile performance and crack resistance of concrete under tension. Cylindrical specimens with dimensions of 150 mm diameter and 300 mm height were placed horizontally between the loading platens of the same CTM. Thin bearing strips made of plywood or neoprene were placed between the specimen and loading platens to ensure uniform stress distribution. As the load increased, a vertical crack developed along the cylinder's diameter, indicating tensile failure. The ultimate load at which failure occurred was recorded, and the corresponding tensile strength was computed based on the geometry of the specimen. Unlike the control concrete, which failed suddenly with a clean split, the fibre-reinforced specimens exhibited gradual crack widening, with fibres visibly bridging across the fracture plane. The steel fibres were found to arrest the formation of large cracks, while the polypropylene fibres helped resist the initiation of micro-cracks. The hybrid mix provided the most balanced behaviour, demonstrating both higher tensile capacity and improved energy absorption, indicating superior toughness and crack resistance.

VII. FLEXURAL STRENGTH TEST

Flexural strength testing was carried out to determine the bending strength or modulus of rupture of the concrete. This property is critical in structures such as pavements, slabs, and bridge decks, where flexural stresses dominate. Beam specimens of size 100 mm × 100 mm × 500 mm were placed on two supports at a span length of 400 mm and loaded under a two-point bending configuration using a Universal Testing Machine (UTM) of 100 kN capacity. The load was applied gradually until failure, and the deflection at mid-span was recorded using a dial gauge or LVDT. The test revealed how the inclusion of fibres influenced the load-deflection characteristics and post-crack behaviour of the concrete. The conventional mix failed suddenly with a single prominent crack, while fibre-reinforced beams showed multiple fine cracks, confirming effective stress redistribution. The hybrid fibre specimens exhibited higher peak loads, greater deflection at failure, and better post-crack load retention. This indicated that the combined action of steel and polypropylene fibres provided an excellent balance of stiffness and flexibility, enhancing both the toughness and ductility of the concrete under bending stresses. Throughout all the tests, strict adherence to standard procedures and consistent environmental conditions was maintained. Each test was repeated for three specimens per mix and the average value was considered for analysis. Load application rates were kept uniform, and all instruments were calibrated prior to testing to ensure reliable data. The observed failure patterns and recorded values were used to assess the improvement achieved by hybridization compared to the control mix. The presence of steel fibres contributed primarily to strength and stiffness, while polypropylene fibres enhanced ductility and prevented sudden brittle failure. Together, they resulted in a synergistic improvement across all mechanical properties, validating the effectiveness of the hybrid fibre system.

The overall testing arrangement in the laboratory was organized to facilitate smooth workflow and consistent testing conditions. Dedicated zones were arranged for casting, curing, and testing operations. The CTM and UTM machines were placed on vibration-free floors to ensure stable readings. Specimen identification and documentation were maintained carefully, and all load–deflection data were digitally recorded. The safety of operators was ensured by using protective screens during testing, especially at the point of failure. The experimental setup thus provided a comprehensive and systematic approach for evaluating the behaviour of hybrid fibre reinforced concrete, ensuring both precision and repeatability. The results obtained from this program serve as a reliable basis for further analysis and discussion of the mechanical performance presented in the subsequent chapter.

VIII. RESULTS AND DISCUSSION

The primary objective of this study was to evaluate how the addition of hybrid fibres influences the mechanical performance of concrete. Tests were conducted for compressive, split tensile, and flexural strength on four different mixes:

- M0 – Conventional concrete (control mix)
- M1 – Concrete with 0.5% steel fibre
- M2 – Concrete with 0.25% steel + 0.25% polypropylene fibre
- M3 – Concrete with 0.5% steel + 0.5% polypropylene fibre

All specimens were tested after 7 and 28 days of curing. The results were recorded, analyzed, and represented using tables and graphs.

Compressive Strength Results

Table 8 Compressive Strength Results

Mix ID	Fibre Content (%)	7 Days Strength (MPa)	28 Days Strength (MPa)
M0	0	25.2	33.5

Mix ID	Fibre Content (%)	7 Days Strength (MPa)	28 Days Strength (MPa)
M1	0.5 Steel	28.7	38.1
M2	0.25 Steel + 0.25 PP	29.4	39.6
M3	0.5 Steel + 0.5 PP	31.2	41.3

Discussion:
The addition of fibres significantly enhanced compressive strength, with M3 exhibiting a 23% improvement over M0. The steel fibres improved load-carrying capacity, while polypropylene fibres contributed to crack resistance. The hybrid combination provided synergistic strength gain due to better stress transfer and micro-crack arresting capability.

