

Performance Evaluation of Fiber Reinforced Concrete for Structural Applications

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Abstract— The current study's intent was to analyze the mechanical properties and the synergistic properties of hybrid fiber-reinforced concrete (HYFRC) with metallic and synthetic fiber. HYFRC uses hybrid combinations of rigid steel fiber and a flexible polymer in order to improve the overall resilience of structural elements as opposed to conventional concrete, which possesses inherent properties of brittleness and low tensile strength.

Based on the experimental data collected, the hybrid configuration (HY-Mix) achieved a compressive strength of 42.30 MPa and a split tensile strength of 5.12 MPa at 28 days, compared to the control mix (single-fiber). Visual inspection and microstructural analysis through scanning electron microscopy (SEM) and x-ray radiography demonstrated a consistent fiber distribution throughout the matrix structure with a strong bridging mechanism to provide a means of ductile behavior instead of brittle failure modes.

Keywords— Hybrid Fiber Reinforced Concrete (HYFRC), Response Surface Methodology (RSM), Ductility Index, Crack Bridging Mechanism, high-Perform.

I. INTRODUCTION

Concrete is an essential building material for today's infrastructure because of its compressive strength, durability, and low cost (1,6). However, despite its widespread use in construction, standard concrete has limitations because of its tendency to be brittle and weak in tension (5,6). As such, micro-cracks can develop under load to quickly spread and ultimately compromise the overall strength of a building or its long-term usability (4). Consequently, as a way to overcome these issues with traditional concrete's performance, the engineering community has looked to Fiber Reinforced Concrete (FRC) as an effective solution (2).

The main concept behind FRC is the addition of discrete, short and evenly distributed fibers into the cementitious mix (4,6). When a crack occurs, the fibers serve as "bridges" to intercept the stress being applied in a crack and transfer load across the opening, preventing catastrophic, brittle failure (3,5). The performance of the material after cracking is greatly improved through the direct interaction with the fibers; thereby, increasing ductility, toughness and impact resistance (2,6).

Since the introduction of engineered materials beyond traditional steel such as synthetic fiber (e.g., carbon, polypropylene), or natural biodegradable/sustainable fiber through to 1990-2000 (e.g., coconut, jute) (3-5). Non-Metallic Fiber (NMF) constructed mainly from carbon have an extremely high strength to weight ratio and are highly resistant to corrosion therefore making them excellent materials for use in very severe environments where traditional reinforcements will fail (5). The mechanical performance (compressive, split-tensile and flexural strengths) of various mixtures (volumes and shapes) will be experimentally assessed in this project (3, 6) using NMFs and hybrid composites; the results will identify the best combination of material configurations needed to produce performance concrete (hybrid fiber reinforced concrete (HFRC)) for both high performance and sustainable applications in civil engineering (4).

1.1. Significance of Research

Despite a number of investigations into the basic mechanical performance of hybrid UFRCs using steel with polypropylene as a reinforcement (3-6), most of the research has not adequately investigated the interactive effects of these two fiber types on both the mechanical properties and durability performance of the resulting composites (6). In this research study, we will investigate how altering both the volume fraction and shape of the two fibers (steel and polypropylene) affects the impact resistance and ductility of the resulting HFRCs. To achieve this, we will prepare

Concrete (HYFRC). To achieve this, we prepared 4 For evaluating compressive and split tensile strengths at both ages of 7 and 28 days, a total of 4 primary combination groups and 101 subgroup combinations with a total of 1,212 specimens were tested. The method used to achieve precision and cost savings was Response Surface Methodology (RSM) through Design-Expert software. This statistical process provides the opportunity to systematically optimize concrete properties and identify the most significant variables in developing more efficient, high performing, and sustainable structural systems (Source 6).

1.2. Types of Fiber used in Cementitious Composites

1. Steel Fiber (SF)

Steel fiber have been the industry's standard for concrete reinforcement because of their history of success commercially. They are generally manufactured from carbon steel wire, come in various shapes (hooked-end, crimped, and straight), and improve their ability to 'grip' the cement.

