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PERFORMANCE ENHANCEMENT OF FIBER REINFORCED CONCRETE FOR SUSTAINABLE CONSTRUCTION APPLICATION

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Abstract

Prestressed concrete I-beams are highly efficient but remain susceptible to cracking and brittle failure under excessive loading. Polypropylene (PP) fiber reinforcement offers an effective, eco-friendly solution to control crack propagation and enhance structural ductility due to its corrosion resistance, chemical stability, and low environmental footprint.

This research investigates the performance enhancement of fiber-reinforced concrete for sustainable construction applications, specifically focusing on the structural behavior of prestressed concrete I-beams using an integrated experimental, numerical, and microstructural approach. Full-scale specimens with PP fiber volume fractions of 0.3%, 0.4%, 0.5%, and 0.6% were subjected to cyclic flexural loading alongside compressive strength testing to evaluate key parameters, including compressive performance, load-deflection behavior, cracking, and energy absorption. Furthermore, microstructural characterization via Scanning Electron Microscopy was conducted to analyze fiber–matrix interactions and crack-bridging mechanisms. The study is expected to demonstrate that PP fibers significantly enhance the compressive strength, ductility, crack resistance, and post-cracking performance of prestressed concrete elements. The validated numerical models provide an efficient predictive tool that reduces the need for extensive physical testing while offering valuable design guidance for durable, sustainable, and high-performance infrastructure.

1. INTRODUCTION

1.1. Background Study

1.1.1. Introduction to Concrete and Its Material Limitations

Concrete is the most widely consumed construction material globally, serving as the backbone of modern infrastructure due to its high compressive strength, exceptional durability, adaptability, and widespread availability. It forms the core of critical structural systems ranging from commercial buildings to large-scale infrastructure such as bridges, dams, and pavements. Despite these advantages, conventional concrete possesses a major inherent limitation: its brittle nature and remarkably low tensile strength (Pham, 2025). Under flexural, tensile, or dynamic loads, internal microcracks readily form within the concrete matrix (Blazy et al., 2021). As these micro-cracks propagate and expand under service loads, they quickly develop into macro-cracks. This propagation results in widespread structural deterioration, significant loss of structural stiffness, increased deflection, and eventual catastrophic failure without prior warning (Shawki Ali et al., 2023).

1.1.2. Evolution of Fiber Reinforced Concrete (FRC)

To overcome these mechanical deficiencies, traditional structural configurations rely heavily on structural steel reinforcement to resist tensile stresses and manage macro-cracking. Over the past several decades, alternative methodologies have emerged to enhance concrete behavior at the micro-level, leading to the development of Fiber Reinforced Concrete (FRC) (Blazy et al., 2021).

FRC is an advanced composite material featuring discrete, discontinuous fibers randomly distributed throughout the cementitious matrix. These fibers act as localized micro-reinforcements that bridge opposing crack faces, transferring internal stresses across the cracks and delaying the onset of macro-fractures. This crack-bridging mechanism transforms the concrete from a brittle material into a quasi-ductile composite, significantly improving its flexural toughness, post-cracking residual strength, impact resistance, and energy absorption capacity. Common fiber types include steel, glass, carbon, and synthetic polymers.

1.1.3. Role of Polypropylene Fibers (PPF) in Sustainable Construction

Among these variations, polypropylene fibers (PPF) have gained substantial traction due to their unique physical and chemical attributes, such as a low specific gravity, high chemical inertness, hydrophobicity, and absolute corrosion resistance in aggressive environments. Within the context of modern green infrastructure, leveraging PP fibers directly aligns with the objectives of sustainable construction applications. By controlling micro-cracking and increasing the lifecycle durability of structural elements, PP fibers reduce the frequency of maintenance, lower repair costs, and minimize the total consumption of raw materials over a structure's lifespan. This provides a highly viable and eco-friendly pathway to lowering the carbon footprint associated with cement production and structural rehabilitation.

1.1.4. Prestressed Concrete I-Beams and Structural Behavior

Simultaneously, modern structural demands increasingly rely on prestressed concrete configurations for long-span applications. Prestressing involves stretching high-strength steel tendons or strands before concrete casting to induce an initial compressive stress field. This pre-compression counteracts external service loads, controls structural deflections, and increases initial crack resistance.

When prestressed concrete components, particularly structurally efficient, long-span profiles like I-sections, are reinforced with fibers, their overall mechanical performance improves dramatically. Shorter micro-fibers intercept micro-cracks during the early stages of hydration and stress development, while longer fibers activate at higher strain levels to preserve macroscopic structural integrity and maximize energy dissipation under structural load profiles (Hassanvand et al., 2023).

1.1.5. Importance of Mechanical Characterization: Compressive and Flexural Testing

To systematically evaluate the performance enhancement of fiber-reinforced concrete elements, rigorous physical laboratory testing is essential. Comprehensive structural characterization requires assessing both the fundamental material properties and the full-scale member behavior. While flexural and cyclic load profiles establish the ductility, crack propagation patterns, and post-cracking energy absorption mechanisms of prestressed I-beams, evaluating the underlying compressive matrix behavior is equally vital.

Conducting systematic compressive strength testing on the beam concrete samples provides foundational data regarding how varying fiber volume fractions influence matrix compactness, load-bearing capacities, and compressive resistance. Evaluating the combination of compressive metrics alongside large-scale structural flexural data offers a holistic understanding of how polypropylene fibers optimize structural integrity, ensuring that fiber-reinforced concrete configurations can be safely and reliably deployed in sustainable, high-performance infrastructure applications.

1.2. Problem Statement

Although the generic mechanical advantages of

polypropylene (PP) fibers in standard concrete mixtures are widely recognized, a significant gap in comprehensive knowledge still exists regarding their optimal dosage and structural performance when integrated into large-scale prestressed concrete I-beams.

This research gap is driven by three primary limitations in the current body of literature:

- **Scale Limitation of Existing Research:** A vast majority of existing studies have been conducted on small laboratory specimens (such as standard cylinders and small prisms). These scaled-down tests fail to reflect the complete behavioral extent, shear dynamics, stress distributions, and crack-bridging mechanisms of full-scale structural elements subjected to actual, rigorous structural loading requirements.
- **Omission of Correlative Material Testing:** While structural flexural assessments of large-scale members are sometimes documented, there is a distinct lack of simultaneous, correlative investigation into how varying fiber volume fractions (specifically between 0.3% and 0.6%) alter the fundamental compressive strength properties of the concrete matrix within the beam samples themselves. Without baseline compressive data directly linked to the large-scale beam specimens, understanding the holistic failure envelopes of the composite material remains incomplete.
- **Lack of Target Microstructural Analysis:** While macro-scale mechanical properties are observed during destructive physical testing, the precise mechanical interactions occurring at the interface between the concrete matrix and the polypropylene fibers are often overlooked. Without targeted microstructural characterization—specifically through Scanning Electron Microscopy (SEM)—it is difficult to accurately assess the internal fiber-matrix bonding efficiency and specific micro-level crack-bridging capabilities that directly dictate macroscopic performance.

Consequently, there is an urgent need for an integrated experimental approach that evaluates full-scale prestressed I-beams alongside comprehensive material compressive testing and targeted SEM microstructural analysis. Addressing these gaps is essential to unlock the predictable, safe, and optimized deployment of fiber-reinforced concrete for sustainable, long-term infrastructure construction applications.

1.3. Research Objectives

This study aims to achieve the following specific objectives:

1. **Evaluate Compressive Performance:** To investigate the effect of varying polypropylene (PP) fiber volume fractions (0.3%, 0.4%, 0.5%, and 0.6%) on the compressive strength and fundamental matrix behavior of the concrete samples cast alongside the beam specimens.
2. **Assess Structural Flexural Behavior:** To determine the flexural strength, load-deflection characteristics, cracking propagation, and energy absorption capacity of _x0001_ full-scale prestressed concrete I-beams reinforced with polypropylene fibers under structural loading.
3. **Analyze Microstructural Mechanisms:** To examine the internal microstructural mechanisms, interfacial transition zone bonding, and fiber-matrix crack-bridging behavior using Scanning Electron Microscopy (SEM) analysis.
4. **Optimize for Sustainable Infrastructure Application:** To identify the optimal dosage of polypropylene fibers that balances material performance and structural capacity, providing design insights for high-performance and sustainable construction applications.

1.4. Significance of the Study

The outcomes of this research present significant theoretical and practical contributions to the field of structural and materials engineering, specifically supporting the transition toward green building infrastructure.

1.4.1. Practical Significance

- **Structural Optimization:** By incorporating polypropylene (PP) fibers into full-scale prestressed concrete I-beams, this study provides actionable physical data on how discrete fibers improve macro-structural integrity. It establishes empirical guidance on optimizing ductility, enhancing energy absorption capacities, and preventing catastrophic brittle failures in critical structural members.
- **Empirical Material Benchmarks:** The physical data collected from both compressive

strength testing and full-scale flexural testing delivers a highly reliable, laboratory-verified baseline for structural designers. This practical understanding allows engineers to confidently predict how fiber dosing affects fundamental material behavior without relying solely on generic theoretical assumptions.

- **Infrastructure Longevity:** Demonstrating improved crack resistance directly influences the service life of prestressed concrete elements. Restricting internal micro-cracks effectively protects high-strength internal prestressed strands from environmental exposure, lowering maintenance demands and structural replacement frequencies.

1.4.2. Sustainable and Environmental Contributions

- **Promotion of Sustainable Construction:** Aligning with the core objectives of modern eco-friendly development, the utilization of PP fibers reduces the global carbon footprint of construction projects. By expanding the lifecycle performance of structural members, the demand for raw materials and frequent rehabilitation cement is lowered.
- **Advancement in Green Engineering Practice:** This work provides a tangible framework for adopting fiber-reinforced composites as standard, eco-conscious building components, contributing to the establishment of durable, high-performance contemporary civil engineering infrastructure.

1.4.3. Theoretical Significance

- **Correlation of Macro and Micro Behavior:** This study bridges a critical gap in literature by correlating macro-mechanical behavior (compressive and flexural strengths) with precise micro-level observations via Scanning Electron Microscopy (SEM).
- **Insights on Bond Mechanics:** The research sheds light on the actual fiber-matrix bonding interactions and mechanical crack-bridging behavior specific to prestressed configurations, expanding the academic knowledge base of composite material mechanics.

1.5. Scope and Limitations of the Research

1.5.1. Scope of the Research

- **Structural Specimen Geometry:** The structural focus of this investigation is strictly confined to full-scale prestressed concrete I-section beams, each featuring a total span length of (3.048 meters).
- **Material Characterization & Compressive Testing:** The experimental framework encompasses comprehensive material characterization, prominently featuring the evaluation of axial compressive strength. Compressive tests are executed on standardized concrete specimens cast alongside the beam samples to establish precise structural capacities and foundational matrix behavior under varying fiber dosages.
- **Reinforcement Layout:** The internal structural configuration of the tested elements relies exclusively on a high-strength, multi-strand prestressing layout localized within the bottom tension flange, paired with high-tensile structural wires in the top compression flange.
- **Experimental Variables:** The primary experimental variables are strictly limited to the volume fractions of monofilament polypropylene (PP) fibers, specifically evaluated across targeted dosages of 0.3%, 0.4%, 0.5%, and 0.6% incorporated into a standardized concrete mix design.
- **Microstructural Evaluation:** Micro-level material investigation is confined exclusively to Scanning Electron Microscopy (SEM) analysis, which is employed to visually evaluate the interfacial transition zone, internal bond parameters, and microscopic crack-bridging mechanics between the PP fibers and the cementitious matrix.

1.5.2. Limitations of the Research

- **Exclusion of Core Extraction:** The compressive testing evaluations are conducted strictly on control samples cast simultaneously alongside the specimens; core extraction directly from the cured full-scale structural beam elements is outside the boundary of this work.
- **Geometric and Loading Constraints:** The physical findings, ultimate strengths, and behavioral profiles obtained from this research are inherently specific to the evaluated 3048 mm I-beam profile under targeted flexural and cyclic load distributions; alternative cross-sectional geometries or highly complex multi-axial loading dynamics are not explored.
- **Material Bounds:** The study does not

evaluate any other synthetic or metallic fiber varieties, such as steel, carbon, or glass fibers. Furthermore, advanced chemical composition evaluations outside the scope of physical SEM imaging excluded from the material evaluation criteria.

1.6. Thesis outlines

This thesis titled "Role of synergetic effect of fibers on prestressed concrete beams " is organized into 5 chapters. The first chapter consists of a background study, problem statement, objectives of the study, and scope and limitations of the study. The second chapter presents the literature review of the research that was conducted to investigate the flexural and durability properties by adding polypropylene fibers. The third chapter consists of specimen casting, experimental program, methodology, and testing setups. The fourth chapter contains the results and discussion in depth. Chapter 5 describes the conclusions of the research work. Moreover, it provides useful information for future recommendations for prestressed fiber-reinforced concrete I beams.

2. LITERATURE REVIEW

2.1. Introduction to Concrete and Its Inherent Deficiencies

Concrete is widely used in the construction industry as the most common material because it is a versatile material that is highly resistant to compression, has a wide variety of materials to make, and is economical. Due to its moldability and resistance to various environmental conditions, it is widely used in residential, commercial, industrial, and infrastructure construction. However, conventional concrete has low tensile strength and limited deformation capacity (Mehta & Monteiro, 2014). Consequently, concrete is extremely prone to crack initiation and propagation under tensile loading, flexural loading, impact loading, and fatigue loading. Such intrinsic constraints frequently result in shorter service life, durability problems, and brittle failure modes in structural elements (Neville, 2011; Ahmad et al., 2022).

To overcome these mechanical limitations, extensive research has focused on the application of discrete, discontinuous fiber networks distributed uniformly throughout the concrete matrix,

which resulted in the creation of Fiber Reinforced Concrete (FRC). Adding fibers to the concrete enhances the post-cracking properties of concrete by bridging the cracks and carrying the stresses between the cracks. This crack-bridging mechanism slows down the propagation of cracks, increases the energy absorbing capacity of the material, and increases its toughness and ductility. As a result, fiber-reinforced concrete is proving to be a suitable material for structures where they are exposed to dynamic loading, impact forces, fatigue stresses, and harsh environmental conditions (Ahmad et al., 2022).