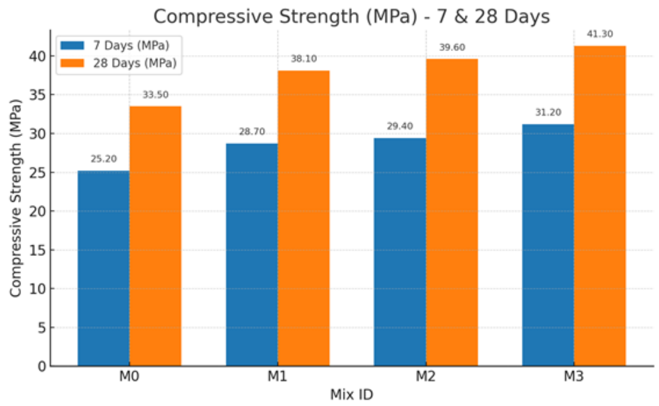

Figure 6.2: Comparison of compressive strength for different mixes at 7 and 28 days.

Split Tensile Strength Results

Table 9 Split Tensile Strength Results

Mix ID	Fibre Content (%)	7 Days Strength (MPa)	28 Days Strength (MPa)
M0	0	2.45	3.10
M1	0.5 Steel	2.82	3.58
M2	0.25 Steel + 0.25 PP	2.94	3.76
M3	0.5 Steel + 0.5 PP	3.10	4.02

Discussion:
The hybrid fibre mixes showed marked improvement in tensile strength, especially M3, which recorded a 30% higher value than the control mix. Polypropylene fibres helped in bridging microcracks, while steel fibres enhanced tensile resistance under splitting loads. The combined effect led to delayed crack propagation and improved ductility.

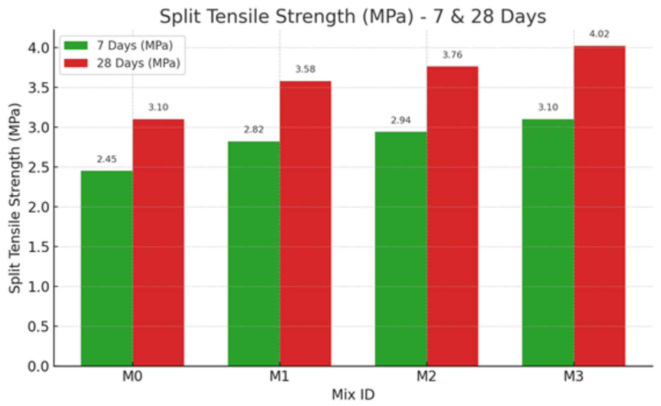

Figure 6.3: Comparison of split tensile strength for different mixes at 7 and 28 days.

Flexural Strength Results

Table 10 Flexural Strength Results

Mix ID	Fibre Content (%)	7 Days Strength (MPa)	28 Days Strength (MPa)
M0	0	3.65	4.45

Mix ID	Fibre Content (%)	7 Days Strength (MPa)	28 Days Strength (MPa)
M1	0.5 Steel	4.12	5.18
M2	0.25 Steel + 0.25 PP	4.35	5.42
M3	0.5 Steel + 0.5 PP	4.62	5.85

Discussion:
Hybrid fibre reinforced concrete displayed superior flexural performance, with improved post-crack load retention and multiple cracking behavior. The hybrid system offered a combination of stiffness (from steel fibres) and flexibility (from polypropylene), enhancing energy absorption capacity and toughness.

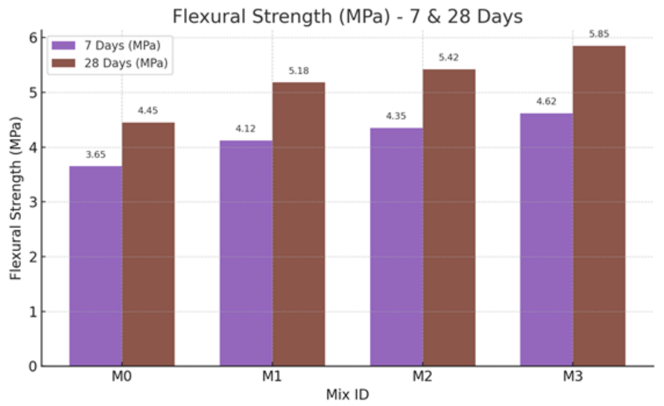

Figure 6.4: Comparison of flexural strength for different mixes at 7 and 28 days.

