Enhancing Mechanical and Durability Properties of Self-Compacting Concrete through Hybrid Fiber Reinforcement – Basalt, Steel, Polypropylene, Glass, PVA, Coconut & E-Waste Fibers

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Abstract

This research delves into the comprehensive evaluation of hybrid fiber reinforcements on the mechanical and durability properties of self-compacting concrete (SCC). The study aims to address the inherent brittleness of SCC by incorporating various fiber combinations, including basalt, steel, and polypropylene, to enhance both short-term and long-term performance characteristics. The selection of these fibers is based on their complementary mechanical properties—basalt for its high tensile strength, steel for its ductility and load-bearing capacity, and polypropylene for its excellent crack resistance and flexibility.A systematic experimental program was carried out to investigate the synergistic effects of these hybrid fiber combinations. Fresh property evaluations included slump flow, V-funnel, and L-box tests, which provided insights into the workability, passing ability, and segregation resistance of the fiber-reinforced SCC mixes. These tests are critical in ensuring that the hybrid fiber-reinforced SCC retains its self-compacting characteristics while incorporating fibers that typically challenge flowability. Mechanical property assessments focused on compressive strength, flexural strength, and tensile strength, measured at different curing ages. The results indicated substantial improvements in the mechanical performance of SCC when hybrid fibers were used. For instance, the inclusion of steel and basalt fibers resulted in an increase in compressive strength, while polypropylene-steel combinations showed a marked enhancement in flexural strength, improving resistance to bending and cracking. Tensile strength was similarly enhanced by the hybrid fiber combinations, addressing one of the key limitations of traditional SCC, which is its poor performance in resisting tensile stresses.In addition to mechanical improvements, the study also investigated the durability aspects of the hybrid fiber-reinforced SCC. Durability tests, such as chloride penetration resistance, carbonation resistance, and freeze-thaw cycling, were conducted to evaluate the SCC's performance under aggressive environmental conditions. The results showed that the hybrid fiber combinations significantly improved the SCC's durability, making it less prone to environmental degradation. The steel-glass-polypropylene combination, in particular, exhibited superior resistance to chloride ingress and freeze-thaw deterioration, suggesting that this mix could be ideal for structures exposed to marine environments or extreme weather conditions.The research also included a microstructural analysis using scanning electron microscopy (SEM) which provided further insights into the interfacial behavior between fibers and the cement matrix. The SEM images revealed that hybrid fibers contributed to a more compact and homogeneous microstructure, with fibers effectively bridging micro-cracks and enhancing the load transfer mechanisms within the concrete matrix. The presence of well-dispersed fibers helped arrest crack propagation, contributing to the overall toughness and longevity of the concrete.In conclusion, the study highlights the potential of hybrid fiber-reinforced SCC as a high-performance material for sustainable construction applications. The combination of basalt, steel, and polypropylene fibers not only improves the mechanical properties of SCC but also enhances its durability, making it a more reliable and long-lasting material for modern construction projects. By optimizing fiber combinations and dosages, this research paves the way for more efficient and sustainable concrete mixes that can withstand both mechanical loads and environmental challenges, ensuring a longer service life and reduced maintenance costs for concrete structures.

Keywords

Hybrid fibers, Self-compacting concrete, Basalt fibers, Steel fibers, Compressive strength, Durability, Flexural strength

1. Introduction

Self-compacting concrete (SCC) is a highly innovative construction material that has revolutionized the concrete industry due to its ability to flow under its own weight and fill formwork without the need for mechanical vibration. Introduced in the late 1980s, SCC was developed to address issues related to poor compaction in areas of highly congested reinforcement and complex formwork geometries, which are common in modern construction projects. The ease of placement, high fluidity, and reduced labor requirements make SCC an attractive option for both large-scale and complex construction projects, including high-rise buildings, bridges, and tunnels. These advantages have led to its widespread adoption in the construction industry, particularly in projects requiring high-performance concrete with enhanced workability and uniformity(Chun et al., 2020).

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However, despite its many advantages, SCC is inherently brittle due to the absence of reinforcement that can resist tensile forces and arrest crack propagation. This brittleness, combined with SCC's low tensile strength, presents challenges in structural applications where high mechanical performance and durability are required over time. Cracking can lead to reduced load-bearing capacity, water infiltration, and corrosion of reinforcing steel, all of which diminish the long-term durability of concrete structures. This limitation has prompted researchers and engineers to explore ways to improve the mechanical properties and durability of SCC, specifically through fiber reinforcement.

