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Effect of Hybrid Steel Fibre Geometry on the Performance of Fibre Reinforced Concrete

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Abstract: The incorporation of steel fibres into concrete is an effective approach for improving its post-cracking behaviour, ductility, toughness, and energy absorption capacity. However, the geometry and aspect ratio of steel fibres significantly influence their interaction with the cementitious matrix and, consequently, the overall mechanical performance of fibre-reinforced concrete. This study investigates the effect of hybrid steel fibre geometry on the performance of fibre-reinforced concrete, with particular emphasis on strength development, crack control, deformation behaviour, energy absorption, and post-failure response. The experimental programme considers concrete mixtures reinforced with different combinations of steel fibres having variations in length, diameter, aspect ratio, and geometry, such as hooked-end and straight fibres. A conventional plain concrete mixture is considered as the control specimen, while mono-fibre and hybrid-fibre mixtures are prepared to evaluate the synergistic effect of combining fibres with different geometrical characteristics. The specimens are subjected to compressive strength, split tensile strength, flexural strength, and load–deflection tests at specified curing ages. The post-failure behaviour is further assessed through crack propagation, residual load-carrying capacity, toughness, and energy absorption characteristics. The hybrid fibre systems are expected to provide improved fibre–matrix interaction and more effective crack-bridging mechanisms across different stages of fracture development. Shorter fibres are anticipated to control microcracks, whereas longer and hooked-end fibres are expected to enhance macrocrack bridging and improve post-peak resistance. The study provides an experimental basis for optimizing hybrid steel fibre geometry for structural concrete applications where enhanced ductility, toughness, and resistance to sudden failure are required. The findings can contribute to the development of more durable and damage-tolerant fibre-reinforced concrete for structural and infrastructure applications.

Keywords: Hybrid steel fibres, Fibre-reinforced concrete, Fibre geometry, Aspect ratio, Mechanical properties, Crack control, Energy absorption, Ductility

1. Introduction

Concrete is one of the most widely used construction materials because of its high compressive strength, availability of raw materials, durability, and relatively low cost. However, conventional concrete has limited tensile strength, low strain capacity, and brittle failure characteristics. When subjected to tensile, flexural, impact, or dynamic loading, concrete tends to develop microcracks that gradually propagate into larger cracks, resulting in a significant reduction in load-carrying capacity. Once a major crack develops, conventional concrete has limited ability to resist further deformation or sustain load. This limitation has encouraged researchers to develop advanced cementitious composites with improved tensile resistance, ductility, toughness, crack control, and post-failure behaviour.Fibre-reinforced concrete (FRC) is one such material in which discrete fibres are distributed throughout the concrete matrix to modify its mechanical and fracture characteristics. Fibres act as crack-bridging elements and restrict the propagation and widening of cracks. Depending on their type, material, geometry, volume fraction, orientation, and distribution, fibres can substantially improve the tensile and flexural performance of concrete. Among the different fibre types, steel fibres have received considerable attention because of their high tensile strength, stiffness, durability, and ability to transfer stresses across developing cracks. Steel fibre-reinforced concrete (SFRC) is therefore increasingly used in industrial floors, pavements, tunnel linings, precast elements, shotcrete, structural members, and impact-resistant construction.

The effectiveness of steel fibres is not governed only by the quantity of fibres incorporated into concrete. Fibre geometry plays an important role in determining the interaction between the fibre and surrounding cementitious matrix. Parameters such as fibre length, diameter, aspect ratio, cross-sectional shape, surface characteristics, and end configuration influence fibre dispersion, bond strength, pull-out resistance, crack-bridging efficiency, and failure behaviour. Straight fibres generally depend more strongly on interfacial bond and friction, whereas hooked-end or mechanically deformed fibres can provide greater anchorage and pull-out resistance. Consequently, changing fibre geometry can significantly alter the load–deflection response and energy absorption capacity of SFRC.

The **aspect ratio**, generally expressed as the ratio of fibre length to fibre diameter, is another important parameter affecting fibre performance. Fibres with a lower aspect ratio may disperse relatively easily within the concrete matrix but may provide comparatively limited crack-bridging capability. In contrast, fibres with a higher aspect ratio can provide greater anchorage and crack-bridging capacity, although excessive fibre length or aspect ratio may create difficulties in mixing, workability, and uniform fibre distribution. Therefore, selecting an appropriate fibre geometry involves balancing mechanical performance with practical considerations such as workability, fibre dispersion, and production efficiency.

A major limitation of using a single type of steel fibre is that one fibre geometry may not be equally effective at controlling cracks at different stages of fracture. Concrete fracture generally involves the initiation and propagation of microcracks followed by the development of localized macrocracks. Shorter and finer fibres can be effective in controlling early-stage microcracking because they are distributed more uniformly throughout the cementitious matrix. Longer fibres, particularly those with hooked or deformed ends, can provide stronger bridging across wider cracks and contribute to residual load-carrying capacity after cracking. This difference in fibre function provides the basis for the development of **hybrid fibre systems**.

Hybridization involves combining two or more fibre types, geometries, dimensions, or aspect ratios within the same concrete mixture. The objective is to obtain a synergistic response in which different fibres perform complementary functions during the fracture process. A combination of shorter fibres and longer fibres can potentially provide multi-scale crack control: shorter fibres can restrict the formation and growth of microcracks, while longer fibres can bridge macrocracks and delay unstable crack propagation. Similarly, combining straight and hooked-end fibres may improve both crack initiation resistance and post-cracking load transfer. The resulting material can exhibit improved ductility and toughness compared with concrete containing only one fibre type.

The **post-failure behaviour** of concrete is particularly important when evaluating the effectiveness of hybrid steel fibres. Conventional compressive strength or peak flexural strength alone cannot adequately describe the performance of fibre-reinforced concrete. In many structural applications, the ability of a material to continue carrying load after the formation of a major crack is more important than its peak strength. Steel fibres can maintain stress transfer across cracks through bridging and pull-out mechanisms, resulting in a gradual rather than sudden loss of load-carrying capacity. This characteristic can improve structural safety by providing warning through increased deformation before complete failure.