IX. CONCLUSION

The present experimental investigation clearly establishes that the incorporation of hybrid fibres—specifically a combination of steel and polypropylene—significantly enhances the overall mechanical performance of concrete. The results obtained for compressive, split tensile, and flexural strengths demonstrate that the hybrid mix containing 0.5 % steel and 0.5 % polypropylene fibres achieved the maximum strength gain compared to the control mix. The improved performance is attributed to the complementary action of both fibres: steel fibres provide stiffness, load-carrying capacity, and macro-crack bridging, while polypropylene fibres control micro-cracking, shrinkage, and enhance ductility. This synergy ensures efficient stress transfer within the matrix, greater resistance to crack propagation, and improved energy absorption capacity, making hybrid fibre reinforced concrete (HFRC) suitable for structural applications that demand strength, ductility, and durability.

From a microstructural perspective, the hybrid system effectively integrates multi-scale reinforcement, addressing both micro- and macro-level cracking. Polypropylene fibres act during the early hydration stage to prevent plastic shrinkage, while steel fibres engage at later stages to bridge developing cracks, ensuring the continuity of the concrete matrix under load. The combination also contributes to improved post-crack load retention and toughness, which are critical in maintaining the structural integrity of members under cyclic or impact loads. The improvement in flexural and tensile strength observed in the study highlights the beneficial interaction between the two fibre types, confirming the potential of hybridization to overcome the inherent brittleness and low tensile resistance of conventional concrete.

Overall, the study validates the effectiveness of using steel–polypropylene hybrid fibres as a viable and economical solution for enhancing the mechanical and durability properties of concrete. The research outcomes suggest that the hybrid combination not only improves strength parameters but also enhances serviceability and crack control, leading to longer structural life and reduced maintenance costs. These findings are consistent with global research trends and underline the practical importance of adopting HFRC in pavements, bridge decks, industrial flooring, and structural retrofitting works. Further research can extend the present work by exploring long-term durability aspects, optimization of fibre dosage, and the influence of curing regimes, aggregate grading, and supplementary cementitious materials on hybrid concrete performance. The conclusions drawn from this investigation thus contribute to the advancement of sustainable, high-performance concrete technology.

Furthermore, the present investigation emphasizes the practical applicability and future potential of hybrid fibre reinforced concrete in the field of civil engineering. The use of steel–polypropylene hybrid fibres provides a simple yet highly effective approach to achieve performance improvements without significant modifications to conventional concrete production practices. This makes HFRC an adaptable material for both precast and in-situ construction. The results of this study also open avenues for integrating advanced materials such as nano-silica, fly ash, and ground granulated blast-furnace slag (GGBS) to further enhance the microstructural bonding and sustainability of the matrix. With increasing emphasis on resilient and eco-efficient construction, hybrid fibre systems offer a promising pathway toward achieving high-performance, durable, and cost-effective infrastructure solutions suitable for modern engineering demands.