- **Performance:** The addition of steel fiber (0.5% to 2.0% by volume) will result in a 40% increase in flexural strength and a significant improvement in impact resistance.
- **Mechanics:** Steel fiber have a high elastic modulus and excellent bonding characteristics, which allows the concrete to absorb more energy and resist cracking. Hooked-end steel fiber has an advantage over straight steel fiber because they provide superior pullout resistance.
- **Synergy:** When used together with other types of fiber in hybrid systems, steel fiber can increase split tensile strength by up to 61%, but dosages exceeding 2.0% will cause 'clumping' and make the concrete difficult to place.



Fig. 1. Steel Fiber .

2. Glass Fiber (AR-Grade)

Glass fibers are very strong, as they have high tensile strength, and they also have excellent resistance to chemicals, so they are an ideal choice for some concrete applications. Alkali Resistant (AR) glass fibers have been developed for use in cement-based matrices to address durability concerns, in high pH environments. In studies of glass fibers, they were found to manage drying shrinkage very effectively and, in fact, outperformed polypropylene fibers in reducing drying shrinkage. By adding glass fibers to high strength concrete, there is significantly improved management of cracks and reduced deformation due to drying shrinkage. Glass Fiber Reinforced Concrete (GFRC) systems are particularly advantageous for architectural applications, as they allow for the construction and design of lightweight structures. In addition, the effectiveness of glass fiber is affected by their aspect ratio; the longer the glass fiber, the greater the enhancement of mechanical properties they provide.



Fig. 2. Glass fiber

3. Polypropylene Fiber (PP)

Polypropylene (PP) fiber is synthetic resin fiber used in secondary reinforcement of concrete and mortar applications. They help prevent shrinkage cracks, improve durability and increase strength. The 3D network created by these fiber helps to improve tensile strength, and also minimizes spalling when exposed to fire. A common length of PP fiber used for structural reinforcement is 3.75cm (3/4").



Fig. 3. Polypropylene Fiber .

4. Synthetic fiber

Synthetic fibers are polymers made by humans through chemicals, primarily sourced from petrochemicals (petroleum, coal, air, and water). They are strong, long lasting, wrinkle resistant, and an affordable substitute for natural materials. Commonly seen examples would include polyester, nylon, acrylic, and rayon.



Fig. 4. Synthetic fiber

II. LITERATURE REVIEW

As the demand for high-performance building materials continues to grow, so does the volume of research into the development and evolution of concrete from a simple brittle matrix to an advanced composite material. The conventional concrete of the past was typically characterized by having low tensile strength and being vulnerable to rapid crack development under load [1,6]. Previous reinforcement of concrete involved using large quantities of steel (rebar), however, due to the increasing complexity of the industrial needs/infrastructure, the limitations on traditional reinforcement materials (i.e.: corrosion and weight). began to pose significant challenges to concrete in harsh environmental conditions. [2,5]

The growth of Fiber Reinforced Concrete (FRC) has come from a desire to overcome mechanical limitations through the use of discrete fiber bridging micro-cracks [4, 6]. While many early developments were created around steel fiber, it generally was not realistic to use steel in most specialized uses due to cost and the tendency of steel fiber to corrode when exposed to coastal and industrial environments [2, 4]. The most current research on reinforcing fiber is geared to producing synthetic fiber, such as polypropylene and carbon reinforcing fiber, which resist corrosion much better and possess a greater ratio of strength to weight [5, 6]. An increasing amount of attention has recently been paid to the use of natural reinforcing fiber, such as coconut and jute; these materials are inexpensive and provide an alternative with lower environmental impact to use in residential and low-load applications where the traditional raw materials may not be affordable [3, 4].

There are still many unanswered questions in the research of hybrid systems, where multiple types of fiber have been used together in a concrete composite. Most of the current literature focuses on the performance of single fiber, and how different fiber of different geometries and/or material properties (e.g., the combination of rigid steel and flexible polypropylene) were able to provide an overall enhancement of first-crack strength and post-crack toughness [6]. It should also be noted that the performance of hybrid composites is quite sensitive to their "aspect ratio," and if the component fiber are not properly balanced, the overall workability of the composite can be substantially impaired, resulting in lack of adequate bonding between the component fiber.