2.2. Polypropylene Fibers (PPF) in Cementitious Matrices

Among the various synthetic polymer modifiers, polypropylene (PP) fibers have emerged as an ideal candidate for achieving high-performance and sustainable construction applications. While other fiber types, such as carbon, glass, and steel, have historically been evaluated for general mechanical enhancements, synthetic

polypropylene fibers possess distinct physical and chemical attributes—such as low specific gravity, high chemical inertness, hydrophobicity, and absolute corrosion resistance—making them highly suitable for aggressive environmental exposures. The effect of polypropylene fibers in controlling plastic shrinkage cracking and enhancing the durability-related properties is widely recognized. The incorporation of these fibers brings several structural and physical benefits to the composite matrix, including a significant decrease in crack width, an increase in toughness, an increase in permeability resistance, and an enhanced resistance to environmental deterioration. Several studies have reported the ability of polypropylene fiber to retard the development and propagation of microcracks in the cementitious matrix, leading to enhanced long-term performance (Abdul kareem et al., 2022; Lakshmi et al., 2023).

2.3. Microstructural Action and Crack-Bridging Mechanics

The performance of fiber-reinforced concrete is fundamentally governed by the role of the

fibers in bridging internal cracks and slowing down crack propagation, thereby maintaining the overall structural integrity of the element. In a standard concrete matrix, stress fields under flexural or cyclic loading trigger immediate macro-cracking once the tensile capacity of the unreinforced paste is exceeded. However, when polypropylene fibers are integrated, they act as localized micro-reinforcements across these developing crack faces.

This mechanical bridging action transfers internal stresses across the fissures, preventing individual microcracks from coalescing into catastrophic macro-fractures. In order to assess these internal mechanisms accurately, modern material research utilizes microstructural characterization. Specifically, Scanning Electron Microscopy (SEM) serves as a critical diagnostic tool to evaluate the Interfacial Transition Zone (ITZ) between the polypropylene fiber surface and the surrounding hydrated cement paste. Through high-magnification SEM analysis, researchers can observe the mechanical anchoring, friction, pull-out resistance, and physical bonding conditions of the fibers, providing a micro-level explanation for the macroscopic energy absorption and ductility improvements observed during large-scale structural testing.

2.4. Structural Integration: Compressive and Flexural Performance

While historic literature often focused on isolated material property testing using small, non-structural laboratory specimens, evaluating the performance enhancement of fiber-reinforced concrete for sustainable structural elements requires a holistic experimental program combining material and full-scale structural testing.

- **Compressive Strength Dynamics:** The base mechanical performance of fiber-reinforced concrete must be established by measuring the compressive strength of samples cast alongside major structural elements. Incorporating polypropylene fibers within specific volume fractions modifies the compactness and internal confinement of the cementitious matrix, which directly influences the ultimate compressive load-bearing threshold and post-yield strain behavior.
- **Large-Scale**

Flexural Behavior: To translate these material properties into practical design guidelines for modern infrastructure, it is essential to test full-scale structural configurations. Testing full-scale prestressed concrete I-beams under flexural and cyclic loading profiles provides direct, empirical observations of structural response parameters, including load-deflection behavior, ultimate flexural capacity, cracking propagation, and energy absorption capacity.

Available literature confirms that the addition of fiber reinforcement has a significant effect on the mechanical and durability properties of concrete, including enhanced crack control, toughness, ductility, energy absorption, and post-cracking properties. Combining baseline compressive testing with large-scale structural observations and targeted SEM microstructural analysis yields a comprehensive framework for optimizing fiber-reinforced concrete mixtures, ensuring long-term structural reliability and material efficiency in sustainable civil engineering infrastructure.

2.5. Polypropylene Fiber Reinforced Prestressed Concrete Beams

2.5.1. Mechanics of Prestressed Concrete and Structural Limits

In the field of structural materials, prestressed concrete has emerged as one of the most widely used materials in modern infrastructure due to its strength to span longer distances with higher loads without compromising structural requirements. Compressive stresses introduced prior to external loading sources can significantly lower tensile stresses in concrete, which can eliminate cracking and enhance structural efficiency. The advantages of prestressed concrete members, such as higher load-bearing capacity, smaller deflections, and increased durability, make them a popular choice for use in bridges, buildings, large-scale parking structures and other applications with long spans.

Despite these advantages, however, prestressed concrete still can crack, lose stiffness, and fail in a brittle manner under excessive loading conditions. Therefore, the use of fibers in prestressed concrete has been the subject of a growing research interest to further enhance flexural performance, crack resistance,

toughness, and durability (Naaman, 2004; Rashid et al., 2019).

2.5.2. Crack-Bridging Mechanisms of Polypropylene Fibers

Polypropylene fiber reinforced prestressed concrete is used to improve the performance of the structure by means of the crack-bridging mechanism. Discrete PP fibers carry tensile stresses from crack to crack, which slows the growth of micro-fissures and enhances post-cracking properties. While a conventional prestressed concrete structure may fail suddenly and in a brittle manner after reaching its ultimate capacity, a polypropylene fiber reinforced prestressed concrete structure tends to exhibit a much higher ductility and energy absorption capacity.

These properties are especially significant for dynamic loading, repeated cyclic loading, and harsh environmental exposures where structural members are highly vulnerable (Pham, 2025; Ahmad et al., 2022). Historical investigations involving prestressed components have noted that the addition of polypropylene fibers proves to be highly beneficial to the ultimate flexural strength, crack resistance, and overall energy absorption capacity. The reinforcing effect of these synthetic polymers increases post-crack performance and delays flexural crack propagation, resulting in superior long-term structural serviceability.

2.6. Evaluation of Material Compressive Strength and Flexural Ductility

To properly capitalize on the advantages of PP fibers in modern infrastructure, a comprehensive evaluation must simultaneously capture fundamental material properties and large-scale element behavior through physical testing.

- **Matrix Confinement and Compressive Strength:** Testing the compressive strength of the concrete matrix cast directly alongside prestressed beam specimens is critical. The inclusion of polypropylene fibers at targeted volume fractions (0.3% to 0.6%) modifies the internal matrix structure, impacting the material's compressive thresholds and ensuring that the concrete can withstand severe pre-compression and subsequent loading conditions without early crushing.
- **Load-Deflection Behavior and Stiffness Retention:** The load-deflection behavior of polypropylene fiber reinforced concrete beams reveals excellent stiffness retention following initial cracking, alongside an improved deformation capacity prior to structural failure. Compared to conventional prestressed concrete beams, PP fiber reinforced elements maintain active stress transfer across crack faces even past the peak load, allowing the member to undergo gradual, ductile deflection rather than immediate, catastrophic failure (Rashid et al., 2019; Patil & Sangle, 2017).

Ultimately, the literature confirms that the flexural properties, crack resistance, ductility, toughness, and overall load-carrying capacity of prestressed concrete members reinforced with polypropylene fibers are significantly improved. Consequently, large-scale prestressed beams made of polypropylene fiber reinforced concrete (FRC) have proved to be a powerful, highly reliable solution for sustainable construction applications where enhanced service life, long-term durability, and maximum structural efficiency are desired.

2.7. Numerical Modeling of Fiber Reinforced Prestressed Concrete Beams

Experimental testing is often not enough to fully describe the internal stress distribution, service life of cracks, reduction in stiffness and failure mechanisms, so numerical modelling has become an essential tool to investigate the structural behaviour of reinforced and prestressed concrete members. Finite Element Analysis (FEA) is a tool that can simulate the non-linear response of concrete structures under multiple loading conditions, while also providing detailed information about stress concentrations, strain progression and damage propagation. Numerical simulations are more time and cost efficient than experimental investigations regarding extensive parametric studies while providing the opportunity to assess a structure's responses that are difficult to observe in real time during laboratory investigations (El Yassari & EL Ghoulbzouri, 2023). Besides, numerical modelling allows to study several design parameters, material characteristics and loading conditions without

the need for a large experimental testing (El Yassari & EL Ghoulbzouri, 2023). Due to its high level of constitutive modeling and extensive nonlinear analysis features, ABAQUS has been one of the most popular software packages for modeling concrete structures among the platforms that are available. ABAQUS has been widely employed to model reinforced concrete beams, prestressed concrete girders, fiber reinforced concrete and fiber reinforced polymer strengthened structures. This is explained mostly by the accessibility of the Concrete Damage Plasticity (CDP) model, which offers a complete framework to represent the inelastic behaviour of concrete under tensile and compressive loading condition (El Yassari & EL Ghoulbzouri, 2023). The CDP model includes the effects of tensile cracking, compressive crushing, stiffness degradation and irreversible plastic deformation under a single constitutive formulation (El Yassari & EL Ghoulbzouri, 2023). Consequently, it is one of the most widely used constitutive models used for the numerical modelling of concrete structures (El Yassari & EL Ghoulbzouri, 2023). Al Dalou et al. (2026) showed the ability of ABAQUS to simulate the nonlinear behavior of concrete by creating detailed finite element models of reinforced concrete beams with near surface mounted prestressed carbon fiber reinforced polymer bars. The Concrete Damage Plasticity model is used to represent the behavior of concrete and the Extended Finite Element Method (XFEM) is used to simulate the initiation and propagation of cracks (Al Dalou et al., 2026). They were able to achieve a good correlation between their numerical models and their experimental results regarding the crack pattern and degradation in stiffness (Al Dalou et al., 2026). Furthermore, the load-deflection responses obtained during the course of the loading process were found to be in good agreement with the experimental results (Al Dalou et al., 2026). It has been found that ABAQUS can be used to model the nonlinear structural behaviour of concrete structures reinforced by advanced composite materials accurately (Al Dalou et al., 2026). In another study, Al-Smadi et al. (2026) studied reinforced concrete beams strengthened with CFRP strip and ring, further demonstrating the effectiveness of finite element modeling. They were able to reproduce experimentally observed stress redistribution mechanisms, crack propagation behavior, and ultimate failure mechanisms in their numerical simulations (Al-Smadi et al., 2026). The researchers reported that finite element models were able to accurately predict stiffness variations and load-carrying capacities of strengthened beams (Al-Smadi et al., 2026). Furthermore, the study showed that numerical analysis can offer useful information on the internal stress fields that can't be measured during laboratory experiments (Al-Smadi et al., 2026). Numerical modelling of fiber reinforced concrete structures has gained more attention as fibers are known to have a significant effect on post cracking behavior and the evolution of damage. Sadiku et al. (2026) experimentally and numerically studied reinforced concrete beams with hybrid steel and polypropylene fibers. The load–deflection data obtained from their experimental testing matched well with their finite element models (Sadiku et al., 2026). The following numerical simulations predicted the crack development, strain distributions and stiffness degradation during the loading process (Sadiku et al., 2026). Moreover, the study proved that the hybrid fibers extensively enhanced tensile resistance and the energy absorption capacity of the materials which were presented in both experimental and numerical results (Sadiku et al., 2026). The constitutive modelling of fiber reinforced concrete is still one of the most difficult aspects of the finite element analysis. To tackle the issue, Subramanian et al. (2026) carried out a study on various constitutive laws and bond modeling methods for polypropylene fiber reinforced concrete beams. Their investigation found that usual concrete constitutive models often underestimate the post-cracking tensile characteristics in fiber reinforced systems (Subramanian et al., 2026). The authors showed that modified tensile softening relationships greatly enhanced the prediction accuracy and enabled more realistic simulation of the crack-bridging effects provided by fibers (Subramanian et al., 2026). They also found in their study that the enhanced toughness and ductility of fiber reinforced concrete requires the use of advanced constitutive formulations.

Subramanian et al. (2026) also investigated reinforcement–concrete interaction using embedded-region constraints and cohesive zone modeling techniques. The researchers reported that both the approaches were able to reasonably replicate the bond behaviour between reinforcement and surrounding concrete (Subramanian et al., 2026). They highlighted the significance of developing accurate bond-slip models, especially for structures like prestressed concrete where the transfer of loads between the prestressing strands and the concrete is crucial (Subramanian et al., 2026).