The incorporation of fibers into SCC is seen as a viable solution to overcome its brittleness and enhance its mechanical performance. Fibers can improve the tensile strength, ductility, and crack resistance of SCC, making it more suitable for structural applications. However, the use of a single type of fiber often results in only partial improvements in certain properties. For instance, steel fibers are highly effective in improving tensile strength and ductility, but they do little to prevent micro-cracks or enhance durability against environmental stressors. Similarly, synthetic fibers like polypropylene are effective in controlling plastic shrinkage cracks but do not contribute significantly to mechanical strength. This has led to the emergence of **hybrid fiber systems**, which combine two or more types of fibers to leverage their complementary properties and provide a more comprehensive solution.

Hybrid fiber-reinforced concrete (HFRC) systems have gained considerable attention in recent years due to their potential to enhance both the mechanical and durability properties of SCC. By combining fibers with different properties, such as high tensile strength, flexibility, and resistance to environmental degradation, hybrid fiber systems can provide a synergistic effect that is greater than the sum of the individual fiber components. For example, the combination of steel and synthetic fibers can improve both the load-bearing capacity and crack resistance of concrete, while also enhancing its resistance to environmental conditions such as freeze-thaw cycles and chloride penetration.

The **primary objective** of this study is to investigate the impact of combining different fiber types—specifically basalt, steel, and polypropylene—on the mechanical and durability properties of SCC. Basalt fibers are known for their high tensile strength and durability, making them an ideal choice for improving the mechanical performance of concrete. Steel fibers, on the other hand, contribute to enhanced ductility and tensile strength, while polypropylene fibers are effective in controlling shrinkage and crack propagation. The study aims to assess how these fibers, when used in hybrid combinations, can improve key properties of SCC, such as compressive strength, flexural strength, and tensile strength.

In addition to mechanical performance, **durability** is a critical aspect of SCC's application, particularly in environments exposed to harsh conditions such as marine structures, industrial floors, and bridges. Durability properties such as resistance to chloride penetration, carbonation, and freeze-thaw cycles are essential for ensuring the long-term service life of concrete structures. This study will evaluate the durability performance of SCC reinforced with hybrid fibers, investigating how the different fiber combinations affect the concrete's ability to withstand environmental stressors and maintain structural integrity over time.

Moreover, the **fresh properties** of SCC are also crucial for its performance in the field. SCC must maintain its self-compacting ability even after fiber reinforcement, as the addition of fibers can often reduce flowability and increase the risk of segregation or bleeding. Therefore, this research will also examine the fresh properties of the hybrid fiber-reinforced SCC, including tests such as slump flow, V-funnel, and L-box, to ensure that the workability of the concrete is not compromised by the addition of fibers.

In summary, this study seeks to bridge the gap between workability, mechanical strength, and durability by exploring the synergistic effects of hybrid fiber combinations in SCC. The research will provide valuable insights into the optimal fiber dosages and combinations that yield the best performance, paving the way for the development of high-performance SCC mixes tailored for modern construction demands. The results of this study have the potential to improve the design and application of SCC in structural projects, offering a more robust, durable, and sustainable construction material that can meet the growing demands of the industry.

➢ Objectives

- To evaluate the workability characteristics of hybrid fiber-reinforced SCC using slump flow, V-funnel, and L-box tests while determining optimal fiber combinations that maintain SCC's self-compacting properties and assessing the passing ability and segregation resistance of various hybrid fiber combinations.
- To investigate the compressive, flexural, and tensile strength improvements of SCC through hybrid fiber reinforcement, evaluate the strength enhancement to address SCC's

brittleness, and quantify the percentage improvements over plain SCC for each hybrid combination.

- To assess chloride penetration resistance for marine environments, evaluate carbonation resistance for long-term durability in aggressive conditions, investigate freeze-thaw resistance for cold climate applications, and determine the optimal hybrid combinations for enhanced durability performance.
- To incorporate waste materials (e-waste, glass) into hybrid fiber combinations, evaluate the performance of eco-friendly fiber combinations, and assess the viability of natural fibers (coconut) in hybrid reinforcement systems for sustainable construction applications.
- To identify the most effective hybrid fiber combinations for specific applications, determine optimal dosages for maximum performance enhancement, and establish comprehensive guidelines for hybrid fiber-reinforced SCC mix design.

2. Experimental Program

The experimental program was designed to evaluate the influence of hybrid fiber reinforcements on the fresh and hardened properties of self-compacting concrete (SCC). The materials selected for this study, including cement, supplementary cementitious materials (SCMs), aggregates, and fibers, were chosen based on their proven effectiveness in concrete applications and their ability to enhance both mechanical and durability properties. Each material plays a specific role in the overall performance of the SCC mix, and the following sections provide a detailed explanation of the materials used in this study.