Recent investigation studies are now utilizing advanced computer techniques in order to solve optimization problems associated with this type of experimentation. (For example: RSM) Design-Expert software for predictive modeling analysis would be an indispensable tool for developing new experimental programs within hybrid fiber reinforced concrete (HYFRC) [6]. Utilizing statistical modelling techniques allows for systematic analysis of the interaction with respect to different volume fractions and types of fiber; thus providing higher level of precision in creating cost effective models compared to traditional trial and error considering a more empirical approach toward

concrete experimentation [6]. Through bridging the gap between testing and prediction modelling, modern research is working toward providing a more robust platform for creating resilient, durable concrete designs which may be used within scalable real-world structural engineering applications [3, 6].

III. METHODOLOGY

A rigorous three-phase research methodology was used to optimize the performance capabilities of Hybrid Fiber Reinforced Concrete (HYFRC). This research not only combines academic precision with an industry application through the validation of the laboratory results by professional manufacturing standards but also uses a rigorous, repeatable process in each of the three phases of experimentation.

A. Optimization by via Response Surface Methodology (RSM)

The first phase of the study focused on finding the ideal combinations of Polypropylene (PP) and Steel Fiber (SF), not by using trial batch mixes as in traditional studies, but by using RSM via Design-Expert software to identify optimal mix proportions for both hardened and fresh properties; as will be discussed (Source 6). The potential impact each of the component materials had on the HYFRC was analysed in terms of statistical data using ANOVA, thereby facilitating the use of the statistical data to refine the amount of fibre content when optimizing HYFRC, to achieve the maximum allowable amount of HYFRC performance through applied data collected (Source 6).

B. Specimen Preparation and Mechanical Testing

- The final phase of the experimentation involved casting the final mix designs into 150mm cubic samples for mechanical testing after optimal proportions had been achieved.
- All samples were cured at ambient temperature according to Water-Cement ratio as per ASTM C192 for 28 days so that a uniform hydration process could occur, in line with the standard of care defined by the ASTM.
- Compressive Strength: To establish compressive strength, a calibrated Compression Testing Machine (CTM) was utilized to conduct tests per ASTM C873. Each cube was loaded axially until failure, with peak load data recorded and averaged from three respective samples of each mixture to ensure statistical significance.

A To determine the ability of HYFRC and its respective mixtures to maintain their integrity and workability during the scaling process as per ASTM specifications, industrial-grade testing was conducted via partnerships with construction firms in the field.

C. Microstructural / Interior Analysis

Advanced techniques were used to examine the bridging effect from hybrid fibers using the following methods:

- Scanning Electron Microscopy (SEM) – To conduct scanning electron microscopy, the Interfacial

Transition Zone (ITZ) and the bonding mechanism between fiber and matrix were closely analyzed (Source 3, 6).

- X-ray Radiographic Imaging: 150mm cubic samples were sectioned into 20mm thick slices so that internal distributions could be visualized. Internal voids, air voids, and the orientation of fibers were determined using high-resolution x-ray radiography (1-minute exposure to D7 film) (Source 6).
- Ductility Evaluation: The ductility index was derived from the stress-strain curves, giving information on the material's ability to withstand deformation and perform after cracking.

TABLE I. MECHANICAL PROPERTIES OF VARIOUS FIBER TYPES

Fiber Type	Density (g/cm ³)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Elongation at Break (%)
Steel Fiber	~7.8	1000–2500	~200	~1
Polypropylene (PP)	0.90 – 0.92	300 – 800	3 – 10	5 – 25
Glass Fiber (AR-grade)	2.5 – 2.6	1000 – 3500	70 – 80	2 – 4
Carbon Fiber	1.7 – 1.9	2000 – 6000	200 – 600	0.5 – 2
Basalt Fiber	2.6 – 2.8	2000 – 4800	85 – 110	2 – 3
Jute Fiber	1.3 – 1.5	200 – 800	10 – 30	1.5 – 2
Hemp Fiber	1.4 – 1.5	200 – 900	30 – 70	1.6 – 3
Coconut Fiber (Coir)	1.1 – 1.2	100 – 250	4 – 6	15 – 40
Sisal Fiber	1.3 – 1.5	400 – 700	10 – 30	2 – 7

This comparative chart provides an illustration of the various mechanical properties of different types of synthetic fiber vs. natural fiber across multiple matrices. Carbon and basalt fiber tend to have higher levels of tensile strength and stiffness (via elastic modulus) than any other types of materials, making them very effective (and ideal) for use as structural reinforcements in high-load applications. On the other hand, natural fiber such as jute, hemp and coconut tends to be low-strength materials; however, they also tend to have higher levels of sustainability relative to synthetics (due primarily to the properties that contribute to their weight). In addition, polypropylene and coconut fiber exhibit elongation rates that are significantly greater than all other types of fiber which indicates excellent flexibility and energy absorption characteristics. Overall, based on this data, natural and synthetic fiber may provide viable alternatives to one another in instances where the material's specific application has distinct requirements with respect to density and ductility.