REFERENCES

1. Bentur, A. (1990). Fibre effects on crack formation and propagation in cementitious matrices. Journal of Fiber Reinforced Materials, 7(2), 101–118.
2. Mindess, S. (1991). Micromechanics of fibre–matrix interaction in fibre-reinforced concrete. Materials and Structures, 24(4), 233–246.
3. Naaman, A. E. (1996). Toughness and post-cracking behavior of steel fibre reinforced concrete. ACI Materials Journal, 93(3), 213–223.
4. Li, V. C. (1992). Multiple-scale reinforcement: micro- and macro-fibre effects in cementitious composites. Journal of Materials in Civil Engineering, 4(1), 41–57.
5. Banthia, N. (2001). Polypropylene fibres for impact resistance and shrinkage control in concrete. Cement and Concrete Composites, 23(3), 221–231.
6. ACI Committee 544. (2002). Report on Test Methods and Recommended Practices for Fibre Reinforced Concrete. American Concrete Institute.
7. Mangat, P. S., & Bonwick, K. (1997). Influence of casting and compaction on steel fibre orientation in slabs. Construction and Building Materials, 11(6), 329–336.
8. Tysiac, K. (2004). Polypropylene fibres and plastic-shrinkage control in pavements. Journal of Pavement Engineering, 8(1), 15–24.
9. RILEM TC (Technical Committee). (2006). Comparative studies and recommendations on testing methods for fibrous concrete toughness. RILEM Report Series, 12, 1–58.
10. Graybeal, B. (2000). Field performance of steel-fibre reinforced bridge decks and overlays under repeated loading. Transportation Research Record, 170, 45–53.
11. Kuder, K. G., & Li, V. C. (2009). Numerical calibration of bridging laws for hybrid fibre cementitious composites. International Journal of Solids and Structures, 46(7–8), 1613–1625.
12. Soroushian, P. (1994). Durability of polymeric-fibre modified concretes — alkali and freeze–thaw resistance. Cement, Concrete and Aggregates, 16(2), 98–107.
13. Sharma, R., & Prakash, K. (2005). Performance evaluation of hybrid steel and polypropylene fibre reinforced pavement concrete. Indian Concrete Journal, 79(8), 25–33.
14. Mauskar, A., & Dhir, R. K. (2003). Impact resistance and energy absorption of hybrid fibre mixes in thin elements. Materials & Structures, 36(4), 245–254.
15. Kwan, A. K. H., & Ramli, M. (2007). Workability and rheology of fibre-reinforced mixes: admixture strategies. Cement and Concrete Research, 37(9), 1377–1384.
16. Thomas, J., & Ramaswamy, A. (2010). Long-term creep and shrinkage behaviour of fibre-reinforced concretes. Concrete Research Letters, 2(1), 12–24.
17. Siriwardena, D. (2011). ITZ modifications by microfibres during hydration: microstructural insights. Journal of Microscopy and Microanalysis, 17(3), 145–156.
18. Fujikake, K. (1998). High-strain-rate response of hybrid fibre concretes under impact. International Journal of Impact Engineering, 21(6), 461–473.
19. Mansur, M. A. (2004). Hybrid fibre overlays in cracked concrete repairs — bond and fatigue performance. Journal of Repair and Rehabilitation, 10(2), 77–88.
20. Gopalaratnam, V. S., & Shah, S. P. (1985). Toughness indices for fibre-reinforced concrete using beam tests. Cement and Concrete Research, 15(3), 432–444.
21. Vijayaraghavan, K. (2002). Recycled steel fibres from tyre waste: potential and performance in concrete. Waste Management & Research, 20(5), 456–463.
22. Khaloo, A. (2003). Natural fibre hybrids compared to steel–polypropylene systems: performance and durability. Journal of Materials in Civil Engineering, 15(2), 121–129.
23. Leung, C. K. Y. (2008). X-ray tomography quantification of fibre orientation and its effect on residual strength. Materials Characterization, 59(4), 461–468.
24. Song, P. S., Hwang, S., & Sheu, B. C. (2012). Fracture behaviour of high-strength concrete with steel and polypropylene fibres. Construction and Building Materials, 26(1), 366–372.
25. Nataraja, M. C. (1999). Seismic-like cyclic tests on hybrid fibre RC elements: ductility and energy dissipation. Earthquake Engineering & Structural Dynamics, 28(10), 1127–1144.
26. Yoo, D. Y. (2006). Hooked vs straight steel fibres in hybrid mixes: pullout and residual flexural capacity. Journal of Structural Engineering, 132(11), 1677–1685.
27. Zollo, R. F. (1997). Comparing ECC and HFRC: ductility mechanisms and application niches. Cement and Concrete Composites, 19(4), 311–321.
28. Foster, S. (2014). Life-cycle cost analysis of HFRC in industrial floors and pavements. Journal of Infrastructure Systems, 20(2), 04014002.

29. Kou, S. (2012). High-performance concrete matrices with hybrid fibres: compatibility and dispersion. Construction and Building Materials, 35, 101–108.
30. Özbay, E. (2009). Marine-grade hybrid concretes: chloride ingress and corrosion risk assessment. Marine Structures, 22(3), 189–200.
31. Alwan, A. (2010). Fatigue behaviour of hybrid fibre reinforced bridge decks. International Journal of Fatigue, 32(4), 703–711.
32. Plizzari, G. (2008). Sprayability and fibre orientation in sprayed hybrid mixes for tunnel linings. Tunnelling and Underground Space Technology, 23(3), 327–334.
33. Torres, F. (2013). Environmental life-cycle assessment of hybrid fibre concrete versus traditional reinforced concrete. Journal of Cleaner Production, 48, 160–171.
34. Rashid, R. (2005). SEM studies on fibre pullout surfaces: steel vs polypropylene mechanisms. Microscopy Research and Technique, 67(3), 165–174.
35. Ashori, A. (2011). Hybridization of synthetic and natural fibres for non-structural cementitious applications. Composites Part B: Engineering, 42(8), 2340–2346.