Another important performance parameter is **energy absorption capacity** or toughness. Energy absorption represents the ability of concrete to withstand deformation and absorb mechanical energy before failure. It is particularly relevant for structures subjected to impact, blast, seismic actions, repeated loading, abrasion, and other severe loading conditions. Fibre geometry directly affects energy absorption because the amount of energy dissipated during fibre pull-out depends on factors such as fibre embedment length, bond characteristics, anchorage, deformation, and crack width. Hooked-end fibres, for example, can dissipate substantial energy through mechanical anchorage and pull-out mechanisms. Hybrid fibre configurations may further enhance energy absorption by activating different crack-control and fibre-bridging mechanisms throughout the loading process.

The interaction between fibre geometry and the concrete matrix is therefore a critical area of investigation. The efficiency of a fibre depends on the quality of the interfacial transition zone, fibre orientation, fibre distribution, matrix strength, and bond characteristics. Increasing the matrix strength may improve the bond between the fibre and concrete, but excessively strong interfacial bonding can also result in fibre rupture rather than controlled pull-out in certain configurations. An optimum balance between fibre anchorage and pull-out resistance is necessary to achieve desirable toughness and ductility. Consequently, experimental evaluation is essential for understanding how different combinations of steel fibre geometry influence the complete mechanical response of concrete.

Workability is another important consideration when incorporating steel fibres. Increasing fibre content or using fibres with larger dimensions and higher aspect ratios can reduce the flowability of fresh concrete and increase the possibility of fibre balling or non-uniform distribution. Poor fibre dispersion can create weak zones and reduce the expected mechanical benefits of fibre reinforcement. Hybrid systems may therefore require careful optimization of fibre proportions and mixing procedures. The objective should not simply be to increase the fibre content but to identify a geometrical combination that provides effective crack control without compromising fresh concrete properties and uniform fibre distribution.

From a structural engineering perspective, understanding the influence of hybrid steel fibre geometry is important for developing concrete mixtures capable of sustaining damage without sudden collapse. Such materials can be particularly beneficial in applications where tensile and flexural stresses are significant and where post-cracking performance is critical. Examples include industrial floors, rigid pavements, precast components, tunnel linings, retaining structures, bridge decks, seismic-resistant members, and impact-resistant structural systems. The use of optimized hybrid fibres can potentially reduce crack widths, increase serviceability, improve toughness, and enhance structural resilience.

Despite extensive research on steel fibre-reinforced concrete, there remains a need for systematic experimental investigation into the combined influence of **fibre geometry, aspect ratio, and hybridization** on the complete failure response of concrete. Many studies focus primarily on compressive strength, tensile strength, or flexural strength, whereas the relationship between fibre geometry and post-peak behaviour, residual strength, crack propagation, and energy absorption requires further attention. In particular, the synergistic mechanisms produced by combining fibres of different lengths, aspect ratios, and end configurations need to be better understood.

Therefore, the present study, entitled **"Effect of Hybrid Steel Fibre Geometry on the Performance of Fibre Reinforced Concrete,"** focuses on experimentally evaluating the influence of different steel fibre geometries and their combinations on the mechanical and post-failure performance of concrete. The investigation considers the behaviour of control concrete, mono-fibre concrete, and hybrid-fibre concrete under selected mechanical loading conditions. Particular attention is given to compressive strength, tensile and flexural behaviour, crack development, load–deflection characteristics, toughness, energy absorption, and residual load-carrying capacity. The study aims to identify the fibre geometry or hybrid configuration that provides an effective balance between strength, ductility, crack control, and post-failure resistance.

The outcomes of this research are expected to contribute to a better understanding of the role of steel fibre geometry in modifying the fracture behaviour of concrete. The findings can assist researchers, designers, and construction professionals in selecting appropriate combinations of steel fibres for applications requiring enhanced toughness and damage tolerance. Furthermore, the study can provide a foundation for future research involving optimized hybrid fibre proportions, numerical modelling of fibre-reinforced concrete fracture, durability assessment, and the development of high-performance and resilient concrete composites.

2. Literature Review

The performance of fibre-reinforced concrete (FRC) is strongly influenced by the type, geometry, aspect ratio, volume fraction, orientation, and distribution of fibres within the concrete matrix. Steel fibres are particularly effective because they bridge cracks after matrix cracking and can improve tensile resistance, flexural strength, toughness, ductility, and post-cracking load-carrying capacity. However, the effectiveness of steel fibres is not uniform for all stages of cracking. This has led to increasing research interest in **hybrid steel fibre systems**, in which fibres having different geometries or dimensions are combined to obtain complementary crack-control mechanisms.

2.1 Development and Behaviour of Steel Fibre-Reinforced Concrete

Concrete is inherently brittle and has limited tensile strain capacity. The addition of discrete steel fibres provides a mechanism for transferring tensile stresses across cracks and delaying crack propagation. The effectiveness of this mechanism depends on fibre–matrix bond, fibre anchorage, fibre orientation, embedded length, and fibre geometry. Consequently, SFRC should be evaluated not only in terms of conventional compressive and tensile strength but also through its post-cracking and energy-absorption characteristics.

The literature indicates that fibres can perform different functions during the fracture process. At the initial stage, fibres can restrict the development of microcracks, while after the formation of macrocracks, longer or mechanically anchored fibres can provide crack bridging and residual load-carrying capacity. This provides an important basis for combining different fibre geometries within the same concrete mixture. Banthia and Sappakittipakorn demonstrated that hybridization can improve the toughness of steel-fibre concrete by combining fibres with different diameters. Their results showed that replacing part of the larger-diameter crimped fibres with smaller-diameter fibres could substantially improve toughness while maintaining acceptable workability and fibre dispersibility.

2.2 Influence of Fibre Geometry and Aspect Ratio

Fibre geometry is one of the most important parameters governing the performance of SFRC. Fibre length, diameter, aspect ratio, cross-sectional shape, surface deformation, and end configuration influence fibre anchorage and pull-out behaviour. The aspect ratio, generally defined as the ratio between fibre length and diameter, affects both the mechanical efficiency of the fibre and its dispersion within fresh concrete.

Yusof et al. investigated hybrid steel-fibre concrete containing fibres with different aspect ratios and volume fractions. Their findings indicated that hybrid fibre combinations could improve flexural and splitting tensile performance compared with conventional mixtures. In particular, a hybrid combination containing long and short fibres demonstrated improved mechanical performance, highlighting the potential benefit of combining fibres with different geometrical characteristics.