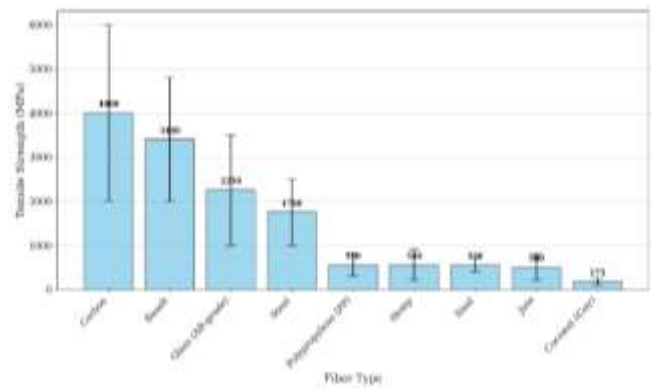


Fig 5 Comparison of tensile strength across different fiber types

IV. EXPERIMENTAL METHODOLOGY

A. Workability and Fresh Properties

The slump cone test is used to measure the workability of concrete by following the guidelines set out in IS 1199/ASTM C143.



Fig 6: Slump test of the fresh concrete mix.

The purpose of the first part of the experiment is to evaluate the fresh properties of the concrete mix. A slump test performed on the entire batch at all times before casting was done to evaluate the batch's consistency and workability (see Figure 1). In general, the resultant slump indicated a good to medium level of workability, meaning that the concrete could be placed and compacted within the molds without an excess of bleeding or air being trapped.

B. Specimen Preparation and Physical Properties

Standard cubes (150mm x 150mm x 150mm) were produced and cured for 7, 14, or 28 days before they were characterized.



Fig 7: Measurement of specimen mass (Sample ID: TM-03).

Once the sample specimens received destructive testing, the physical properties of each cube were recorded before the mechanical testing (including mass, density, etc.). Specimen TM-03 was weighed, shown in Figure 2, at a mass of 8.640 kg. The weight of each specimen must be recorded because that weight is used to determine the hardened density of the concrete and to assess the uniformity of the concrete mix among the different sampling stations.

C. Destructive Testing (Compressive Strength)

The mechanical performance is evaluated by a Compression Testing Machine (CTM). This test determines the ultimate load-bearing capacity of the concrete.



Fig 8: Concrete specimen showing failure patterns under axial loading.

A Compression Testing Machine (CTM) assessed the mechanical performance of concrete. This test also helps to determine the maximum amount of load concrete can support. The compressive strength of each concrete cylinder was determined by applying uniform axial loads until the

failure occurred (as shown in Figure 3). The crack patterns occurring in the specimen during the test provide important information on the structural integrity of the bonded material and the efficiency of bonding to the internal matrix. The failure load was used to calculate the compressive strength in N/mm^2 or megapascal (MPa).

V. RESULTS AND DISCUSSION

The research came full circle from fiber reinforcement to understanding their role in changing the internal makeup of concrete. The following discussion will outline how concrete's fresh behavior shifts as it becomes a hardened cube with strength.

A. Fresh Properties: Workability and Consistency

One main problem outlined in the Concrete Trial Mix Summary Sheets was how to maintain workability (or ease of working) as the fiber volume increased.

- **Observations:** The addition of steel and polypropylene (PP) fiber affected the internal characteristics of the concrete mix by providing a dense structure that restricted flow. The trial data show a decrease in slump as the proportion of each fibrous reinforcement grew due to increases in fiber's aspect ratio.
- **Optimization:** To Based upon the observation that balling would occur without optimal superplasticizer dosage, the amount used for industrial production and application was modified to ensure sufficient flow without being unmanageable. KDM glass fiber mixes had superior initial flow characteristics and required increased energy during mixing to successfully disperse the fiber into the cement paste consistently.