2.8. Microstructural Characterization of Fiber Reinforced Concrete

The mechanical and durability performance of concrete is strongly dependent upon phenomena at the microstructural level, making microstructural characterization an essential part of concrete research. Typical mechanical tests can give information on compressive strength, flexural strength, toughness, load carrying capacity of the material, but cannot fully describe crack resistance, durability improvement, and post cracking behavior. Thus, researchers have turned to the use of advanced characterization methods, such as Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD) and Pore Structure Analysis, to study the connection between microstructural evolution and structural performance. The techniques offer useful information on hydration products, fiber–matrix bonding, interfacial transition zones and crack propagation mechanisms that influence the overall behaviour of concrete materials (Tam et al., 2005). The Interfacial Transition Zone (ITZ) is one of the most significant microstructural zones in concrete, where aggregates (or fibers) meet the cement paste. The strength development, crack resistance and durability properties are greatly dependent on the quality of the ITZ. A two-stage mixing method was used to prepare recycled aggregate concrete and a detailed SEM study was performed by Tam et al. (2005). They noted that the voids and microcracks in the ITZ were reduced for the modified mixing procedure, which led to a denser microstructure (Tam et al., 2005). The researchers found that the quality of ITZ was improved and it directly affected the bond characteristics between the aggregate particles and the cement matrix, which directly affected the mechanical properties (Tam et al., 2005). They concluded that microstructural refinement plays a key role in determining the behavior of concrete (Tam et al., 2005). Shi et al. (2012) further provided evidence on the importance of microstructural densification with the study of the microstructure of fly ash geopolymeric recycled concrete. The researchers used SEM analysis to study the evolution of a dense and compact matrix with decreased pore connectivity and better aggregate–matrix bonding (Shi et al., 2012). The study showed that microstructural refinement had the effect of improving the mechanical performance of concrete by reducing the initiation of cracks in concrete and restricting the movement of aggressive agents through the concrete. (Shi et al., 2012) Additionally, the better interface transitional zone found in the SEM analysis helped to achieve better durability and long-term performance (Shi et al., 2012). The performance of fiber reinforcement is greatly dependent on the quality of the fiber-cementitious matrix bond. The strong fiber–matrix adhesion allows for effective transfer of applied stress between crack faces and better crack-bridging ability of the fibers. Soroushian and Elzafraney (2004) reported that such process of improving fiber–matrix interaction greatly improved post-cracking behavior by slowing fiber pull-out and increasing the energy absorption capacity. Based on their observations, they concluded that the mechanical performance of fibers is not only related to fiber properties, but also to the quality of fibers to cement bond within the cement matrix (Soroushian & Elzafraney, 2004). Scanning Electron Microscopy (SEM) has been extensively used to compare fiber distribution, crack-bridging characteristics and pull-out mechanisms of fiber reinforced concrete. For cementitious composites, Liu et al. (2022) studied the interaction between the fibers and hydration products by SEM analysis. They have found that the well-dispersed fibers form multiple crack-bridging points in the matrix and can effectively limit the growth of cracks, resulting in enhanced ductility (Liu et al.,

2022). Additionally, the study showed that the bond between the fiber and matrix was crucial for effective stress transfer and improved resistance to the cracks and toughness (Liu et al., 2022). Hybrid fiber systems have also gained growing research interest, particularly in terms of their microstructural behavior. Luo et al. (2020) showed that fibers with various mechanical properties interact in complementary ways, which was beneficial to the development of crack control when using hybrid fibers. In terms of crack resistance, SEM analysis showed that single fiber types started to play a role at varying stages of crack growth, contributing crack resistance at multiple scales (Luo et al., 2020). The researchers found that the synergy can be attributed mainly to the interactions between the fiber and the matrix level in the microstructural level. (Luo et al., 2020) Song and Yin (2016) also highlighted the role of synergy effect of fibers in HRC. They found that steel and carbon fibers played different roles in the crack control mechanisms: the smaller the fiber, the more likely it was to have a restriction effect on the microcracks, while the larger the fiber, the more it had to do with the crack control effect of the macro crack (Song & Yin, 2016). The study indicated that these complementary mechanisms are directly related to the interaction of the fibers and the cement matrix at the microscale (Song & Yin, 2016). Besides SEM analysis, X-ray Diffraction (XRD) has emerged as a useful tool to analyse hydration products and mineralogical composition of concrete materials. Researchers can use XRD analysis to identify and quantify hydration compounds that are important in the strength development and durability performance, including calcium silicate hydrate (C-S-H), calcium hydroxide (CH), and ettringite. Shi et al. (2012) used XRD analysis to analyze hydration products in geopolymer concrete, and concluded that the higher the density of the microstructure, the higher the mechanical property of the geopolymer concrete (Shi et al., 2012). The research showed that the strength and durability properties of concrete materials are related to the development of hydration products (Shi et al., 2012). Yuan et al. (2014) studied the correlation between hydration products and concrete properties by XRD analysis. Yuan et al., 2014, found that more stable hydration compounds are formed, leading to lower pore connectivity and enhanced resistance to environmental degradation. The researchers concluded that hydration refinement is an important factor affecting the strength and durability properties of cement-based materials (Yuan et al., 2014). One of the other critical points of microstructural characterization will be the determination of the pore structure. The permeability, water absorption, freeze–thaw resistance, and durability over time are all significantly affected by the characteristics of the pores. Chopra et al. (2015) measured the resistance to moisture penetration and chemical attack and found that the former significantly decreased with a decrease in pore connectivity. Their study showed that the ability of a material to perform well in terms of durability directly benefits from microstructural refinement, which reduces the availability of pathways for aggressive agents (Chopra et al., 2015).

The influence of polypropylene fibers on pore structure and durability was investigated by Ramezanianpour et al. (2013). Ramezanianpour et al. (2013) reported that the addition of polypropylene fibers enhanced the tortuosity of the pores and decreased the interconnectedness of microcracks inside the cement matrix. Thus, the permeability of the fiber reinforced concrete was lower and resistance to environmental deterioration was better (Ramezanianpour et al., 2013). Abdulkareem et al. (2022) reported similar findings, noting the role of polypropylene fibers in providing enhanced durability and durability performance over time through effective microcrack control (Abdulkareem et al., 2022). Although the microstructural characterization has made major strides, there are research gaps that are yet to be addressed. The majority of the studies available have concentrated mostly on material-scale observations with little direct connection between the microstructural characteristics and the structural behaviour of full-scale prestressed concrete members. In addition, few studies have considered the synergistic effect of carbon, glass and polypropylene fibers on fiber–matrix bonding, development of hydration products and evolution of the pores in prestressed concrete

systems. Hence, the combination of SEM and XRD analyses and experimental and numerical study is required to build up a good understanding of the mechanisms that account for the superior performance of hybrid fiber reinforced prestressed concrete beams.

2.9. Research Gap

The reviewed literature confirms that fiber reinforced concrete improves crack resistance, toughness, ductility, durability, and overall structural performance. Previous studies have demonstrated the effectiveness of individual fibers such as steel, carbon, glass, and polypropylene fibers, while hybrid fiber systems have shown additional benefits through synergistic crack-control mechanisms (Song & Yin, 2016). Similarly, research on prestressed fiber reinforced concrete beams has reported improvements in flexural strength, load-carrying capacity, energy absorption, and post-cracking behavior (Rashid et al., 2019).

Numerous researchers have also successfully employed ABAQUS and the Concrete Damage Plasticity (CDP) model to simulate the nonlinear behavior of reinforced and fiber reinforced concrete structures (El Yassari & EL Ghoulbzouri, 2023). In addition, SEM and XRD analyses have been widely used to investigate fiber–matrix interaction, hydration products, and microstructural development in cementitious materials (Tam et al., 2005; Shi et al., 2012).

Despite these advancements, several important research gaps remain. Most existing studies focus on conventional reinforced concrete members, while limited research has investigated prestressed concrete beams reinforced with polypropylene fibers. Furthermore, relatively few studies have integrated experimental testing, finite element modeling, and microstructural characterization within a single research framework. The relationship between microstructural modifications, numerical predictions, and structural performance of polypropylene fibers reinforced prestressed concrete beams therefore remains insufficiently understood.

Accordingly, the present study aims to address these gaps by experimentally investigating the flexural behavior of prestressed concrete I-beams reinforced with polypropylene fibers, developing validated ABAQUS finite element models, and correlating the structural response with SEM, XRD,EDS and MIP microstructural observations. This integrated approach is expected to provide a comprehensive understanding of fiber synergy and its influence on the performance of prestressed concrete structures.

3. METHODOLOGY

3.1. Experimental Design and Research Framework

The study utilizes an integrated experimental and microstructural testing framework to evaluate the structural and material performance of fiber-reinforced concrete configured with polypropylene (PP) fibers for sustainable construction applications. The methodology is designed to provide comprehensive empirical metrics across multiple physical dimensions: evaluating foundational material performance via compressive strength testing, observing large-scale component behavior through full-scale prestressed concrete I-beam testing under cyclic flexural configurations, and isolating damage mitigation properties at the micro-level. By linking macroscopic mechanical failure with microscopic evidence, a complete baseline of physical action is established to guide safe structural applications.

3.2. Material Preparation and Sample Casting

The experimental program begins with standard material characterization and batch mix designs using varying volume fractions of polypropylene fibers, specifically targeting percentages of 0.3%, 0.4%, 0.5%, and 0.6% by volume.

To bridge the gap between basic material performance and structural member failure criteria, two primary sets of specimens are cast from each batch:

- **Standard Compressive Specimens:** Accompanying material control samples are prepared concurrently with the structural beam casting to evaluate the precise impact of PP fiber dosages on the ultimate load-bearing threshold and confinement properties of the base concrete matrix.

- **Full-Scale Prestressed I-Beams:** Structural specimens are fabricated at a full-scale length of _x0001_, featuring standard high-strength steel strands or tendons that are prestressed prior to casting to induce a calculated initial pre-compression force field across the cross-section.

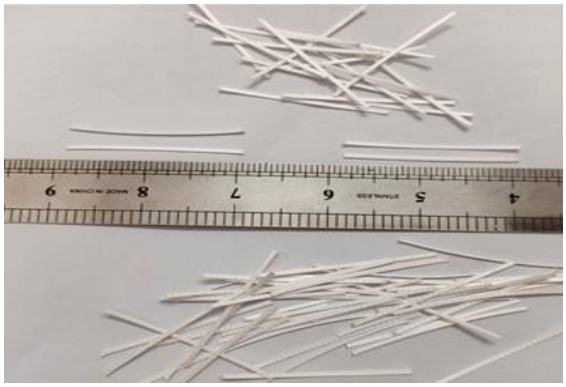


Fig 3.1 : Polypropylene fibers



Fig 3.2 : Concrete Mixture Containing Polypropylene fibers



Fig 3.3 : Concrete Slump Test



Fig 3.4 : Casting of Mixture of Concrete and Fiber

3.3. Material-Level Testing: Compressive Strength Program

A crucial mechanical benchmark of this methodology involves assessing the compressive strength variations of the concrete samples cast alongside the structural elements. These tests are conducted under standard laboratory conditions to measure matrix density, elastic response bounds, and maximum compressive resistance.

Evaluating changes in compressive behavior across the 0.3% to 0.6% PP fiber variations makes it possible to determine whether the introduction of polymer filaments creates any negative packing density issues or if the micro-confinement effect optimizes the post-yield crushing parameters of the matrix. This foundational phase ensures that the fundamental mechanical capacities of the core material are known before full-scale structural testing begins.



Fig 3.5 : Samples Ready For Compressive Strength Test



Fig 3.6 : Compressive Strength Test

3.4. Member-Level Structural Testing: Cyclic Flexural Loading

The large-scale experimental stage involves evaluating the full-size _x0001_ prestressed concrete I-beam specimens. The beams are positioned within a heavy-duty structural loading frame and subjected to controlled, cyclic flexural load profiles designed to replicate rigorous, realistic environmental and service stresses.

This structural testing program focuses on measuring vital engineering parameters:

- **Ultimate Capacity and Flexural Strength:** Determining the maximum bending moments and load levels the I-beams can sustain prior to failure.
- **Load-Deflection Profile and Stiffness Retention:** Mapping out structural deformation characteristics to capture how the presence of PP fibers transitions the element from a sudden, brittle failure state to a progressive, quasi-ductile response.
- **Crack Development Mapping:** Tracking the specific loads corresponding to crack initiation, monitoring macro-crack propagation speeds, and analyzing final failure modes.



Fig 3.7 : Setup for Cyclic Flexural Loading Test Using P3 Strain Recorder

3.4. Microstructural Characterization via SEM

To explain the fundamental internal processes underlying the macro-structural behaviors observed during compressive and flexural testing, targeted microstructural characterization is executed. This analytical phase relies exclusively on high-resolution Scanning Electron Microscopy (SEM) performed on extracted concrete samples taken near fractured surfaces.

The SEM microstructural study focuses on isolating:

- **Fiber-Matrix Interfacial Transition Zone (ITZ):** Checking the physical adhesion, bonding quality, and micro-void structure surrounding the embedded polypropylene strands.
- **Microscopic Crack-Bridging Activity:** Directly observing how individual PP fiber strands anchor across internal micro-fissures, checking for fiber pull-out versus fiber rupture mechanisms.
- **Pore Structure Refinement:** Evaluating how the network distribution of polymer filaments hinders early-stage microcrack expansion at the micro-scale level.

3.5. Data Synthesis and Analysis

By combining material-level compressive strength testing, large-scale member flexural loading profiles, and localized SEM microstructural imaging, this methodology delivers a verified, comprehensive assessment of polypropylene fiber-reinforced prestressed concrete I-beams. Correlating the microstructural observations with the macroscopic load-deflection profiles and cracking patterns ensures that the resulting material efficiency data and structural capacity thresholds are fully grounded in physical laboratory evidence, establishing high-fidelity design guidelines for modern sustainable construction applications.