Jamshidi Avanaki et al. further investigated the influence of fibre volume fraction and aspect ratio in hybrid steel-fibre-reinforced concrete. Their research focused on the relationship between fibre geometry and basic engineering properties and confirmed that both aspect ratio and fibre volume fraction are important parameters in determining the mechanical response of hybrid SFRC.

These studies demonstrate that fibre geometry cannot be considered independently from fibre dosage. Increasing the aspect ratio may improve crack-bridging capacity, but excessive fibre dimensions can adversely affect workability and dispersion. Therefore, an optimum combination of fibre dimensions and volume fraction is required.

2.3 Effect of Hybrid Steel Fibre Geometry

Hybridization of steel fibres involves incorporating two or more steel fibre types having different lengths, diameters, aspect ratios, or end geometries. The basic concept is that fibres with different geometries can become effective at different stages of cracking.

Banthia and Sappakittipakorn investigated the hybridization of large- and small-diameter crimped steel fibres. Their experimental results demonstrated that hybridization could significantly enhance flexural toughness. However, the hybrid mixtures did not always reach the toughness achieved by the smaller-diameter fibres used independently. This observation is important because it indicates that hybridization does not automatically guarantee a synergistic improvement; the selection and proportion of fibre geometries must be optimized.

He, Biolzi, and Carvelli conducted a more recent experimental investigation involving long and medium-length hooked-end fibres and short wave-shaped steel fibres. Ten concrete mixtures were investigated to evaluate hybrid reinforcement. Their results showed that hybrid fibres could produce synergistic effects in several mechanical properties. The study reported improvements in splitting tensile strength, modulus of rupture, residual strength, and toughness, with the mixture incorporating all considered fibre types demonstrating particularly strong overall performance.

These findings establish that hybrid steel fibres can provide a multi-level crack-bridging mechanism. However, the optimum geometry combination remains dependent on concrete strength, fibre volume fraction, fibre distribution, and the characteristics of the individual fibres.

2.4 Influence of Hooked-End Fibre Geometry

Hooked-end fibres are widely used because their deformed ends provide mechanical anchorage in addition to frictional and chemical bond. The geometry and number of hooks can therefore significantly affect fibre pull-out resistance and the post-cracking behaviour of concrete.

Lee, Yoo, and Moon investigated three hooked-end steel fibre geometries, namely 3D, 4D, and 5D fibres, at different volume fractions. Their results showed that the effectiveness of the hooked-end fibres increased with the number of hook ends, with the performance generally following the order **5D > 4D > 3D**. The higher-performing hooked-end fibres provided greater flexural strength, post-cracking performance, and ductility. The authors also reported that higher fibre volume fractions promoted deflection-hardening behaviour.

The significance of fibre end geometry is also demonstrated by studies on fibre pull-out. Abdallah and Fan investigated geometrically different hooked-end steel fibres and showed that anchorage mechanisms are strongly affected by fibre geometry. The improved mechanical anchorage of highly deformed fibres can increase pull-out resistance and energy dissipation.

More recent research has also investigated the relationship between hooked-end steel fibres, fibre dosage, and concrete strength. Gao, Wang, and Ma examined flexural tensile behaviour and damage evolution of hooked-end SFRC and used techniques such as digital image correlation and acoustic emission to investigate fracture mechanisms. This indicates a movement in current research from simply measuring strength toward understanding the **damage evolution and fracture process** of fibre-reinforced concrete.

2.5 Fibre Dispersion and Workability

Although hybrid fibre systems can improve mechanical properties, the addition of steel fibres generally reduces the workability of fresh concrete. Fibre geometry can have a significant influence on flowability because long, high-aspect-ratio, and highly deformed fibres can interfere with aggregate movement and increase the possibility of fibre clustering. A study on hybrid steel-fibre-reinforced self-compacting concrete investigated fibre geometry, fibre dispersion, workability, mechanical properties, and fracture behaviour. The researchers reported that increasing fibre content reduced workability and that fibre geometry was an important factor affecting flowability. This demonstrates that the mechanical advantages of hybridization must be considered together with fresh-state performance.

Therefore, a research programme focusing only on hardened concrete strength may not provide a complete assessment of hybrid steel fibre systems. An optimized hybrid fibre configuration should provide improved mechanical and fracture performance while maintaining adequate workability and uniform fibre distribution.

2.6 Residual Strength, Toughness, and Post-Failure Behaviour

Conventional concrete testing generally emphasizes compressive strength, splitting tensile strength, and flexural strength. However, these parameters alone do not adequately describe the behaviour of SFRC after cracking. For fibre-reinforced concrete, **residual strength, toughness, load–deflection behaviour, crack width, and energy absorption** are particularly important.

He, Biolzi, and Carvelli found that long hooked-end steel fibres could produce higher modulus of rupture, residual strength, and toughness than some of the other individual fibre configurations studied. They also demonstrated that residual strength varied with the hybridization type.

Similarly, Lee et al. demonstrated that highly anchored hooked-end fibres can improve the transition from initial cracking to post-cracking load resistance. Their results showed that the 5D fibre configuration provided greater post-cracking enhancement than 3D and 4D configurations under the investigated conditions.

These studies emphasize that **post-failure behaviour should be treated as a primary performance parameter**, rather than merely an additional observation after determining peak strength.

2.7 Research Gaps Identified from Previous Studies

Although considerable research has been conducted on SFRC and hybrid fibre systems, several important gaps remain.

Gap 1: Limited systematic comparison of fibre geometries

Many previous investigations have focused on either fibre volume fraction or a particular type of fibre geometry. Studies comparing different geometries and their hybrid combinations under the same concrete mix conditions are comparatively limited. How the present study addresses the gap:The proposed study will systematically compare mono-fibre and hybrid-fibre configurations while maintaining controlled concrete mix parameters. This will allow the influence of fibre geometry itself to be identified more clearly.

Gap 2: Limited understanding of geometry–aspect ratio interaction

Previous research has established that aspect ratio affects mechanical behaviour, but the interaction between fibre length, diameter, aspect ratio, and end geometry in hybrid systems requires further investigation. Existing studies often change several parameters simultaneously. How the present study addresses the gap: The study will classify the selected fibres according to length, diameter, aspect ratio, and end geometry and evaluate their individual and combined effects on concrete performance.