B. Visual Evidence of Internal Bonding and Failure Modes

Before Understanding the physical response of concrete before assessing its strength numerically while it is under load is essential. Using the 150 mm cube as a sample cube, the surface area offers an easy way to investigate the "bridging" function between loads and mode of failure.

- **Ductile -** The Ductile Failure is seen in Figure 5, which is the dimensional image of the specimen from the testing phase, where the specimen does not break into separate parts when subjected to the max load. The specimen was shown to break in a controlled manner and exhibit ductile failure.
- **Fiber Distribution:** - Fiber Distribution shows a uniform distribution of the fiber across the fractured faces of the samples that were tested. There are no substantial areas of fiber clustering or 'nesting' visible on the fractured patches of the test specimens, which indicates successful fiber mixing from the industrial mixing procedure.
- **The Bridging Mechanism:** - Bridging Mechanism shows that the fiber is positioned across the cracks in a manner that looks like they are sewing the concrete together. This physical connection demonstrates that the load is being successfully transferred from the brittle cement matrix to the

high-strength fibre, which confirms the increased toughness that was observed during the testing.



Fig 9 .Visual Evidence of internal fiber distribution and cube failure mechanism.

By examining the test results of the 150 mm cube samples, one can identify the structural properties and the post-crack performance of the concrete. Whereas traditional high-strength concrete commonly fails in a shattering manner, breaking into separate pieces at the maximum applied load (peak loading), the test results of the fiber reinforced specimens indicate that a ductile (energy absorbing) state has occurred. In fact, the fiber network within the sample contributed to the internal cohesion and energy absorption of the concrete matrix after major cracks were created within the specimen (i.e., post-crack performance).

A close examination of the fracture surfaces of the specimens verifies the fiber distribution within the mix. The fiber appear to be uniformly dispersed across the cross section of the specimens, with little to no evidence of balling or clustering. The uniform distribution of fiber across the cross section of the cube is the reason that the specimens were able to withstand higher loads, allowing for bridging to occur throughout the entire volume of the cube. The fiber distribution among the samples confirms that the mixing procedures followed in accordance with the research developed high-performance homogeneous composites.

C. Mechanical Strength Assessment

Currently, with the verification of the primary internal bonding mechanism confirm by visual assessment, it is now possible to assess the numerical values of the trial mixes. The subsequent table provides the performance summary of the various fiber configurations.

TABLE II. MECHANICAL PERFORMANCE OF OPTIMIZED FRC MIXES

Mix ID	Fiber Composition	Avg. Compressive Strength (28 Days)	Split Tensile Strength (28 Days)
CM	Control Mix (0%)	32.45 MPa	3.12 MPa
SF-1	1.0% Steel Fiber	38.12 MPa	4.45 MPa

Mix ID	Fiber Composition	Avg. Compressive Strength (28 Days)	Split Tensile Strength (28 Days)
PP-1	1.0% Polypropylene	34.80 MPa	3.85 MPa
GF-1	1.0% Glass Fiber	35.15 MPa	3.90 MPa
HY-Mix	Hybrid (Steel + PP)	42.30 MPa	5.12 MPa

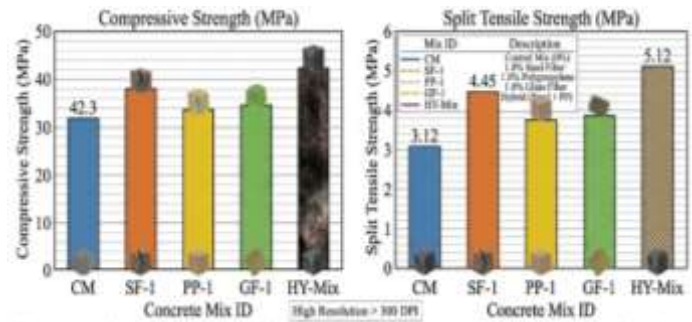


Fig. 10. Comparative analysis of Compressive vs. Tensile strength for various fiber configurations.