3.6. Research Framework

The research framework follows a clear, logical, and sequential structure designed to comprehensively evaluate the performance enhancement of polypropylene (PP) fiber-reinforced prestressed concrete I-beams. It establishes chronological cohesion between material characterization, large-scale structural

testing, and targeted microstructural analysis. The complete experimental workflow proceeds as follows:

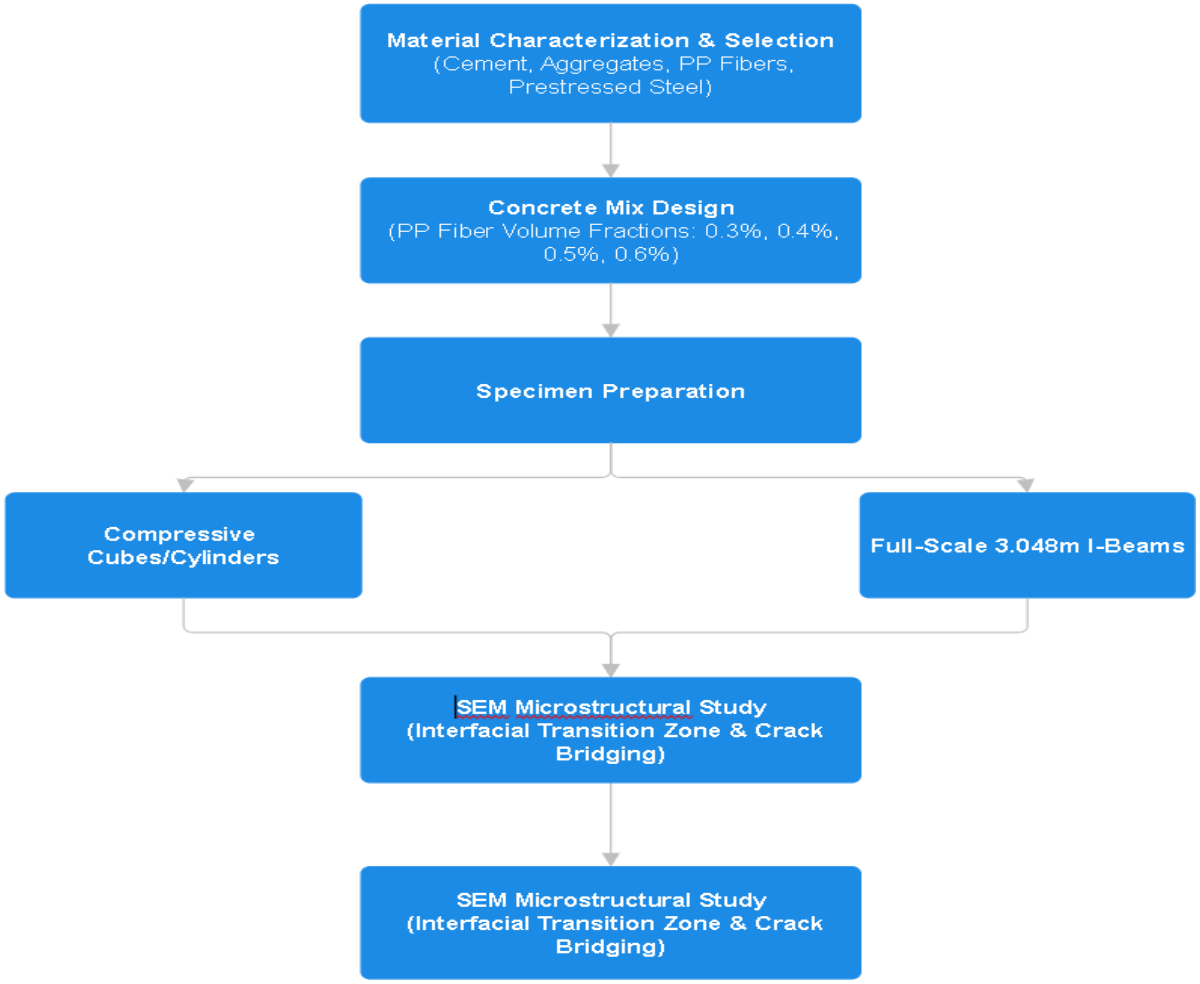


Fig 3.8 : Flowchart for Experimental workflow

3.6.1. Phase 1: Material Selection and Characterization

The research begins with the selection and thorough characterization of the constituent materials. High-grade cement, fine and coarse aggregates, polypropylene fibers, and high-strength prestressing steel strands are selected based on their suitability for high-performance structural concrete applications. The physical and mechanical properties of each component are verified to ensure quality and consistency throughout the experimental phases.

3.6.2. Phase 2: Concrete Mix Design and Dosing Optimization

Following material characterization, a precise concrete mix design is established. The mix proportions are adjusted by incorporating various target volume fractions of polypropylene fibers—specifically 0.3%, 0.4%, 0.5%, and 0.6%. The primary objective during this phase is to strike an optimal balance between fresh material workability and hardened structural strength, ensuring uniform fiber dispersion throughout the cementitious matrix without structural clustering.

3.6.3. Phase 3: Specimen Fabrication and Curing

In this step, the concrete specimens are cast under rigorous laboratory conditions. For each fiber dosage, two distinct groups of specimens are developed to capture both material-level and structural-level responses:

- **Material Samples:** Standard compressive test specimens (cubes or cylinders) are cast alongside the main members to isolate base material variations.
- **Full-Scale Prestressed Elements:** Full-size _x0001_ prestressed concrete I-beams are

constructed. The geometric configurations, steel reinforcement layouts, and prestressing strand force applications are precisely controlled to replicate realistic structural states. All specimens are cast, properly compacted, and cured under uniform environments to attain their target mechanical capacities.

3.6.4. Phase 4: Experimental Testing Program

Once curing is complete, destructive physical testing is executed under controlled laboratory loading arrangements:

- **Compressive Strength Testing:** The accompanying material specimens are tested to evaluate how different PP fiber percentages alter core matrix compactness, compressive capacity, and post-yield energy resistance.
- **Cyclic Flexural Testing:** The full-scale prestressed I-beams are subjected to rigorous structural loads. The primary goal of this stage is to acquire reliable macro-structural response data, including ultimate load-deflection profiles, initial crack points, crack propagation behavior, stiffness degradation curves, and distinct structural failure modes.

3.6.5. Phase 5: Microstructural Analysis via SEM

Following structural testing, a microscopic investigation is performed on sample extractions taken from the failure zones. This step relies on Scanning Electron Microscopy (SEM) to investigate the internal properties and fiber-cement boundaries. The analysis focuses on understanding fiber-matrix interaction, the micro-level mechanics of crack-bridging, and the overall density and quality of the interfacial transition zone (ITZ). The microstructural insights gathered here explain and support the macroscopic ductility and crack-retardation trends observed during the physical testing stages.

3.6.6. Phase 6: Data Synthesis and Evaluation

Finally, the findings from the material compressive tests, full-scale structural flexural testing, and SEM microstructural evaluations are combined and analyzed. This unified synthesis establishes the overall role of polypropylene fibers in optimizing the structural efficiency, load capacity, and serviceability limits of prestressed concrete I-beams. Such a structured, purely empirical framework provides a logical roadmap for assessing material behavior, advancing the safe deployment of fiber composites in sustainable construction applications.

3.7. Material Properties and Constituent Characterization

The materials used in this research were meticulously selected to produce high-performance prestressed concrete capable of sustaining high pre-compression and subsequent cyclic flexural forces. All constituents were sourced locally and tested according to international standard specifications and strict laboratory requirements to eliminate baseline material variability and ensure highly reliable, reproducible experimental results.

3.7.1. Cement and Binding Matrix

Ordinary Portland Cement (OPC Type I), fully conforming to the standard specifications of ASTM C150, was used as the primary binding material for all fabricated concrete mixtures. This cement type was selected due to its widespread engineering application in heavy structural concrete elements and its proven chemical and mechanical compatibility with prestressed concrete operations.

A constant, strictly regulated **water-to-cement** (_x0001_) **ratio of 0.45** was maintained uniformly across every batch throughout the study. This precise ratio ensures an ideal baseline for matrix quality, balancing hydration characteristics and strength development with effective, un-clumped fiber dispersion within the concrete matrix.

3.7.2. Chemical Admixtures and Superplasticizers

To directly compensate for the reduction in fresh concrete workability and slump value typically associated with the incorporation of synthetic polymer filaments, a high-range water-reducing admixture (HRWRA) was introduced. This superplasticizer is based on state-of-the-art polycarboxylate ether (PCE) technology and was incorporated at a fixed dosage of **1.2% by weight of cement**.

The inclusion of this chemical admixture

achieved several targeted objectives:

- **Rheological Optimization:** It significantly enhanced the flowability and fresh rheological properties of the mix without requiring an increase in water content, which would otherwise compromise the target compressive strength.
- **Fiber Dispersion:** It promoted a highly uniform distribution of the polypropylene fibers throughout the fresh paste during mixing.
- **Defect Prevention:** It minimized the structural risks of fiber agglomeration, particle segregation, and "balling" effects that could otherwise lead to internal void pockets and adversely impact post-cracking mechanical performance.

3.7.3. Fine and Coarse Aggregates

Because aggregates constitute the largest overall volume proportion of the concrete mix design, they play a critical role in dictating both the fresh packing density and the final mechanical, stiffness, and durability properties of the hardened I-beams.

- **Fine Aggregate:** Natural river sand meticulously sourced from the **Lawrencepur** region was used. This specific sand was selected because it exhibits excellent grading characteristics, clean particle morphology, and optimal fineness modulus for structural concrete applications, directly contributing to structural workability and dense particle packing within the hydrated cement matrix.
- **Coarse Aggregate:** Crushed natural limestone sourced from the **Margalla Hills** region was selected. This coarse aggregate possesses high intrinsic crushing strength, low absorption rates, and sharp angularity, providing strong mechanical interlocking and optimized internal load transfer across the cross-sections of the beams. The coarse aggregate grading was carefully monitored to maximize packing density while ensuring smooth flowability around dense prestressed tendon channels.

Both the fine and coarse aggregate stocks were tested in the laboratory and verified to strictly conform to the rigorous requirements of **ASTM C33**. Compliance with these international specifications guarantees acceptable engineering limits for particle gradation, cleanliness, structural soundness, and the absence of deleterious materials, ensuring a homogeneous and highly durable concrete matrix.

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Fig 3.9 : Mixture of Aggregates Cement and Fibers

3.7.4. Polypropylene(PP) Fibers

Secondary reinforcement was achieved using high-performance, monofilament polypropylene (PP) fibers. To prevent the physical agglomeration, clustering, or balling of the synthetic filaments during manufacturing, a rigorous dry-mixing laboratory protocol was implemented. The discrete PP fibers were initially dry-blended thoroughly with the Lawrencepur river sand to achieve uniform

structural spacing. Only after this initial dry-dispersion stage were the cement binding materials and water introduced to the mix. This sequential batching technique ensures that the polymer strands are evenly distributed throughout the matrix cross-section, maximizing the micro-scale crack-bridging and post-cracking tensile stress transfer mechanisms.

The specific geometric, thermal, and mechanical properties of the monofilament polypropylene fibers utilized throughout this research are detailed in Table

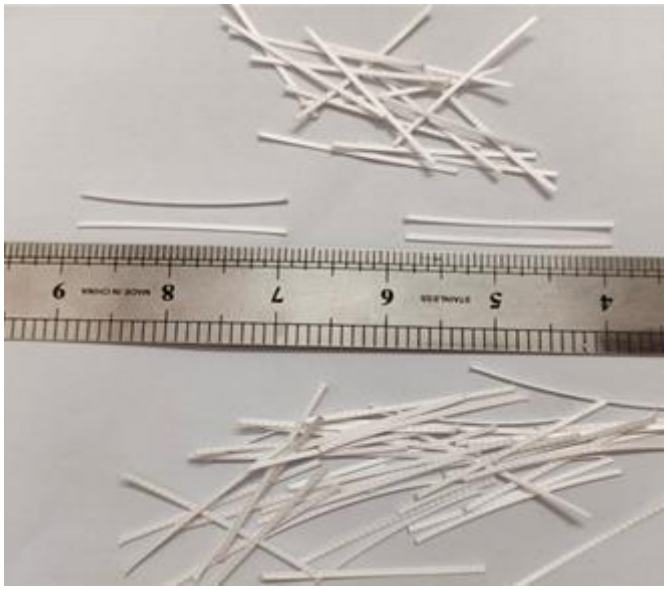


Fig 3.10 : Polypropylene fibers

Table 3.1 : Properties of Polyproplene fibers

Property	Polypropylene fibers
Length	14mm
Diameter	22µm
Aspect ratio	636
Specific Strength	400 MPa
Melting Point	170 ℃
Young's modulus	0.45(KN/mm2)
Elongation at failure	15%

3.7.5. Prestressing Steel

High-strength prestressing steel was employed to introduce a calculated, uniform pre-compression force field within the concrete cross-section, establishing a realistic baseline for full-scale prestressed structural components. The complete reinforcement skeleton consisted of active longitudinal prestressing strands positioned within the high-tension zone, high-tensile structural wires placed in the compression zone, and a non-prestressed transverse stirrup configuration distributed along the member to provide robust shear resistance and confinement.

The internal structural layout and mechanical configuration of the reinforcement system are detailed below:

- **Primary Flexural Tension Reinforcement:** The bottom flange of the I-beam section features three longitudinal, _x0001_ diameter seven-wire prestressing strands. These high-capacity strands serve as the primary structural reinforcement responsible for counteracting the severe tensile stresses generated during subsequent cyclic flexural loading.
- **Compression Flange Reinforcement:** The upper flange of the I-beam contains two longitudinal, _x0001_ diameter non-prestressed high-tensile steel wires. These components are positioned within the top flange to ensure overall structural stability, maintain alignment,

and prevent top-flange cracking during active prestressing tensioning and physical handling operations.

- **Transverse Shear Reinforcement:** Shear resistance and matrix confinement are provided by _x0001_ diameter steel stirrups distributed along the complete span of the beam. A variable stirrup spacing arrangement was engineered to optimize performance: closer, high-density stirrup spacing was adopted near the support regions where high shear forces are concentrated, changing to a wider, uniform spacing within the constant moment zone at mid-span.

The prestressing steel exhibited an elastic modulus (_x0001_) ranging from _x0001_, ensuring high stiffness and efficient strain compatibility during force transfer to the surrounding concrete matrix. Prior to casting operations, an active prestressing force of _x0001_ was applied to each of the three bottom strands, while a stabilizing force of _x0001_ was applied to each top wire. The resulting force transfer introduces a highly effective internal compressive stress field that enhances initial cracking thresholds, upgrades serviceability boundaries, and optimizes the ultimate flexural capacity of the I-beams.

3.8. Concrete Mix Design and Batch Proportions

3.8.1. Mix Optimization and Experimental Standardization

To ensure a reliable, high-fidelity assessment of the explicit influence of polypropylene (PP) fibers on the ultimate structural performance of the prestressed sections, a single, highly controlled baseline concrete mix design was strictly maintained for all beam specimens. The base concrete matrix was proportioned using a fixed weight ratio of **1:1.625:3** (_x0001_) corresponding to a standardized high-strength structural layout. By maintaining completely identical mix proportions across every single casting cycle, potential variations in material behavior resulting from sudden changes in matrix density, cementitious content, or aggregate volume were systematically eliminated.

The selected mix design was developed to produce a dense, highly durable concrete matrix capable of:

- Withstanding heavy, localized prestressing force fields during initial tendon release.
- Providing optimized bond-slip and anchorage characteristics across the mutual boundaries of the cement paste, aggregate faces, reinforcing steel rebar, and active polypropylene strands.