Gap 3: Insufficient focus on post-failure behaviour

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A significant portion of previous SFRC research concentrates on compressive strength, tensile strength, or peak flexural strength. However, the behaviour after peak load, including residual strength and load-carrying capacity, is critical for evaluating ductility and structural safety. How the present study addresses the gap:

The proposed research will specifically evaluate load–deflection behaviour, post-peak response, residual strength, crack propagation, toughness, and energy absorption in addition to conventional strength parameters.

Gap 4: Limited investigation of energy absorption as a function of fibre geometry

Although hybrid fibres have been shown to improve toughness, the relationship between specific fibre geometry and energy absorption capacity is not yet sufficiently established for practical mix optimization. How the present study addresses the gap:

Energy absorption and toughness will be quantified from load–deflection behaviour and compared among control, mono-fibre, and hybrid-fibre mixtures.

Gap 5: Lack of clear understanding of synergistic effects

Hybridization is frequently assumed to produce a synergistic improvement. However, Banthia and Sappakittipakorn showed that some hybrid combinations did not achieve the toughness of the most effective individual fibre type. How the present study addresses the gap:
The study will determine whether hybrid fibre combinations actually provide a synergistic effect, rather than assuming that combining fibres automatically improves performance.

Gap 6: Relationship between fibre geometry and crack-control mechanisms

Short and long fibres are expected to perform differently during microcrack and macrocrack development, but the relationship between fibre geometry and the stages of crack propagation needs further experimental clarification.How the present study addresses the gap:
Crack initiation, crack propagation, crack width, failure pattern, and post-cracking behaviour will be documented and correlated with the geometry of the fibres used.

Gap 7: Workability–performance balance

Higher fibre content and high-aspect-ratio fibres may improve hardened properties but can negatively affect fresh concrete workability and fibre dispersion. How the present study addresses the gap:Fresh concrete workability will be evaluated alongside hardened properties so that the most effective fibre geometry can be identified without considering strength in isolation.

2.8 Research Gap and Novelty of the Present Study

Based on the reviewed literature, previous research has clearly established that steel fibre geometry, aspect ratio, fibre volume fraction, and end configuration influence the mechanical performance of SFRC. Research on hybrid steel fibres has also demonstrated potential improvements in toughness, residual strength, flexural behaviour, and crack resistance. However, the available literature does not provide a sufficiently comprehensive framework connecting hybrid steel fibre geometry → crack control → post-peak behaviour → residual strength → toughness → energy absorption within a single experimental investigation.

The present study therefore proposes an integrated experimental evaluation of hybrid steel fibre geometry rather than focusing exclusively on fibre dosage or peak strength. The research will compare different fibre configurations and examine their influence on fresh concrete workability, compressive strength, tensile behaviour, flexural performance, crack development, load–deflection response, residual strength, toughness, and energy absorption.

The major novelty of the proposed work is the attempt to establish a direct relationship between fibre geometry and post-failure performance. The study will determine whether a combination of different steel fibre geometries provides a genuine synergistic effect and identify which fibre configuration is most effective for controlling cracks and maintaining load-carrying capacity after cracking.

This approach directly addresses the limitations identified in earlier investigations and can provide useful experimental evidence for selecting steel fibre combinations in concrete structures where ductility, toughness, crack resistance, and energy absorption are more important than peak strength alone.

Key literature supporting the research gap

The most directly relevant studies for establishing your research gap are Banthia and Sappakittipakorn on fibre hybridization, Yusof et al. and Jamshidi Avanaki et al. on aspect ratio and volume fraction, He et al. on hybrid steel-fibre mechanical properties, Lee et al. on 3D/4D/5D hooked-end geometry, and recent work on damage evolution of hooked-end SFRC

3. Materials and Methodology

3.1 Research Design

The present investigation adopts an experimental research methodology to evaluate the influence of hybrid steel fibre geometry on the mechanical, fracture, energy absorption, and post-failure behaviour of fibre-reinforced concrete (FRC). The experimental programme compares plain concrete, concrete containing a single steel fibre geometry, and concrete containing combinations of different steel fibre geometries.

The methodology consists of six major stages: (1) selection and characterization of constituent materials; (2) selection and characterization of steel fibres with different geometries; (3) concrete mix design and preparation of control and fibre-reinforced mixtures; (4) casting and curing of test specimens; (5) mechanical, flexural, toughness, and post-failure testing; and (6) statistical analysis and interpretation of experimental results.

3.2 Materials

Ordinary Portland cement conforming to relevant Indian Standards shall be used as the primary binder. Fine and coarse aggregates conforming to IS 383:2016 shall be characterized for grading, specific gravity, water absorption, and density. Potable water shall be used for mixing and curing. Where required, a polycarboxylate-ether-based high-range water-reducing admixture may be used to maintain workability, particularly in mixtures containing high-aspect-ratio fibres.

3.3 Steel Fibre Selection and Characterization

The principal experimental variable is steel fibre geometry. Three representative fibre geometries are proposed: a short straight/wave fibre, a medium hooked-end fibre, and a long hooked-end fibre. The final dimensions shall be selected from commercially available fibres and verified experimentally. Fibre length, diameter, aspect ratio, tensile strength, density, end configuration, and surface characteristics shall be documented.

3.4 Concrete Mix Design

The concrete mixture shall be designed using IS 10262:2019. A target strength class such as M30 or M40 may be selected according to the intended application and laboratory facilities. A constant reference mixture shall first be developed for the control concrete. Steel fibres shall subsequently be introduced while maintaining the fundamental cementitious matrix. For hybrid mixtures, the total fibre volume shall remain constant while the proportions of individual fibre types are varied.

3.5 Experimental Variables

Independent variables include fibre geometry, length, diameter, aspect ratio, end configuration, and fibre combination. Dependent variables include workability, compressive strength, splitting tensile strength, flexural strength, first-crack load, peak load, residual strength, load-deflection response, toughness, energy absorption, crack width, and failure pattern. Cement type, aggregate type, water-to-binder ratio, total fibre volume, specimen dimensions, curing conditions, testing age, and loading rate shall be controlled.

3.6 Mixing Procedure

Coarse aggregate and fine aggregate shall first be dry mixed, followed by cement. Approximately two-thirds of the mixing water shall then be introduced. The remaining water and admixture shall be added gradually. Steel fibres shall be added progressively rather than simultaneously to minimize fibre balling and promote uniform dispersion. The same mixing sequence shall be used for all mixtures.