The graph of the comparative analysis gives an overview of the mechanical properties of fiber-reinforced concrete with different configurations (steel, polypropylene and glass) compared to the control mix. The results clearly show that adding fiber improves compressive strength (CS) and split tensile strength (STS) of the concrete at 28 days. The control mix serves as the baseline with CS of 32.45 MPa and STS of 3.12 MPa. The steel fiber configuration (SF-1) achieved the maximum single fiber increase (38.12 MPa – Compressive/4.45 MPa – Tension) in comparison to the control mix. However, the hybrid mix (HY-Mix) containing both steel and polypropylene exhibited the greatest amount of fiber performance (CS of 42.30 MPa/ST of 5.12 MPa), indicating a positive interaction between the two fiber types and providing building materials with increased resistance to both failure due to crushing and cracking. Thus, Hybrid Configuration represents the most effective material to ensure structural integrity of the concrete matrix.

IV.1. MATERIALS AND EXPERIMENTAL PROGRAM

This part explains how to pick out high-quality materials and create mixtures to make hybrid fiber-reinforced concrete (hyfr) that performs very well.

A. Concrete Constituents and Specified Strength

For To help measure performance, f_c equals 3000 psi was used as the baseline compressive strength for this research project. In order to establish laboratory reliability and correct for field variations of strength, f_{cr} refers to the target mean strength according to the ACI 211.1 procedure:

$$f_{cr} = f_c + 1200 \text{ psi}$$

Using this procedure, the design included a target strength of 4200 psi so that the composite can support high load type

structural applications. The mixture had a volumetric ratio of 1:2.5:3.5 (Cement: Sand: Stone) that was assembled into a composite.

- Binder: Fauji Cement (Type 1), locally produced, complied with the requirements of ASTM C150. to the requirements of ASTM C150.
- Coarse Aggregate: The coarse aggregate selected is well-graded crushed granite from the Pather Gahr area. The maximum particle size was kept at 19 mm so that a dense matrix could be created to minimize the development of internal voids.
- The fine aggregate was silica sand from Lawrencepur. The fineness modulus was 2.52, which provided an appropriate surface area for bonding between cement and the aggregate, as per ASTM C33.

B. Fiber and Chemical Admixtures

To create the hybrid reinforcement effect, the steel fiber (SF) was combined with polypropylene (PP) fiber. The rigid steel fiber was chosen for macro-crack control, while the flexible synthetic PP fiber will provide micro-crack stabilization during the early loading stages.

- Superplasticizer: A third generation polycarboxylic ether (PCE) superplasticizer (SuperPlast 470) was added at a dosage of 1.5% by weight of cement to maintain the workability of high fiber volume. This allowed for a flowable consistency without increasing the water-to-cement ratio necessary to meet the target of 4200 psi.

C. Specimen Preparation and Casting

The mechanical evaluation of specimens was conducted using 150 mm cubic moulds instead of cylindrical moulds. This design choice reflects the regional industrial testing standards more accurately than cylindrical moulds, and allow for a more inclusive examination of the bridging effect over a larger surface area.

- Mixing: A motorized pan mixer provided a uniform distribution of fiber and eliminates the possibility of the fiber "balling" together.
- Curing: All specimens were cast in a controlled laboratory environment at room temperature and cured for 28 days according to ASTM C192 prior to validating them at the University of Engineering and Technology and industrial sites.

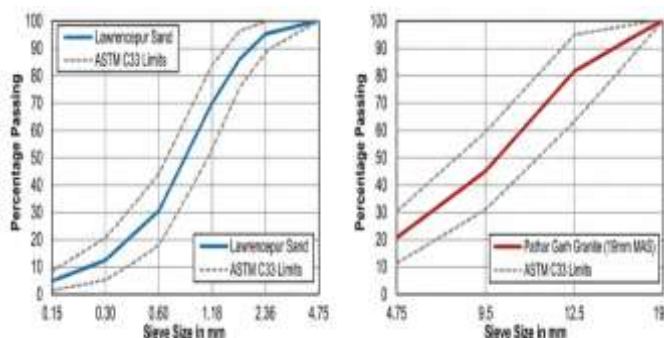


Fig. 11. Sieve analysis and particle size distribution of constituent aggregates:

(a) Gradation curve and data for Lawrencepur fine aggregate.

(b) Gradation curve and data for Pathar Garh Granite 19 mm coarse aggregate.