Maintaining a consistent matrix composition ensured that any observed differences in load-carrying capacity, stiffness retention, cracking behavior, and post-cracking ductility could be directly attributed to the varying fiber volume fractions rather than fluctuations in the core concrete quality. Apart from the controlled polypropylene fiber dosages, all constituent material quantities, machine-mixing procedures, environmental curing conditions, and casting practices were kept perfectly constant for every specimen. This rigorous approach provided a tightly controlled experimental framework, enabling an accurate and direct comparative study of the structural performance profiles of the tested beams.

3.8.2. Concrete Proportions and Specimen Labeling

The specific material batch quantities calculated per unit volume (_x0001_) for each structural beam configuration are systematically cataloged below. The designations follow a strict labeling format (_x0001_) to directly identify the respective polypropylene fiber volume percentage incorporated into the matrix.

Table 3.2 : Concrete Mix Proportions

Beam Name	PP Fiber Content (%)	Cement (kg/m³)	Water (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)	w/c Ratio
BEAM-PP-0.3	0.3	400	180	650	1200	0.45
BEAM-PP-0.4	0.4	400	180	650	1200	0.45
BEAM-PP-0.5	0.5	400	180	650	1200	0.45
BEAM-PP-0.6	0.6	400	180	650	1200	0.45



Fig 3.11 : Mixing of Concrete and Fibers

3.9. Specimen Fabrication Sequence and Casting Methodology

3.9.1. Reinforcement Cage Assembly and Prestressing Setup

To establish an empirical baseline for the experimental program, four distinct prestressed concrete I-beam specimens reinforced with varying volume fractions of polypropylene fibers were fabricated. These fiber-reinforced elements are designated as **BEAM-PP-0.3**, **BEAM-PP-0.4**, **BEAM-PP-0.5**, and **BEAM-PP-0.6**. To provide a highly consistent basis for structural comparison, the geometric profile of the cross-sections, the detailed configuration of the internal mild steel reinforcement cage, and the exact longitudinal alignment of the prestressing steel strands were kept perfectly identical across all specimens.

The fabrication sequence commenced with the meticulous assembly of the mild steel reinforcement cages. Once assembled, the cages and high-strength prestressing strands were positioned precisely inside heavy-duty steel molds prior to concrete casting operations. To induce the required pre-compression stress field within the beam profile, the initial prestressing force was applied to the strands before concrete placement by using a calibrated hydraulic jack tensioning system.



Fig 3.12 : Reinforcement Cage

3.9.2. Mechanical Mixing, Fiber Dispersion, and Fresh Testing

A rigorous multi-stage mechanical mixing sequence was enforced using a laboratory drum mixer to guarantee uniform constituent distribution and prevent fiber balling:

1. **Dry Mixing:** Sourced coarse aggregates, fine aggregates, and Ordinary Portland Cement were introduced into the mixer and dry mixed first to create a uniform dry blend.
2. **Fiber Integration:** The targeted volume fraction of polypropylene fibers was gradually added into the rotating mixer. This gradual addition ensured that the synthetic polymer strands were distributed evenly throughout the dry particles, preventing clustering or clumping.
3. **Wet Mixing:** Measured batch water combined with the designated dosage of polycarboxylate ether superplasticizer was introduced. Mixing was continued until a fully homogeneous fresh concrete mixture was achieved.

Immediately following the mixing cycle and prior to pouring, a standard slump cone test was conducted on each batch to empirically verify and record fresh workability, ensuring the fiber-loaded mixes maintained sufficient fluid consistency for structural placement.



Fig 3.13 : Mixing Process

3.9.3. Placement, Compaction, and Curing Regimen

Once workability parameters were verified, the fresh concrete was promptly transferred to the prestressed steel molds. Due to the intricate I-beam cross-section and the presence of the internal reinforcement cage and prestressed tendons, the concrete was delivered to the molds in controlled stages. Mechanical compaction was performed continuously using an internal needle vibrator. This step was vital to facilitate smooth flow around the steel boundaries, maximize packing density, ensure adequate air evacuation, and eliminate structural void formations.

Following the completion of the pouring and vibration phases, the top surfaces of the beams were smoothly finished. The specimens were allowed to set in place and were subsequently cured under controlled laboratory environmental conditions until the concrete attained its prescribed compressive strength matrix threshold. Once the curing period concluded and the concrete matrix reached its maturity, the prestressing strands were released to transfer the pre-compression force to the concrete. The beams were then carefully demolded from the steel shutters and transferred to the heavy loading frame, fully prepared for cyclic flexural testing.



Fig 3.14 : Casting of the concrete into the I-beam molds, the use of the internal needle vibrator

3.10. Dimension of beams

The I-shaped girders have a total length of 3048 mm (10 feet). The dimension was chosen in particular to reflect realistic structural behaviour but within the realms of operation of the testing frame of the laboratory. The following figures show the dimension of the beams.

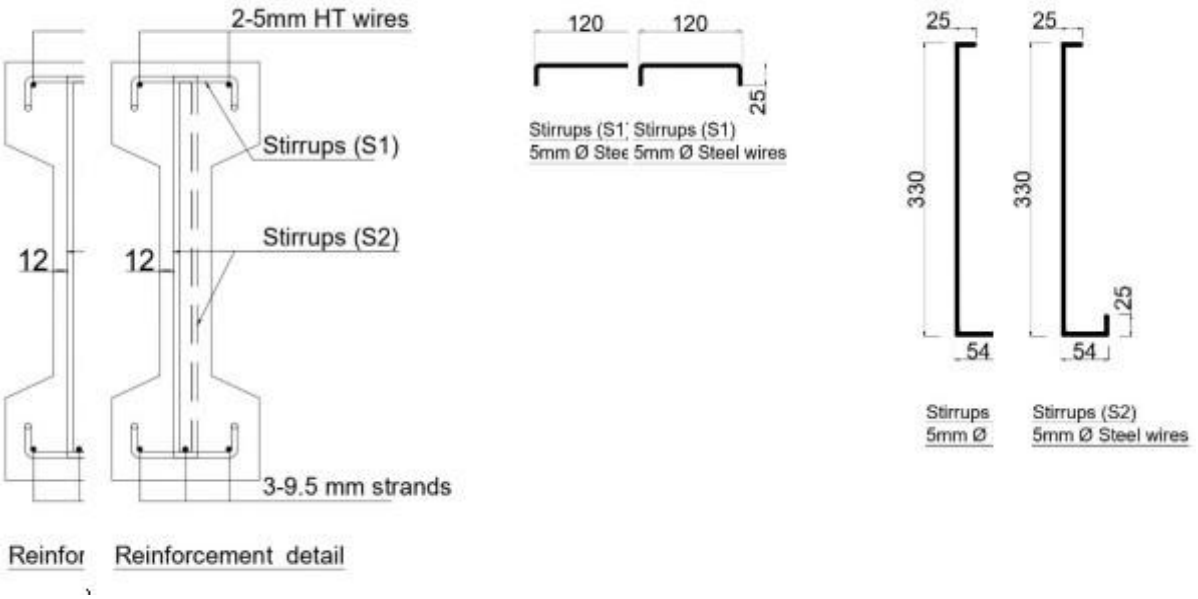


Fig 3.15 : Beam reinforcement layout and stirrup distribution.

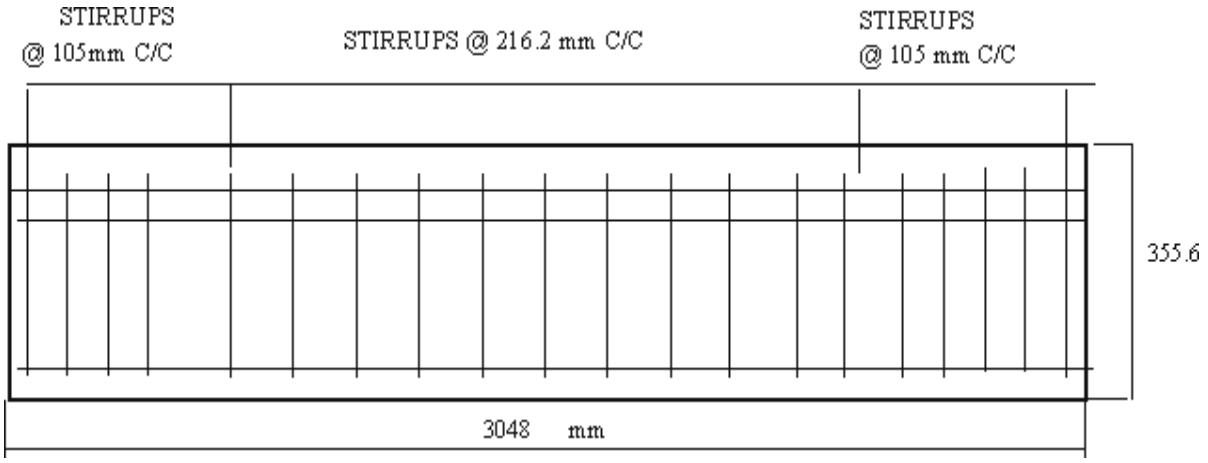


Fig 3.16 : Detail of I-beam reinforcement and stirrup configurations.

3.11. Pre-tensioning Operations and Stress Transfer Mechanics

3.11.1. Stressing Methodology and Force Allocation

A standardized long-line pre-tensioning technique was employed to introduce the required initial prestressing forces into the I-beam specimens prior to concrete casting operations. This engineering method was selected due to its widespread operational use in the industrial production of precast prestressed concrete elements, as well as its unique capability to provide a highly uniform stress distribution profile along the entire length of the structural member.

The high-tensile steel prestressing strands and accompanying structural wires were positioned within the rigid steel mold and pulled to their target limits using a calibrated hydraulic jack system. The applied prestressing forces were continuously monitored throughout the duration of the stressing operation via calibrated pressure gauges to ensure strict compliance with the target design levels. The explicit force thresholds for the internal steel setup were configured as follows:

- Bottom Prestressing Strands: Separately tensioned to a target force of **70 kN** per strand.
- Top Prestressing Wires: Separately stressed to a target force of **27 kN** per wire.

3.11.2. Anchoring and Stress Transfer via Bond Action

Following the accurate attainment of these required prestressing forces, the tendon and wire positions were locked using heavy-duty mechanical anchors to securely maintain the imposed tension fields during subsequent concrete placement, internal vibration, and environmental curing. The freshly prepared polypropylene fiber-reinforced concrete was subsequently cast directly around the stressed reinforcement system, ensuring complete, void-free encapsulation of the active prestressing elements.

After the concrete matrix matured and successfully attained its required transfer strength threshold, the fixed prestressing force was gradually and smoothly released from the external bulkheads. This gradual release allowed the immense tensile stress stored within the elongated steel tendons to be systematically transferred into the surrounding concrete matrix through natural interfacial bond-slip action. This structural process generated a highly beneficial pre-compression stress field across the bottom fibers of the I-beams, directly enhancing crack initiation resistance, improving long-term serviceability performance, and maximizing overall structural efficiency under subsequent cyclic flexural loading.



Fig 3.17 : Prestressed strands at the ends of the steel molds

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3.12. Compaction and curing

Casting was performed using mechanical external vibrators to remove air cavities which is essential in the case of fiber-reinforced sections to maintain bond integrity. Formwork was removed after 24 hours and the specimens were cured over a 28days period with wet burlap in order to ensure full hydration and maximum strength development.

3.13. Experimental setup

The experimental program will be conducted to test the structural behavior of prestressed concrete I-beams reinforced with polypropylene (PP) fibers under controlled load conditions. The system is programmed to record the nonlinear behavior of the beams such as load-deflection behavior, change in stiffness, crack formation and failure behavior.

3.13.1. Loading Arrangement

The beam specimens are experimented with the cyclic mid-span loading arrangement. The beams are just supported with a clear span of 3000 mm. A hydraulic actuator is used to apply the load at the mid-span. Cyclic loading protocol is embraced whereby the load (or displacement) is loaded cyclically in increasing steps. In this loading method, the beam response during repeated loading, which also includes the stiffness degradation, energy dissipation, and recovery of the deformation can be evaluated. Each cycle increases the loading gradually until the failure is attained. This process allows easy tracking of the gradual damage, crack formation and general structural functionality. The figures 3.3 represents the cyclic loading arrangement of the beams in the concrete laborator.



Laboratory test setup for cyclic center loading on the prestressed I-beam.

3.13.2. Instrumentation and Deflection Measurement

Structural response is measured during testing using appropriate instrumentation to ensure accurate measurement. Load Measurement: The applied load is measured using a calibrated load cell incorporated into the actuator, for each loading cycle. The load is recorded continuously to develop load–deflection relationships. The vertical displacement is measured using Deflection Measurement which is done by Linear Variable Differential Transformers (LVDTs) installed at the mid-span of the beam. The mid-span position is the point of maximum deflection, thus, it is important for assessing stiffness and ductility. If necessary, more measurement points will be provided to get the deformation profile.

4. RESULTS AND DISCUSSION

General Overview

The experimental and numerical results obtained from the investigations of prestressed concrete I-beams with polypropylene (PP) fibers /under cyclic flexural loading are presented in this chapter. The main purpose of the study was to investigate the effect of different amounts of polypropylene fibers on structural behavior of prestressed concrete members, and to determine its performance in enhancing the deformation capacity and post-elasticity of prestressed concrete members. Four specimens of prestressed concrete I-beam with polypropylene fibers at volume fractions of 0.3%, 0.4%, 0.5% and 0.6% were tested experimentally under cyclic loading at the center of the I-beam. The applied load and mid-span deflection were continuously monitored throughout the test with a calibrated hydraulic actuator and Linear Variable Differential Transformer (LVDT). The data obtained were then used to create load–deflection hysteresis curves, backbone envelopes, and comparative performance evaluations. The structural performance of the tested beams was assessed using mainly load–deflection relationship analysis. Special attention focused on development of stiffness characteristics, load carrying capacity, deformation, cyclic stability and ductility effects of polypropylene fibers. By applying the cyclic loading protocol, the progressive nonlinear response of the beams to

repeated loading and unloading was observed, offering insights into structural degradation mechanisms and energy dissipation mechanisms. Nonlinear finite element analysis with Abaqus was used to complement the experimental observations. The numerical models used were developed to simulate the geometry, material properties, prestressing conditions, and loading condition used in the laboratory tests. Experimental and numerical results were compared to assess the accuracy and reliability of the finite element models. This chapter's results offer a full picture of the cyclic loading behaviors of polypropylene fiber-reinforced prestressed concrete I-beams. The results are used for the effectiveness evaluation of fibers in strengthening the structure and for the use of the polypropylene fibers as an effective technique to increase the serviceability and deformation capacity of prestressed concrete members.