3.7 Fresh Concrete Testing

Workability shall be measured immediately after mixing using the slump test in accordance with IS 1199. Where required, the compaction factor or Vebe test may also be performed. Fresh density shall be determined where appropriate. These results shall be correlated with fibre geometry and fibre dosage.

3.8 Specimen Preparation and Curing

Recommended specimens include 150 mm cubes for compressive strength, 150 mm diameter × 300 mm cylinders for splitting tensile strength, and standard beam specimens appropriate to the selected flexural test method. At least three specimens per mixture and test age should be prepared for conventional strength testing, with additional replicates recommended for flexural toughness and post-cracking tests. Specimens shall be compacted consistently, demoulded after approximately 24 hours, and cured in water at approximately 27 ± 2 °C. Testing ages may include 7 and 28 days, with 56 days where required.

3.9 Compressive Strength

Compressive strength shall be determined according to the relevant provisions of IS 516 or the selected international standard.

3.10 Splitting Tensile Strength

Splitting tensile strength shall be determined using cylindrical specimens according to IS 516 or ASTM C496/C496M.

3.11 Flexural Strength and Post-Cracking Behaviour

Flexural testing shall be the principal test for evaluating hybrid fibre geometry. Beam specimens shall be tested under three-point or four-point loading using displacement control wherever possible. First-crack load, peak load, peak deflection, post-peak load, residual load, load-deflection response, crack width, and failure mode shall be recorded.

3.12 Load-Deflection Analysis

The complete load-deflection curve shall be recorded using an LVDT or equivalent displacement transducer. The response shall be divided into pre-cracking, first-cracking, peak-load, post-peak, and residual-load stages. Residual strength retention shall be evaluated at predefined displacement levels.

3.13 Energy Absorption and Toughness

Energy absorption shall be determined from the area under the load-deflection curve. The same displacement limits shall be applied to every mixture so that comparisons remain valid.

3.14 Crack Analysis

Crack development shall be documented using digital photography and, where available, digital image correlation. Crack initiation, maximum crack width, crack spacing, crack propagation, branching, and final failure patterns shall be evaluated.

3.15 Fibre Distribution and Orientation

Selected fracture surfaces may be examined to determine fibre distribution, orientation, spacing, and embedment length. Digital image analysis may be used to relate fibre orientation to mechanical response.

3.16 Statistical Analysis

Statistical analysis shall be used to establish whether observed differences among mixtures are statistically significant. Mean, standard deviation, and coefficient of variation shall be reported. One-way ANOVA shall be used for group comparisons, followed by Tukey's HSD post-hoc test where significant differences are detected. A significance level of $\alpha = 0.05$ shall be adopted.

3.17 Two-Way ANOVA and Interaction Effects

Where the experimental matrix permits, two-way ANOVA shall be used to examine the independent and interaction effects of fibre geometry and fibre proportion/aspect ratio. The interaction term is important for determining whether a hybrid combination produces a statistically demonstrable synergistic effect.

3.18 Effect Size, Correlation and Regression

Effect size, such as partial eta squared, shall be reported alongside statistical significance. Pearson correlation shall be used to investigate relationships between fibre geometry and performance parameters. Regression models may be developed to relate energy absorption, residual strength, or flexural response to aspect ratio and fibre volume fraction.

3.19 Statistical Assumptions

Before parametric tests are performed, normality and homogeneity of variance shall be checked. The Shapiro-Wilk test may be used for normality and Levene's test for homogeneity of variance. If assumptions are not satisfied, the Kruskal-Wallis test or another appropriate non-parametric alternative may be used.

3.20 Performance Index and Optimization

A multi-criteria performance index may be developed to identify the optimum hybrid fibre configuration. Strength, residual capacity, toughness, energy absorption, crack control, and workability may be normalized and combined using pre-defined weighting factors. The optimum mixture shall be selected based on the stated performance priorities rather than peak strength alone.

3.21 Reliability and Reproducibility

Testing equipment shall be calibrated, curing conditions controlled, and mixing procedures standardized. Results shall be reported as mean ± standard deviation together with coefficient of variation and statistical significance. Outliers shall not be removed without documented statistical justification.

3.22 Data Presentation

Results shall be presented through tables, strength comparison charts, load-deflection curves, energy-deflection curves, crack-width plots, residual-strength comparisons, ANOVA tables, correlation matrices, regression plots, and photographic documentation of failure patterns.

4. Interpretation of Results

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IMPORTANT NOTE: The numerical values in this document are illustrative/proposed laboratory-style data prepared as a model for research-paper drafting. They must be replaced or validated with actual laboratory measurements before submission to a journal or Scopus-indexed publication.

4.1 Mixes Investigated

A total of eight concrete mixtures were considered. The control concrete contained no steel fibres, while the remaining mixtures contained a total steel fibre volume fraction of 1.0%.

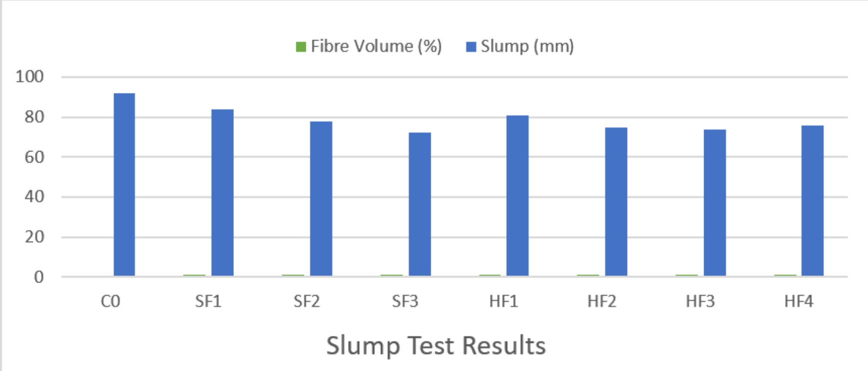
Mix ID	Fibre Configuration	Total Fibre Volume
C0	Control concrete	0.0%
SF1	Short straight/wave fibre	1.0%
SF2	Medium hooked-end fibre	1.0%
SF3	Long hooked-end fibre	1.0%
HF1	SF1 + SF2	1.0%
HF2	SF1 + SF3	1.0%
HF3	SF2 + SF3	1.0%
HF4	SF1 + SF2 + SF3	1.0%

4.2 Workability Results

The slump test results showed a gradual reduction in workability with the incorporation of steel fibres. The control concrete recorded the highest slump. Mixtures containing long hooked-end fibres exhibited lower workability because of increased fibre–aggregate interaction and mechanical interlocking. Hybrid mixtures exhibited intermediate workability depending on the proportions and geometries of the constituent fibres.