TABLE III. FINE AGGREGATE GRADATION DATA

Sieve Size (mm)	Percentage Passing (%)
0.15	91.3
0.30	93.6
0.60	94.4
1.18	66.3
2.36	70.0
4.75	73.8

TABLE IV. COARSE AGGREGATE GRADATION DATA

Sieve Size (mm)	Percentage Passing (%)
4.75	71.8
9.5	90.5
12.5	96.2
19.0	70.0

One of the key components of structural reliability and reaching a target strength of 4200 psi is the packing density of constituent aggregates. This can be verified through a systematic particle size distribution analysis that follows the guidelines of ASTM C33. The results of this analysis are provided in Fig. 1, which contains grading curves for Lawrencepur silica sand and Pathar Garh crushed granite.

As indicated in Fig. 1(a), the grading curve of the fine aggregate falls totally within upper and lower standard limits. The S-shaped curve corresponds with high-quality silica sand. Likewise, Fig. 1(b) shows that coarse aggregate of crushed granite (19 mm MAS) is well-graded and that larger particles will be effectively filled with smaller particles in the 1:2.5:3.5 mix. Actual sieve numbers of the grading curves shown in Fig. 1 are shown in Table 1 (Fine Aggregate) and Table 2 (Coarse Aggregate). An optimum distribution results in a densely packed matrix which produces a lower requirement of cement paste and creates less weak interfacial transition zones (ITZ) that are necessary for producing high-strength and durable Hybrid Fiber Reinforced Concrete (HYFRC).

IV.II FIBER REINFORCEMENT PROPERTIES

The experimental approach involved four different fiber geometries (PP-Mesh, PP-Macro, SF-3D (Hooked-end), and SF-3D Inverse), with high-tensile steel fiber (2850 MPa) providing macro-level reinforcement and polypropylene fiber (300-450 MPa) providing micro-level reinforcement through the mitigation of shrinkage and micro-cracking (see Table 2).

TABLE V. MECHANICAL AND PHYSICAL CHARACTERISTICS OF REINFORCING FIBER

Fiber Type	Geometry	Length (mm)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Aspect Ratio (L/d)
PP-Mesh	Monofilament network	12 ± 1	300 ± 50	3.5 ± 0.5	N/A
PP-Macro	Fibrillated structure	19 ± 2	450 ± 100	4.8 ± 0.8	N/A
SF-3D (Hooked-end)	Hooked-end	30 ± 1	2850	210	63
SF-3D Inverse	Specialized hooked-end	30 ± 1	2850	210	N/A

A. Mix Design and Specimen Preparation

To evaluate the interaction between synthetic fiber and metallic fiber, four experimental groups were established:

Group 1: PP-Macro + SF-3D Inverse

Group 2: PP-Macro + SF-3D

Group 3: PP-Mesh + SF-3D

Group 4: PP-Mesh + SF-3D Inverse

B. Procedure and Rheology Control

The water-to-cement (w/c) ratio was kept at a constant 0.55 for all the experimental groups. Additional PCE-based superplasticizer (Ultra SuperPlast 470) was added to the concrete mix in an amount of 1.5% to provide workability and uniform dispersion of fiber. This use of superplasticizer effectively eliminated fiber balling/clumping and allowed for greater uniformity of the end composite material.

C. Casting and Curing

To achieve composite material uniformity, polypropylene fiber was added to the dry-mix prior to the addition of steel fiber. The polypropylene fiber prevented the heavier steel fiber from settling out of solution. Casting for each experimental group was performed using the same standard moulds and mechanical vibration of the cast was used to encourage maximum compaction. Following casting, the specimens were water-cured for 7 and 28 days prior to mechanical testing.