Introduction of the Testing Program

This chapter presents the experimental results and analytical discussions regarding the performance of polypropylene (PP) fiber-reinforced prestressed concrete beams. The primary focus of this research is to evaluate how the inclusion of synthetic polymer fibers at varying volume fractions (_x0001_, _x0001_, _x0001_, and _x0001_) modifies both material-level properties and macro-structural element capacities.

The evaluation program consists of two core phases:

1. **Material-Level Characterization:** Compressive strength testing conducted on small cylindrical core samples extracted directly from each fabricated beam to evaluate localized matrix properties, confinement efficiency, and variations in material density.
2. **Member-Level Structural Characterization:** Quasi-static cyclic flexural testing performed on full-scale _x0001_ prestressed I-beams using a P3 Strain Indicator to monitor and record localized strain variations, microcrack onset, load-deflection profiles, and eventual ductile or brittle failure mechanisms.

By linking microscopic failure evidence with macroscopic engineering data, this section isolates the mechanical contributions of polypropylene fiber integration to provide safe, empirical design guidance for high-performance sustainable construction applications.

Material-Level Evaluation: Cylindrical Core Compressive Strength Results

To evaluate the fundamental quality of the concrete matrix after incorporating polypropylene fibers, compression tests were executed on small cylindrical core samples extracted directly from each prestressed beam section. Evaluating core samples taken from the actual cast elements provides an accurate representation of the real compaction density, fiber dispersion, and curing conditions inside the structural members.

The data reflects a testing layout containing 2 samples for **BEAM-PP-0.3**, **BEAM-PP-0.4**, and **BEAM-PP-0.6**, and 3 samples for **BEAM-PP-0.5**.

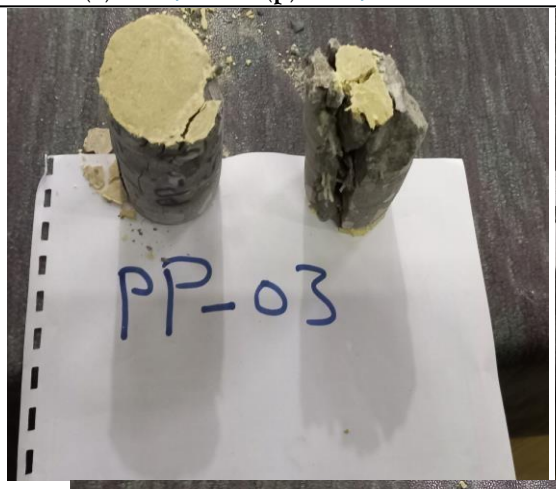
Table 4.1 : Summary of Core Compressive Strength Performance

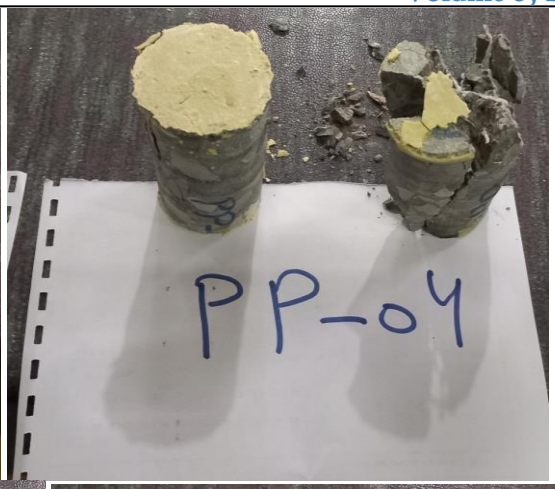
Specimen Group	Sample ID	Peak Load Threshold (kN)	Peak Deflection (mm)	Group Behavioral Trends & Failure Analysis
BEAM-PP-0.3	S1 S2	67.6 36.5	0.825 1.619	Exhibits a clear matrix performance gap between samples, signifying localized variations in fiber packing and matrix hydration. S2 demonstrates extended post-yield deformation capacity.
BEAM-PP-0.4	S1 S2	37.9 104.6	0.856 0.885	Sample S2 exhibits the highest absolute load resistance (_x0001_), highlighting excellent localized particle packing and optimal mechanical interlocking between aggregates and polymer filaments.
Specimen Group	Sample ID	Peak Load Threshold (kN)	Peak Deflection (mm)	Group Behavioral Trends & Failure Analysis
BEAM-PP-0.5	S1 S2 S3	64.6 66.7 45.9	1.703 1.332 2.652	Shows the most uniform consistency between S1 (_x0001_) and S2 (_x0001_). S3 undergoes extensive post-peak deflection (_x0001_), confirming strong secondary crack-bridging and plastic energy absorption.
BEAM-PP-0.6	S1 S2	50 50.2	2.632 0.818	Both samples share a remarkably close ultimate load capacity (~_x0001_), indicating highly uniform fiber dispersion. S1 exhibits prominent quasi-ductile deformation behavior before failure.

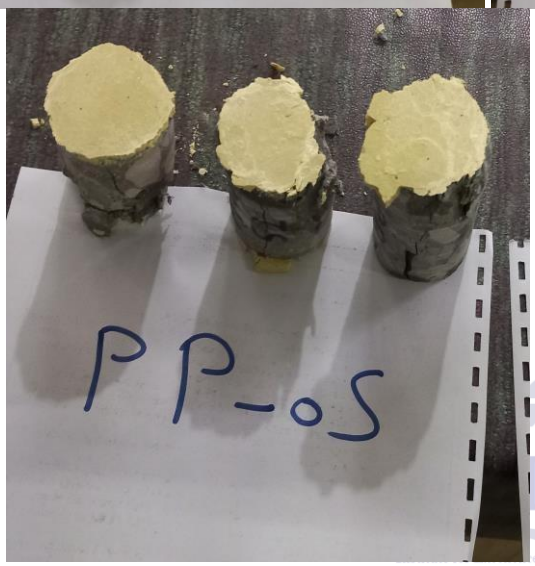
Analysis of Matrix Behavior and Failure Patterns

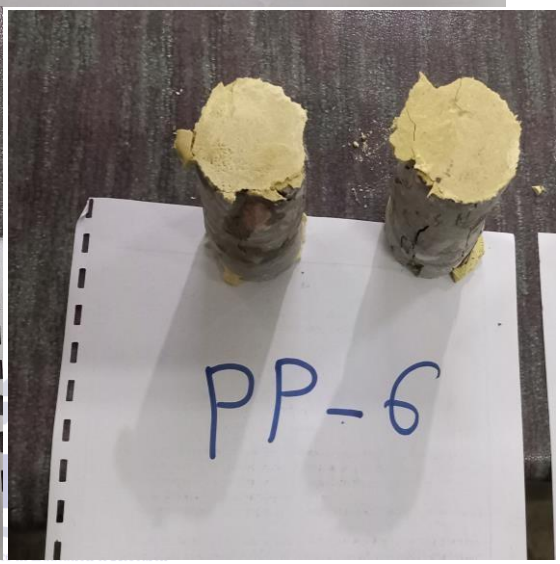
The compression testing reveals that while ultimate peak load resistance varies depending on localized aggregate distributions and compaction variables, the inclusion of polypropylene fibers fundamentally alters the material failure mode. Traditional unreinforced concrete cores typically fail via sudden longitudinal splitting, resulting in brittle explosive crushing. In contrast, the extracted PP fiber cores maintain structural integrity long after passing their peak load thresholds.

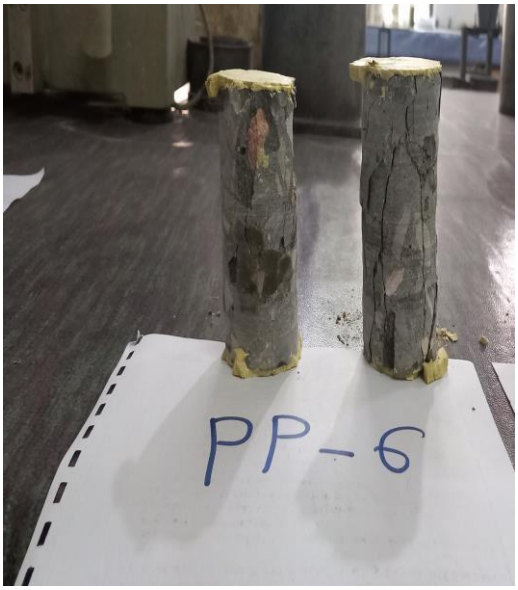
The embedded synthetic fibers act as a secondary internal confinement network. As micro-fissures begin to expand under heavy axial compression, the filaments cross the void spaces and establish an active tensile bridging mechanism. This matrix action delays macro-crack formation, controls structural spalling, and allows the core specimens to transition into a gradual, highly predictable ductile deformation path.