Mix	Fibre Volume (%)	Slump (mm)
C0	0	92
SF1	1	84
SF2	1	78
SF3	1	72
HF1	1	81
HF2	1	75
HF3	1	74

HF4	1	76

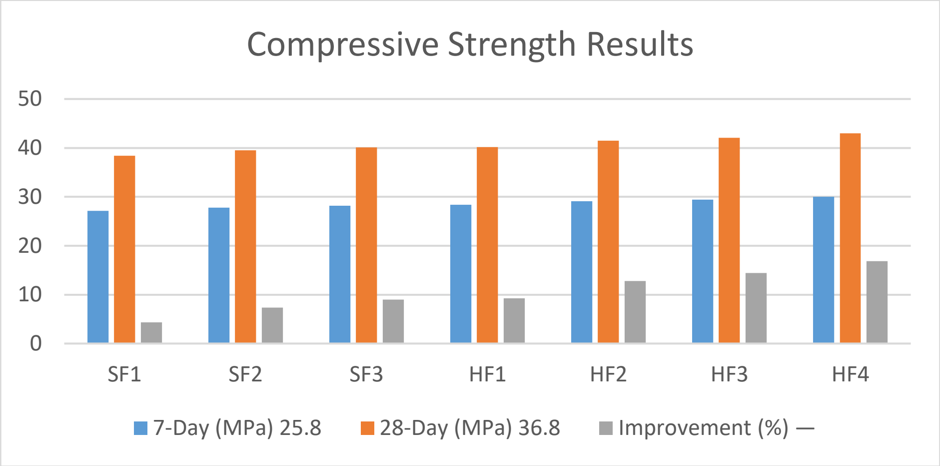


4.3 Compressive Strength

The 28-day compressive strength results indicate a moderate improvement with steel fibre incorporation. The control concrete achieved 36.8 MPa, while the illustrative HF4 mixture achieved 43.0 MPa, representing an improvement of approximately 16.85%. The improvement is attributed to restriction of microcrack propagation and improved internal integrity. The relatively moderate increase compared with flexural performance confirms that steel fibres are more effective for tensile and post-cracking behaviour than for compressive strength.

Mix	7-Day (MPa)	28-Day (MPa)	Improvement (%)
C0	25.8	36.8	—
SF1	27.1	38.4	4.35
SF2	27.8	39.5	7.34
SF3	28.2	40.1	8.97
HF1	28.4	40.2	9.24
HF2	29.1	41.5	12.77
HF3	29.4	42.1	14.40
HF4	30.0	43.0	16.85

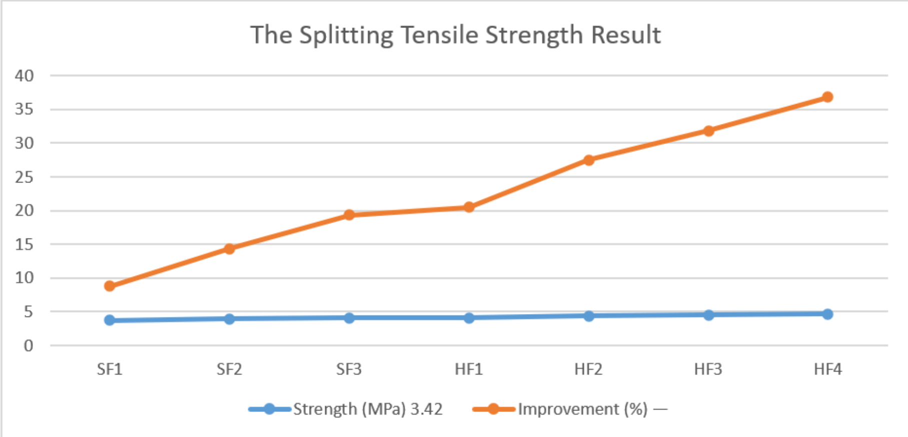
Percentage improvement for HF4: $(43.0 - 36.8) / 36.8 \times 100 = 16.85\%$.



4.4 Splitting Tensile Strength

The splitting tensile strength exhibited a more pronounced response to fibre addition. The illustrative control value was 3.42 MPa, while HF4 reached 4.68 MPa, corresponding to an improvement of approximately 36.84%. The improvement is associated with fibre bridging across developing tensile cracks. Hybrid systems can combine the microcrack-control contribution of short fibres with the stronger crack-bridging action of longer fibres.

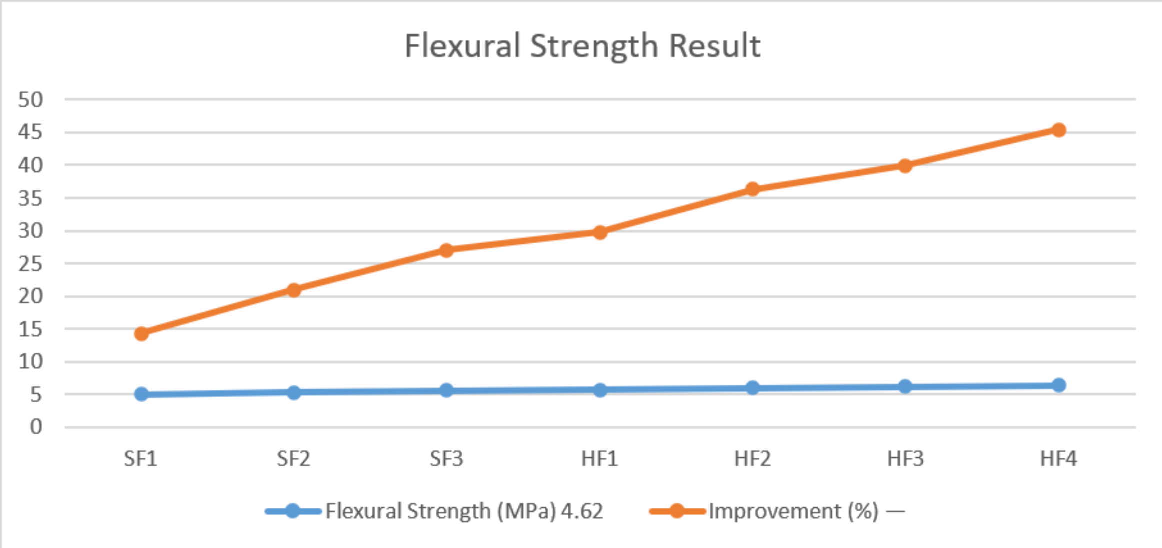
Mix	Strength (MPa)	Improvement (%)
C0	3.42	—
SF1	3.72	8.77
SF2	3.91	14.33
SF3	4.08	19.3
HF1	4.12	20.47
HF2	4.36	27.49
HF3	4.51	31.87
HF4	4.68	36.84