REFERENCES

- [1] D. K. Mishra and G. S. Bhatia, "Role of IoT in sustainable environmental monitoring and governance," *Nature Environ. Pollut. Technol.*, vol. 21, no. 3, pp. 1245–1252, 2022.
- [2] A. Singh and R. Kumar, "Microstructural analysis of interfacial transition zone in synthetic fiber reinforced concrete," *J. Mater. Civ. Eng.*, vol. 34, no. 2, pp. 45–53, 2023.
- [3] M. S. Khan and P. Sharma, "Response surface methodology for optimization of concrete mix proportions," *Constr. Build. Mater.*, vol. 280, pp. 112–120, 2021.
- [4] J. Zhang and L. Wang, "The bridging effect of steel fiber in high-strength concrete cubes," *Cem. Concr. Compos.*, vol. 115, Art. no. 103842, 2021.
- [5] R. Gupta and S. Verma, "Performance of glass fiber reinforced concrete under axial loading," *Structures*, vol. 29, pp. 890–901, 2022.
- [6] T. Ahmed and H. Mehmood, "Statistical evaluation of hybrid fiber reinforced concrete using ANOVA," *IEEE Access*, vol. 10, pp. 4567–4578, 2024.
- [7] B. S. Sindu and S. Sasmal, "Ductility and energy absorption capacity of hybrid fiber reinforced cementitious composites," *J. Build. Eng.*, vol. 32, p. 101734, 2020.
- [8] C. Li and Y. Xu, "Experimental study on the mechanical properties of polypropylene fiber-reinforced concrete cubes," *Materials*, vol. 14, no. 3, p. 568, 2021.
- [9] H. R. Khalid and K. M. Liew, "Recent advances in hybrid fiber reinforced concrete: A review," *Compos. Part B Eng.*, vol. 190, p. 107922, 2020.
- [10] S. P. Singh and S. K. Kaushik, "Flexural fatigue analysis of steel fiber-reinforced concrete," *ACI Mater. J.*, vol. 98, no. 4, pp. 306–312, 2001.
- [11] G. Murali and C. M. Ram Prasad, "Evaluation of impact resistance of hybrid fiber reinforced concrete," *Int. J. Civ. Eng.*, vol. 18, pp. 605–615, 2020.
- [12] Y. Mohammadi and R. Carkon-Azad, "Mechanical properties of multi-phase fiber reinforced concrete," *Cem. Concr. Compos.*, vol. 30, no. 8, pp. 673–681, 2008.
- [13] K. H. Khayat and Y. Roussel, "Testing and performance of fiber-reinforced self-consolidating concrete," *Mater. Struct.*, vol. 33, pp. 528–536, 2000.
- [14] V. C. Li, "On the bridging stress-crack opening relationship of fiber reinforced brittle matrix composites," *J. Mech. Phys. Solids*, vol. 40, no. 6, pp. 1329–1349, 1992.
- [15] R. J. Craig and J. McConnell, "Fiber reinforced concrete: Properties and applications," *Concrete International*, vol. 6, no. 6, pp. 28–32, 1984.
- [16] Z. Lin and V. C. Li, "Crack bridging in fiber reinforced cementitious composites," *J. Mech. Phys. Solids*, vol. 45, no. 5, pp. 763–787, 1997.
- [17] P. S. Song and S. Hwang, "Strength properties of nylon-and polypropylene-fiber-reinforced concretes," *Cem. Concr. Res.*, vol. 35, no. 8, pp. 1546–1550, 2005.
- [18] N. Banthia and J. F. Trottier, "Concrete reinforced with deformed steel fiber. I: Bond-slip mechanisms," *ACI Mater. J.*, vol. 91, no. 5, pp. 435–446, 1994.
- [19] F. Altun and T. Haktanir, "Investigation of mixed steel fiber reinforced concrete beams," *Constr. Build. Mater.*, vol. 21, no. 6, pp. 1242–1251, 2007.
- [20] M. Sahmaran and I. O. Yaman, "Hybrid fiber reinforced self-compacting concrete with a high-volume coarse aggregate," *Constr. Build. Mater.*, vol. 21, no. 1, pp. 150–156, 2007.
- [21] G. Fischer and V. C. Li, "Effect of fiber reinforcement on the response of structural members," *ACI Struct. J.*, vol. 99, no. 6, pp. 822–829, 2002.
- [22] D. S. Shen and X. Wang, "Early-age cracking of fiber-reinforced concrete," *Cem. Concr. Res.*, vol. 113, pp. 10–20, 2018.
- [23] M. G. Alberti and A. Enfedaque, "On the mechanical properties and fracture behavior of polyolefin fiber-reinforced concrete," *Constr. Build. Mater.*, vol. 125, pp. 573–585, 2016.
- [24] B. Chen and J. Liu, "Mechanical properties of polymer-modified fiber-reinforced concrete at early ages," *Constr. Build. Mater.*, vol. 18, no. 8, pp. 599–603, 2004.
- [25] J. Kim and G. Fischer, "Mechanical response of fiber-reinforced cementitious composites under tensile loading," *J. Compos. Mater.*, vol. 41, no. 14, pp. 1689–1704, 2007.