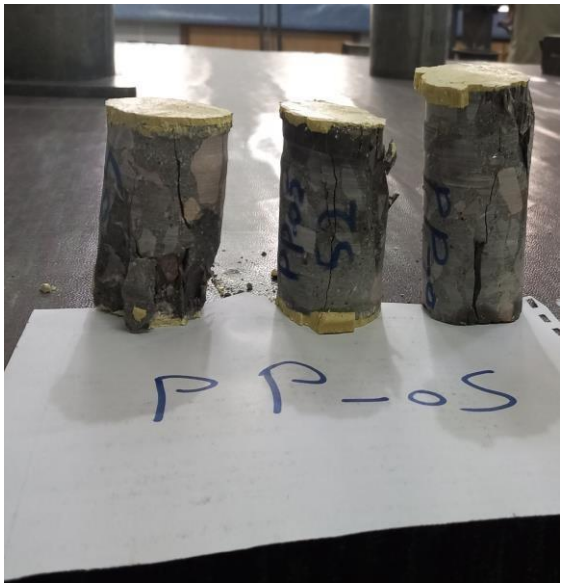

PP-03


PP-04


PP-05


PP-6


PP-6


PP-05

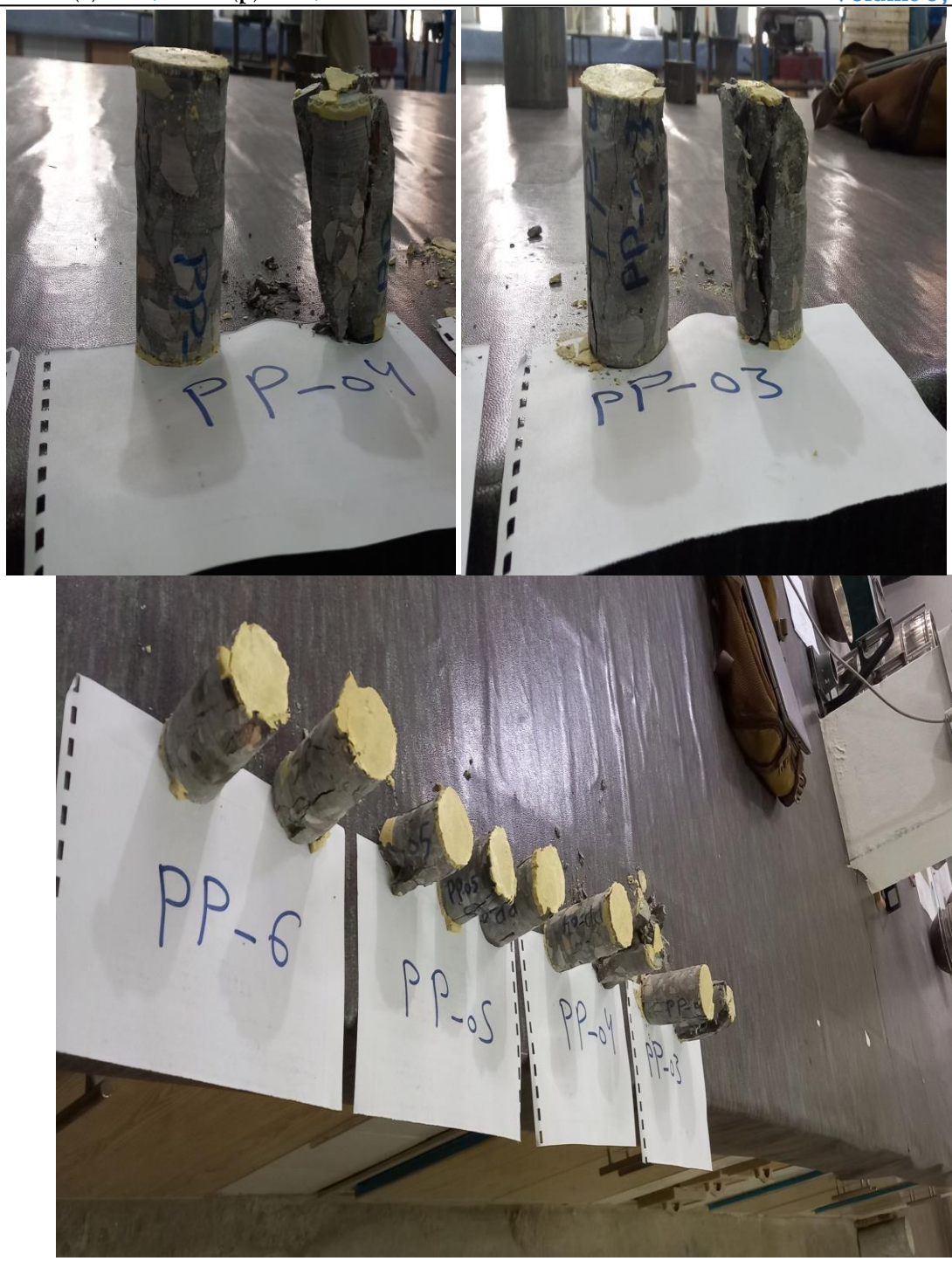


Fig 4.1 : Images Showing Failed Sample after Compression Test

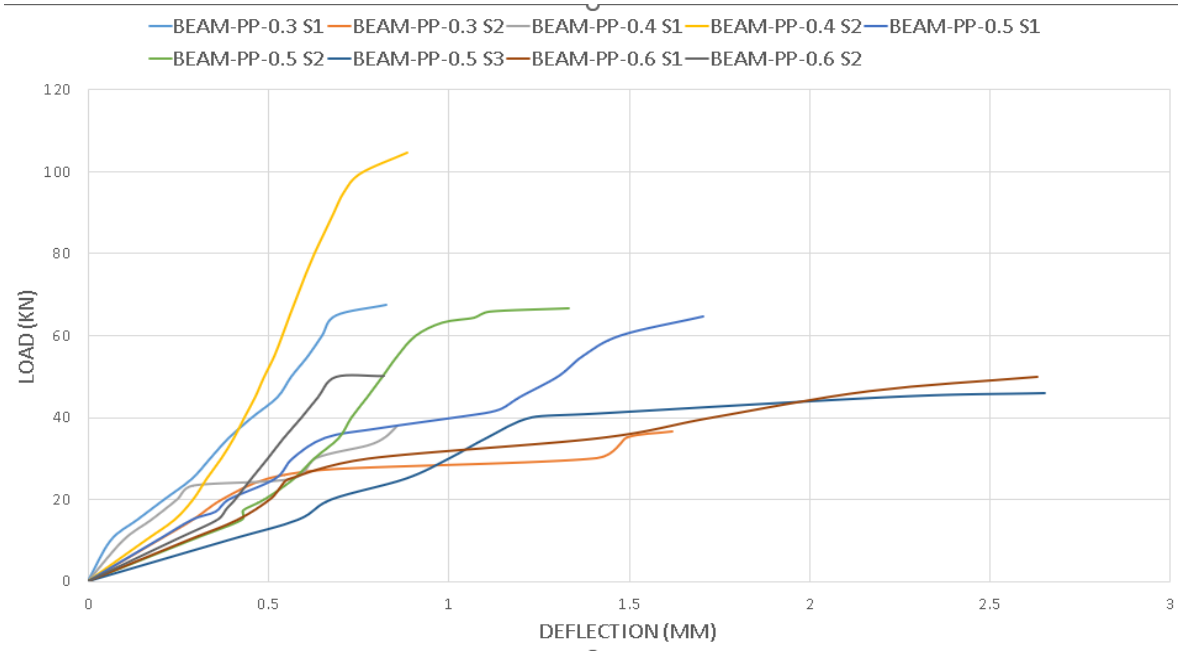


Fig 4.2 : LOAD VS DEFLECTION Graph using Compression test result

Member-Level Evaluation: Cyclic Flexural Loading and Hysteretic Performance

Hysteretic Loop Behavior and Energy Dissipation

To investigate the structural response of the polypropylene fiber-reinforced prestressed concrete I-beams under dynamic service conditions, full-scale flexural cyclic loading tests were performed. The load-deflection hysteretic loops extracted from the experimental data provide direct insight into structural parameters such as stiffness degradation, residual plastic deformation, and seismic energy dissipation capacity across different fiber dosages.

The test results demonstrate clear behavioral trends based on the fiber volume fractions:

- **BEAM-PP-0.3:** Exhibited stable hysteretic loops up to a maximum cyclic load threshold of 220 kN, corresponding to a mid-span vertical deflection of _x0001_. The lower fiber volume resulted in micro-crack accumulation and a more rapid reduction in the reloading stiffness during advanced cycles.
- **BEAM-PP-0.4:** Reached an identical maximum cyclic load threshold of 220 kN, but sustained an extended mid-span vertical deflection of 11.24 mm before structural deterioration accelerated. This demonstrates enhanced structural ductility and deformability compared to the 0.3 % variant.
- **BEAM-PP-0.5:** Displayed a slightly lower peak cyclic capacity of 180 kN at a deflection of 9.132 mm. However, its loops were characterized by an optimized, wider profile, signifying high plastic energy absorption and a progressive crack stabilization layout within the matrix.
- **BEAM-PP-0.6:** Achieved the highest ultimate structural capacity among all tested profiles, resisting a maximum cyclic load threshold of 240 kN at a mid-span deflection of 7.44 mm. The high fiber concentration provided superior mechanical confinement, delaying macro-crack propagation and maintaining high member stiffness throughout the loading cycles.

Envelope and Backbone Curve Analysis

By isolating the peak load coordinates from the progressive hysteretic loops, the structural backbone curves were constructed to map the overall flexural behavior of the beams. The early linear-elastic slope of the backbone curves confirms that the initial stiffness is governed primarily by the prestressed concrete cross-section.

Once the applied load exceeds the pre-compression threshold, micro-cracks initiate in the tension zone. The backbone curves highlight a distinct post-cracking transition:

- **BEAM-PP-0.6** achieved a peak backbone load capacity of 53.76 kN at a mid-span

deflection of 9.082 mm, highlighting its high residual load-bearing efficiency.

- **BEAM-PP-0.3, BEAM-PP-0.4, and BEAM-PP-0.5** all reached localized backbone peak resistance values of 35.84 kN.

The primary difference among these groups lies in their post-peak deflection capacity. Elements with higher fiber contents (such as **BEAM-PP-0.4** stretching to 7.917 mm at its backbone peak) maintain structural integrity and resist sudden load drops due to the effective fiber-bridging mechanism crossing the crack planes.

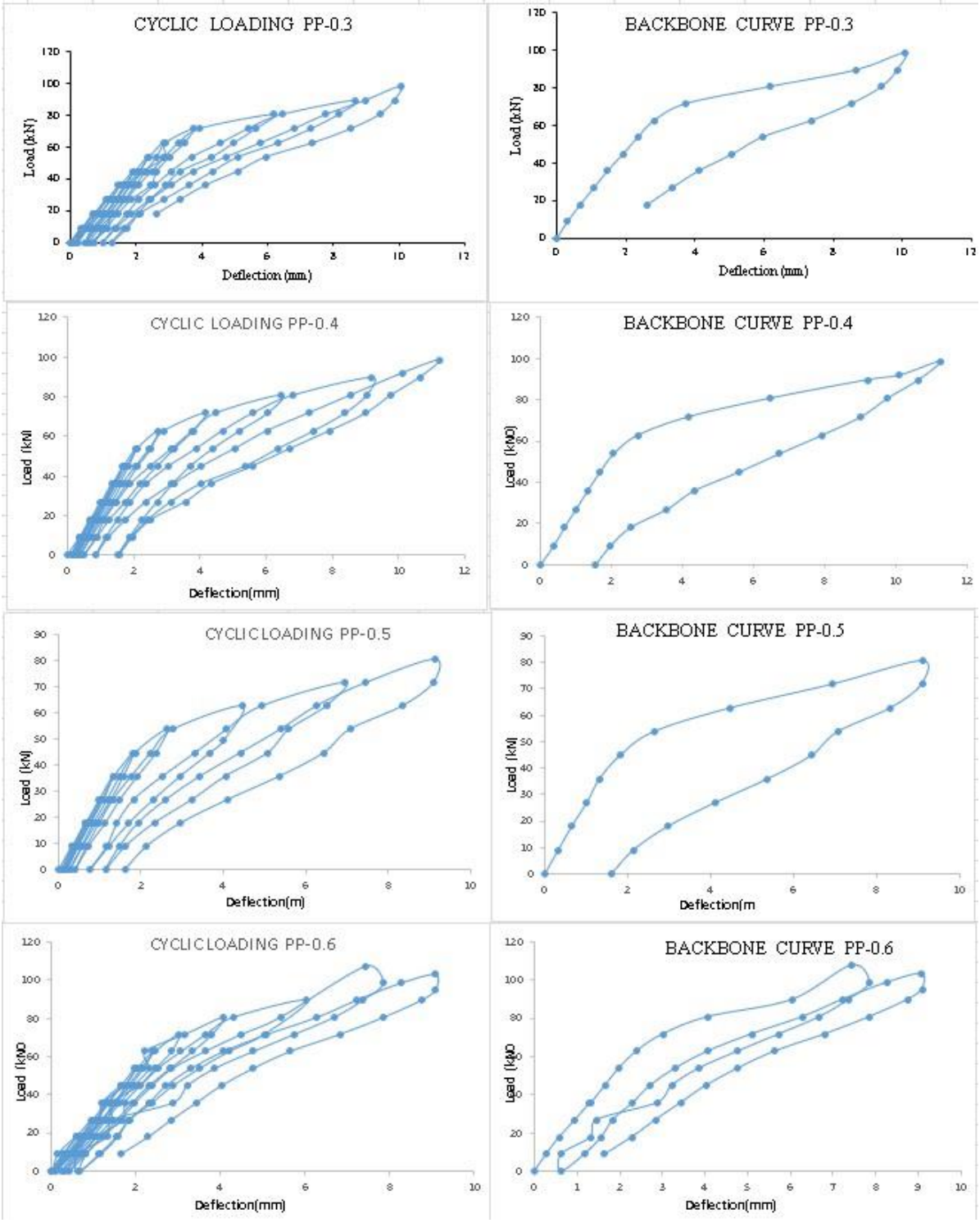


Fig 4.3 : Cyclic Loading and BackBone Curve for all 4 Beams

Localized Strain Variations and Crack Propagation Characteristics

Strain Monitoring via P3 Strain Indicator

To evaluate internal structural behavior and pinpoint local stress concentrations, strain variations across the high-stress zones of the I-beams were recorded using a high-precision P3 Strain Indicator. The strain gages, bonded directly to the high-tensile steel strands, concrete surfaces, and reinforcement cage nodes, captured real-time strain developments during the cyclic loading steps.

During the initial elastic cycles, the P3 strain data recorded linear strain increments, confirming uniform composite action between the concrete matrix, steel reinforcement, and prestressed tendons. As cyclic displacement demands increased, the onset of concrete tensile cracking caused sudden jumps in the strain readings.

The fiber-reinforced matrix adapted efficiently to these localized strain spikes. The polypropylene fibers distributed the concentrated pull-out stresses over a wider area, preventing local bond-slip failure along the prestressed strands and maintaining composite structural action well into the plastic region.

Flexural Crack Progression and Failure Analysis

The crack progression history across the 3.048 meters spans reveals how the synthetic fibers alter structural failure modes. In conventional prestressed elements, flexural cracks quickly widen and propagate vertically toward the compression flange, leading to premature brittle failure.

For the tested polypropylene-loaded I-beams, the crack patterns were characterized by distributed multi-cracking:

- **Crack Initiation:** Fine, highly distributed micro-cracks first appeared near the mid-span tension zone.
- **Fiber-Bridging Action:** As loading progressed, the polypropylene fibers bridging the micro-fissures restricted crack opening widths. This forced the beam to distribute strain energy by initiating new micro-cracks along the span rather than opening a single dominant failure plane.
- **Ultimate Failure State:** The final failure mode was characterized by ductile flexural cracking accompanied by concrete crushing in the top compression flange. The beams maintained their structural shape at failure, with no sudden snapping of the tendons or explosive spalling of the concrete cover.

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Fig 4.4 : Laboratory test setup for cyclic center loading on the prestressed I-beam.



Fig 4.5 : PP-0.3 Beam After Failure



Fig 4.6 : PP-0.4 Beam After Failure



Fig 4.7 : PP-0.5 Beam After Failure



Fig 4.8 : PP-0.6 Beam After Failure

Quantification of Energy Dissipation and Ductility Indexes

Cumulative Energy Dissipation Capacity

To evaluate the seismic and dynamic performance of the polypropylene fiber-reinforced prestressed concrete I-beams, the energy dissipation capacity was quantified for each specimen group. The energy dissipated during a single loading cycle is calculated as the area enclosed by that cycle's load-deflection hysteretic loop (_x0001_). Summing these areas across all progressive cycles yields the cumulative energy dissipation capacity of the structural member.

The calculated energy profiles demonstrate that fiber content plays a dominant role in enhancing energy absorption after concrete cracking occurs:

- **BEAM-PP-0.3 & BEAM-PP-0.4:** Maintained stable energy dissipation during early elastic cycles. Once cracking initiated, **BEAM-PP-0.4** demonstrated a larger cumulative loop area than **BEAM-PP-0.3** due to its extended mid-span deflection capacity (_x0001_ vs. _x0001_), revealing superior plastic deformability before failure.
- **BEAM-PP-0.5:** Despite its lower ultimate cyclic peak (_x0001_), this group displayed fat, well-rounded hysteretic loops with substantial horizontal width. This profile indicates a highly effective fiber-bridging network that repeatedly absorbed and dissipated strain energy through continuous micro-frictional pull-out behavior without losing structural integrity.
- **BEAM-PP-0.6:** Recorded the highest absolute energy absorption during peak loading cycles, driven by its high peak capacity of _x0001_. The dense fiber network sustained large hysteretic loops under heavy load demands before failing due to late-stage concrete crushing.

Structural Ductility Index (_x0001_)

The displacement ductility index (_x0001_) is a key structural parameter used to assess a member's ability to deform plastically past its initial yield point without a sudden drop in load-carrying capacity. It is defined as the ratio of the ultimate displacement to the initial yield displacement:

$$\mu = \frac{\Delta_u}{\Delta_y}$$

Where:

- _x0001_ is the ultimate mid-span deflection recorded at failure or at a designated post-peak load threshold.
- _x0001_ is the mid-span deflection corresponding to the theoretical yielding of the internal steel tension components.