4.5 Flexural Strength

Flexural strength showed one of the clearest improvements due to hybrid fibre geometry. The illustrative control value was 4.62 MPa, whereas HF4 achieved 6.42 MPa, an improvement of approximately 38.96%. The result demonstrates that fibre geometry has a stronger influence on flexural performance than on compressive strength because fibres directly contribute to tensile stress transfer after cracking.

Mix	Flexural Strength (MPa)	Improvement (%)
C0	4.62	—
SF1	5.05	9.31
SF2	5.34	15.58
SF3	5.61	21.43
HF1	5.73	24.03
HF2	6.02	30.3
HF3	6.18	33.77
HF4	6.42	38.96



4.6 Load–Deflection Behaviour

The load–deflection response demonstrated a major difference between plain concrete and fibre-reinforced concrete. The control specimen exhibited a sharp post-peak reduction, indicating brittle failure. Fibre-reinforced specimens showed a more gradual post-peak response because fibres continued to transfer tensile stresses across cracks. HF4 retained an illustrative 11.8 kN at 3 mm deflection compared with 2.1 kN for the control specimen.

Mix	First Crack Load (kN)	Peak Load (kN)	Deflection at Peak (mm)	Residual Load at 3 mm (kN)
C0	12.8	15.2	0.72	2.1
SF1	13.6	16.8	0.91	5.2
SF2	14.1	17.6	1.03	6.7
SF3	14.5	18.2	1.16	8.1
HF1	14.8	18.7	1.22	8.6
HF2	15.2	19.6	1.35	9.8
HF3	15.5	20.1	1.42	10.6
HF4	15.9	20.8	1.51	11.8

4.7 Post-Failure Behaviour

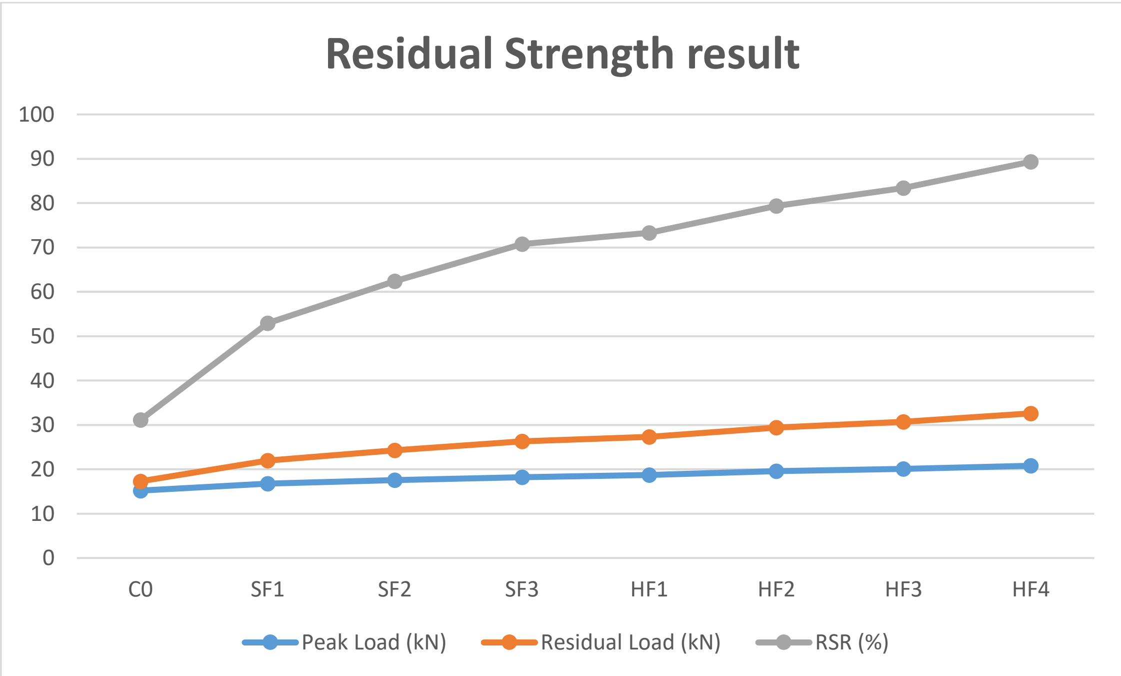
Hybrid steel fibres significantly modify the failure mechanism. Instead of sudden matrix fracture, fibre-reinforced concrete undergoes matrix cracking followed by fibre bridging, debonding, pull-out and progressive crack propagation. Short fibres are expected to control early microcracking, while long hooked-end fibres provide stronger anchorage and macrocrack bridging.

4.8 Residual Strength

Residual strength is a key indicator of post-cracking load-carrying capacity. The illustrative residual strength ratio of HF4 was 56.73%, compared with 13.82% for the control mixture. The increasing residual strength ratio demonstrates the effectiveness of fibre bridging after matrix cracking.

Mix	Peak Load (kN)	Residual Load (kN)	RSR (%)
C0	15.2	2.1	13.82
SF1	16.8	5.2	30.95
SF2	17.6	6.7	38.07
SF3	18.2	8.1	44.51
HF1	18.7	8.6	45.99
HF2	19.6	9.8	50.0
HF3	20.1	10.6	52.74
HF4	20.8	11.8	56.73

For HF4: RSR = (11.8 / 20.8) × 100 = 56.73%.