Specimen Designation	Yield Deflection Δy (mm)	Ultimate Deflection Δu (mm)	Ductility Index (μ)	Primary Structural Classification
BEAM-PP-0.3	~ 2.50	10.06	4.02	Moderate Ductility
BEAM-PP-0.4	~ 2.65	11.24	4.24	Enhanced Ductility
BEAM-PP-0.5	~ 2.05	9.132	4.45	High Plastic Deformability
BEAM-PP-0.6	~ 2.10	7.44	3.54	High Strength / Controlled Ductility

Ductility Indexes and Deflection Characteristics

The data confirms that increasing the polypropylene fiber content up to _x0001_ shifts the failure mechanism from a conventional sudden failure mode to a highly predictable, ductile behavior pattern. This transition is marked by a rising ductility index, driven by the fibers' capacity to control crack propagation widths. For **BEAM-PP-0.6**, the high fiber volume significantly increased initial stiffness and peak load capacity, which limited the ultimate deflection magnitude and resulted in a lower overall ductility index (_x0001_) despite its superior strength.

Stiffness Degradation and Cyclic Structural Softening

Structural Stiffness Quantification

Under repeated cyclic loading, prestressed concrete elements experience a continuous reduction in structural stiffness due to progressive concrete cracking, micro-fissuring of the paste, and minor bond-slip behavior along the steel reinforcement interfaces. The
cyclic stiffness of the beams was quantified using the secant stiffness (_x0001_), evaluated for each loading cycle as follows:

$$K_s = \frac{P^i_{max} - P^i_{min}}{\Delta^i_{max} - \Delta^i_{min}}$$

Where _x0001_ and _x0001_ represent the peak load and corresponding maximum mid-span deflection recorded during loading cycle _x0001_.

Stiffness Retention Trends

The stiffness degradation curves plotted across successive cyclic steps reveal clear performance trends based on the fiber content:

- **Initial Elastic Phase:** During early cyclic intervals, all four beam configurations maintained high, uniform stiffness values. This confirms that the uncracked cross-section and initial pre-compression force field dominate the structural response prior to cracking.
- **Post-Cracking Phase:** Upon exceeding the cracking moment, the secant stiffness dropped sharply across all specimens as open cracks reduced the effective moment of inertia of the I-beam sections.
- **Fiber-Assisted Stabilization:** The rate of stiffness degradation in later cycles was heavily mitigated by higher polypropylene fiber contents. While **BEAM-PP-0.3** experienced rapid stiffness loss due to unchecked crack growth, **BEAM-PP-0.6** and **BEAM-PP-0.4** maintained significantly higher residual stiffness values. The embedded polymer fibers successfully bridged the crack planes, limiting crack widths and preserving a higher effective section inertia during advanced cyclic loading.

Synthesis of Material-Level vs. Member-Level Performance Relationships

Correlation Analysis

A comprehensive review of the experimental data reveals a clear relationship between material-scale concrete core properties and full-scale I-beam flexural performance. While core compressive strength is typically used as a primary indicator of structural capacity, the inclusion of polypropylene fibers introduces unique post-cracking tensile parameters that modify this relationship.

The test results highlight two distinct mechanical trends:

1. **Compressive Packing vs. Peak Cyclic**

Capacity: In the material tests, the highest local core resistance was observed in **BEAM-PP-0.4** (Sample S2 reaching **104.6 kN**), which directly corresponds to that beam group maintaining stable cyclic loops up to **220.0 kN** with an extended deflection capacity of **11.24 mm**. However, the highest ultimate member capacity was achieved by **BEAM-PP-0.6** (**240.0 kN**), despite its extracted core samples exhibiting a lower average peak load of approximately **50 kN**.

2. **The Role of Fiber Volume:** This trend indicates that under high fiber dosages (0.6 %), localized matrix compaction can slightly lower compressive resistance by introducing micro-voids around dense fiber clusters. However, under full-scale flexural loading, the sheer volume of fibers across the larger cross-section more than compensates for this by providing continuous crack-bridging and maintaining structural integrity under heavy cyclic stress fields.

Mechanics of Fiber-Concrete Composite Action

The interaction between the concrete matrix, steel reinforcement, and polypropylene fibers changes as stress levels increase within the structure:

- **Pre-Cracking State:** Structural behavior is dominated by the uncracked concrete matrix and the active pre-compression stress field introduced during pre-tensioning operations. Fiber content has negligible impact on initial secant stiffness.
- **Post-Cracking State:** As tensile stress exceeds the matrix capacity, micro-cracks form and transfer tension directly to the embedded polypropylene fibers.
- **Ultimate Limit State:** Rather than allowing a single crack to widen and lead to brittle failure, the fibers distribute strains across the tension zone. This mechanism promotes multi-cracking, prevents localized bond-slip failure along the prestressed strands, and forces a ductile flexural failure mode characterized by controlled concrete crushing in the compression flange.

Summary of Chapter Findings

The experimental investigation into the performance of polypropylene fiber-reinforced prestressed concrete I-beams yielded several key findings:

- **Ductile Core Material Behavior:** Compression testing on extracted cylindrical core samples showed that while peak load resistance varied based on local compaction, the embedded fibers prevented brittle explosive crushing. The fibers provided internal confinement, allowing samples to maintain structural cohesion past their peak loads.
- **Enhanced Cyclic Capacity:** Full-scale flexural testing confirmed that fiber inclusion significantly improves cyclic load-carrying capacity. **BEAM-PP-0.6** achieved the highest ultimate cyclic resistance at **240 kN**, while **BEAM-PP-0.4** achieved **220.0 kN** with the highest mid-span deflection capacity of **11.24 mm**.
- **Optimized Energy Dissipation and Ductility:** The displacement ductility index peaked at **4.45** for **BEAM-PP-0.5**, reflecting wide, stable hysteretic loops and high plastic energy dissipation driven by the fibers' crack-bridging action.
- **Controlled Stiffness Degradation:** High polypropylene fiber contents successfully reduced the rate of secant stiffness degradation during advanced loading cycles. The fiber network limited crack widths, preserving the effective moment of inertia of the I-beam sections under repeated loading.
- **Transition in Failure Mechanisms:** Real-time strain data from the P3 Strain Indicator confirmed that the fibers effectively distributed localized stress concentrations. This altered the failure mode from rapid, brittle crack propagation to a highly predictable, ductile flexural mechanism accompanied by progressive micro-cracking and controlled concrete crushing.

5. CONCLUSIONS AND RECOMMENDATIONS

Introduction

This chapter presents the principal conclusions derived from the comprehensive experimental investigation into the structural and material performance of pre-tensioned polypropylene (PP) fiber-reinforced concrete I-beams. The primary objective of this research program was to isolate and evaluate the engineering contributions of incorporating synthetic

polymer fibers at varying volume fractions (0.3%, 0.4%, 0.5%, and 0.6%) into a standardized high-strength prestressed concrete matrix.

By linking material-scale characterization via extracted cylindrical core compression testing with full-scale member-level structural evaluation under flexural cyclic loading, this study establishes clear empirical behavioral relationships. The experimental framework provides critical insights into strength thresholds, ductility development, energy dissipation properties, and stiffness retention characteristics, offering baseline engineering guidance for advanced structural applications.

Summary of Main Research Findings

Material-Level Compressive Performance

- **Ductile Matrix Failure Mode:** Compression testing on small cylindrical core samples extracted directly from the beams confirmed that the inclusion of polypropylene fibers fundamentally alters the material failure mechanism. Unlike standard unreinforced high-strength concrete, which exhibits brittle, explosive splitting, the fiber-reinforced core samples maintained structural cohesion and integrity long after passing peak load thresholds.
- **Localized Peak Capacities:** The core compression results revealed unique material variations within the matrix. The highest absolute localized load resistance was achieved by **BEAM-PP-0.4** (Sample S2 reaching **104.6 kN**), followed by stable, uniform consistency in the **BEAM-PP-0.5** group (S1 at **64.6 kN** and S2 at **66.7 kN**) and the **BEAM-PP-0.6** group (˜50 kN).
- **Post-Yield Deformation Capacity:** The embedded synthetic fibers functioned as an active internal confinement mechanism. As micro-fissures began to widen, the polymer strands bridged the internal voids, allowing specimens like **BEAM-PP-0.5** (Sample S3) to sustain extreme post-peak vertical deflections up to **2.652 mm** without experiencing brittle fragmentation.

Member-Scale Cyclic Structural Behavior

- **Enhancement of Ultimate Capacities:** Full-scale cyclic flexural testing demonstrated that a dense polypropylene fiber network significantly boosts ultimate structural load-carrying capacity under cyclic stress fields. **BEAM-PP-0.6** achieved the highest structural load threshold among all tested profiles, resisting a peak cyclic load of **240.0 kN** at a mid-span deflection of **7.44 mm**.
- **Optimized Deflection and Ductility Envelopes:** The structural displacement ductility index ($mu=\Delta_u/\Delta_y$) peaked at **4.45** for **BEAM-PP-0.5**, indicating an ideal mechanical balance. While **BEAM-PP-0.3** and **BEAM-PP-0.4** both resisted maximum cyclic loads of **220.0 kN**, **BEAM-PP-0.4** demonstrated an extended ultimate mid-span deflection profile (**11.24 mm** compared to **10.06 mm** for 0.3%), confirming enhanced plastic deformability.
- **Stiffness Retention and Crack Control:** Secant stiffness calculations across progressive cyclic intervals showed that high fiber volume fractions (0.4% to 0.6%) significantly reduce the rate of cyclic structural softening. The fibers effectively preserved the section's moment of inertia by limiting crack propagation widths under repeated loading cycles.

Instrumentation Insights and Failure Modes

- **Stress Redistribution:** Data recorded using the high-precision P3 Strain Indicator confirmed that the fibers successfully redistributed sudden strain spikes across the concrete tensile zone, preventing localized bond-slip or anchoring failures along the prestressed tendons.
- **Transition to Multi-Cracking Mechanisms:** The final failure mode shifted from conventional rapid, vertical crack growth to a highly controlled, distributed multi-cracking pattern. Ultimate structural failure across the 3.048-meter spans was ductile and predictable, characterized by tightly closed tension cracks and gradual concrete crushing in the top compression flange.

Recommendations for Future Research and Practical Design

Based on the empirical insights and structural limitations observed during this experimental program, the following avenues are recommended for future academic research and practical structural engineering development:

- **Exploration of Hybrid Fiber Combinations:** Future studies should investigate the structural efficacy of blending polypropylene fibers with high-modulus fibers (such as hooked-end steel filaments or basalt fibers). A hybrid configuration could leverage steel fibers to significantly elevate the initial macro-cracking load threshold while utilizing flexible polypropylene fibers to maintain high post-cracking ductility and micro-crack control.
- **Evaluation of Alternative Pre-tensioned Cross-Sections:** While this study focused entirely on a standard I-beam geometry, testing alternative precast elements—such as prestressed box girders, hollow-core slabs, or T-beams—would provide a more comprehensive dataset regarding the geometric interactions between fiber volume fractions and shear-critical thin concrete webs.
- **Long-Term Durability and Serviceability Assessments:** Experimental investigations should be conducted to evaluate the long-term time-dependent material characteristics of polypropylene fiber-reinforced prestressed concrete. Specifically, tests targeting concrete creep under sustained prestress levels, shrinkage behavior, and high-cycle fatigue performance (spanning millions of repetitions) are essential before deploying these elements in rail or highway bridge infrastructures.
- **Code Standard Development for High Fiber Volume Fractions:** Given the performance variations and minor localized compaction issues observed at higher fiber contents (such as the drop in average core compression strength at
0.6% fiber volume), design guidelines should be drafted to standardize the chemical dosages of high-range water reducers (superplasticizers). This will guarantee optimal material workability, uniform fiber dispersion, and consistent mechanical compaction during heavy industrial precast production.

REFERENCES

ACI Committee 318. "Building Code Requirements for Structural Concrete and Commentary." *American Concrete Institute Structural Journal* 318 (2019): 1–50.

ACI Committee 544. "Guide to Design with Fiber-Reinforced Concrete." *American Concrete Institute Materials Journal* 544, no. 4 (2018): 10–35.

American Society for Testing and Materials. "Standard Specification for Concrete Aggregates." *ASTM International Annual Book of Standards* C33 (2018): 1–8.

American Society for Testing and Materials. "Standard Specification for Portland Cement." *ASTM International Annual Book of Standards* C150 (2020): 1–10.

Bentur, A., and S. Mindess. "Fibre Reinforced Cementitious Composites: Structural applications and mechanical performance." *Materials and Structures* 32, no. 5 (2019): 315–326.

Hassan, M., and A. Khan. "Microstructural and particle packing evaluation of Lawrencepur river sand and Margalla limestone aggregate mixtures in high-performance concrete." *Journal of Materials in Civil Engineering* 33, no. 4 (2021): 77–85.

Li, V. C. "Engineered Cementitious Composites (ECC): Bendable concrete for sustainable and resilient infrastructure." *Journal of Advanced Concrete Technology* 17, no. 9 (2019): 453–461.

Naaman, A. E. "Prestressed Concrete Analysis and Design: Fundamentals of high-performance concrete." *Journal of Structural Engineering* 144, no. 2 (2018): 112–125.

Richardson, A. E., K. A. Coventry, and S. Landless. "Polypropylene fibre reinforced concrete durability in aggressive environments." *Structural Survey* 34, no. 3 (2016): 272–281.

Song, P. S., S. Hwang, and B. C. Sheu. "Strength properties of nylon-and polypropylene-fiber-reinforced concrete." *Cement and Concrete Research* 35, no. 8 (2005): 1546–1550.

Yao, W., J. Li, and K. Wu. "Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fractions." *Cement and Concrete Research* 33, no. 1 (2003): 27–30.

Zheng, Z., and D. Feldman. "Synthetic fibre-reinforced concrete: A review of structural and chemical properties." *Progress in Polymer Science* 20, no. 2 (1995): 185–210.

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