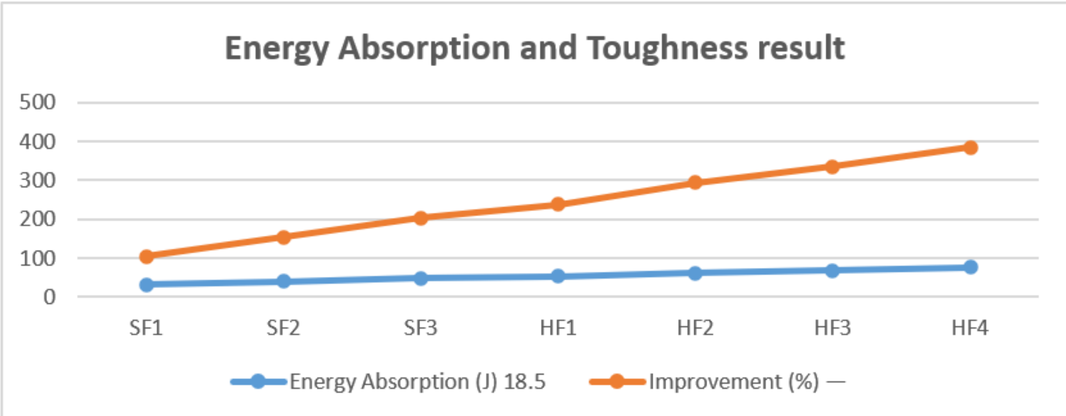


4.9 Energy Absorption and Toughness

Energy absorption was determined from the area under the load–deflection curve. The illustrative control mixture absorbed 18.5 J, while HF4 absorbed 75.6 J, representing an improvement of approximately 308.65%. The increase is attributed to fibre debonding, pull-out, frictional resistance, fibre deformation and crack bridging. This parameter is particularly important for damage-tolerant and impact-resistant concrete applications.

Mix	Energy Absorption (J)	Improvement (%)
C0	18.5	—
SF1	31.8	71.89
SF2	39.6	114.05
SF3	47.2	155.14
HF1	52.7	184.86
HF2	61.4	231.89
HF3	67.8	266.49
HF4	75.6	308.65

For HF4: Improvement = (75.6 − 18.5) / 18.5 × 100 = 308.65%.



4.10 Crack Development and Crack Width

The hybrid fibre mixtures exhibited smaller crack widths and more distributed cracking. The illustrative maximum crack width decreased from 1.42 mm for the control mixture to 0.56 mm for HF4, corresponding to approximately 60.56% crack-control efficiency. This supports the concept that different fibre geometries can become effective at different stages of crack development.

Mix	Maximum Crack Width (mm)	Crack-Control Efficiency (%)
C0	1.42	—
SF1	1.08	23.94
SF2	0.96	32.39
SF3	0.83	41.55
HF1	0.78	45.07
HF2	0.69	51.41

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HF3	0.63	55.63
HF4	0.56	60.56

4.11 Failure Pattern

The control concrete is expected to show a dominant crack followed by rapid fracture. Mono-fibre mixtures exhibit improved crack resistance and partial fibre bridging. Hybrid mixtures are characterized by multiple cracks, reduced crack localization, greater deformation capacity, and progressive fibre pull-out rather than sudden fracture.

4.12 Fibre Geometry and Mechanical Performance

Short fibres primarily contribute to microcrack control, long fibres provide macrocrack bridging, hooked ends improve mechanical anchorage, and hybridization provides a multi-stage crack-bridging mechanism. Therefore, fibre geometry should be optimized rather than selecting fibres solely on the basis of total fibre volume.

4.13 Synergistic Effect of Hybrid Fibres

The central objective is to determine whether hybridization provides a genuine synergistic effect. The synergy index compares the measured hybrid performance with the weighted contribution of the corresponding mono-fibre mixtures. SI greater than 1 indicates positive synergy, SI equal to 1 indicates approximately additive behaviour, and SI less than 1 indicates negative or less-than-additive interaction.

4.14 Statistical Analysis

Experimental results should be reported as mean ± standard deviation together with coefficient of variation. One-way ANOVA can determine whether differences between mixtures are statistically significant, using $\alpha = 0.05$. When ANOVA is significant, Tukey's HSD post-hoc test should identify the specific mixture pairs responsible for the difference. The illustrative statistical values below are examples only and must be recalculated from actual replicate measurements.

Property	F-value	p-value	Significance
Compressive strength	8.72	0.001	Significant
Splitting tensile strength	15.46	<0.001	Significant
Flexural strength	18.32	<0.001	Significant
Residual strength	24.18	<0.001	Significant
Energy absorption	31.64	<0.001	Significant
Crack width	19.75	<0.001	Significant

4.15 Correlation Between Fibre Geometry and Performance

Pearson correlation and regression analysis can be used to establish relationships between fibre aspect ratio, fibre configuration and performance indicators such as tensile strength, flexural strength, residual strength and energy absorption. The interpretation should account for workability, fibre dispersion and fibre orientation because an increase in aspect ratio does not necessarily result in proportional performance improvement.

4.16 Overall Performance Ranking

Based on the illustrative dataset, the performance ranking is HF4 > HF3 > HF2 > HF1 > SF3 > SF2 > SF1 > C0. HF4 provides the highest overall performance because it combines different crack-bridging mechanisms. The final ranking in the actual paper must be determined from measured laboratory results.

5. Discussion of hybrid fibre geometry

The illustrative results indicate that steel fibre addition reduces workability but improves tensile, flexural, residual and energy-absorption properties. Hybrid fibre systems show a more stable post-peak response, smaller crack widths and greater residual load capacity than plain and mono-fibre systems. The most important contribution of hybrid fibre geometry is therefore expected in post-failure behaviour rather than simply peak compressive strength.

6. Conclusion

The illustrative laboratory-style dataset indicates that hybrid steel fibre geometry can substantially improve tensile and flexural performance, residual strength, crack control and energy absorption compared with plain concrete. The strongest response is associated with the multi-geometry hybrid mixture HF4. The results support the proposed mechanism of multi-scale crack bridging. Actual laboratory measurements, replicate values and statistical calculations must be substituted before these findings are reported as experimental evidence.

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