2.1 Materials

Cement

Ordinary Portland Cement (OPC) was used as the primary binding material in the SCC mix. OPC is widely used in concrete construction due to its ability to develop early strength, ensuring the structural integrity of the concrete. In this study, OPC Grade 43 was selected to provide the required compressive strength for the SCC mixes. The specific gravity of the cement was approximately 3.15, which aligns with standard values for OPC. Cement content was optimized to maintain a good balance between workability and strength, ensuring that the

SCC could achieve self-compaction without the need for additional vibration (Han, Zhang, & Ou, 2017).

Supplementary Cementitious Materials (SCMs)

SCMs are added to concrete to improve both fresh and hardened properties. In this study, **fly ash** and **silica fume** were incorporated as SCMs to enhance the workability, durability, and long-term performance of the SCC mixes.

- **Fly ash**, a byproduct of coal combustion in power plants, was used as a partial replacement for cement. It constituted **20% of the binder weight** in the mix. The addition of fly ash is known to improve the flowability of SCC, reduce water demand, and enhance resistance to chemical attacks such as sulfate exposure. Fly ash contributes to the pozzolanic reaction, which helps refine the pore structure and improve the long-term strength and durability of the concrete.
- **Silica fume**, a highly reactive pozzolanic material, was included at **6% of the binder weight**. Silica fume is characterized by its ultra-fine particles, which significantly enhance the density of the cementitious matrix and improve the bond between the paste and aggregates. The addition of silica fume increases the mechanical properties, such as compressive and tensile strength, while also improving the concrete's resistance to chloride ingress and other forms of environmental deterioration.

The combination of fly ash and silica fume not only contributes to the mechanical performance of SCC but also enhances the sustainability of the mix by reducing the overall cement content and utilizing industrial byproducts.

Aggregates

The role of aggregates in SCC is crucial for maintaining a balance between workability and mechanical strength. In this study, both coarse and fine aggregates were carefully selected and graded to optimize the flowability and packing density of the concrete.

Coarse aggregates with a maximum size of 12 mm were used in the mix. This size was chosen to ensure that the aggregates could pass easily through densely reinforced sections without causing blockages, thereby preserving the self-compacting characteristics of the concrete. The coarse aggregates were crushed stone, which provides good interlocking and contributes to the overall strength of the SCC. The specific gravity of the coarse aggregates was approximately 2.7.

Fine aggregates consisted of well-graded natural sand with a specific gravity of approximately 2.65. The fine aggregates were included to fill the voids between the coarse aggregates and enhance the cohesiveness of the mix. The gradation of the fine aggregates was optimized to prevent segregation and bleeding, two issues commonly encountered in SCC when improperly graded fine materials are used.

The combination of coarse and fine aggregates in appropriate proportions ensures that the SCC mix maintains its self-compacting properties while achieving the desired mechanical performance. To address the brittle nature of SCC and enhance its mechanical and durability properties, hybrid fiber reinforcements were incorporated into the mix. Three types of fibers were selected for their complementary properties: basalt fibers, steel fibers, and polypropylene fibers. The rationale behind combining these fibers was to leverage their individual strengths in improving different aspects of the SCC's performance.

Basalt fibers were chosen for their high tensile strength and excellent durability. Basalt fibers are derived from volcanic rock and exhibit superior mechanical properties compared to synthetic fibers. Their high modulus of elasticity contributes to the improvement of both tensile and compressive strengths in concrete. Additionally, basalt fibers are resistant to environmental factors such as alkali attack and corrosion, making them suitable for enhancing the long-term durability of the concrete. In the SCC mixes, basalt fibers were included at a dosage of 0.3% by volume.

Steel fibers were incorporated to improve the tensile strength, flexural strength, and ductility of the SCC. Steel fibers are widely used in fiber-reinforced concrete due to their ability to bridge cracks and enhance post-cracking behavior. In this study, steel fibers were included at a dosage of 1.0% by volume. Their addition is expected to significantly increase the load-bearing capacity of the SCC and improve its resistance to dynamic loads and impact forces. Moreover, steel fibers improve the toughness of the concrete, allowing it to absorb more energy before failure.

Polypropylene fibers were selected to control shrinkage cracks and improve the flexibility of the concrete. Polypropylene fibers are synthetic fibers that are highly effective in reducing plastic shrinkage and early-age cracking in concrete. They also enhance the SCC's resistance to water penetration and improve its durability under freeze-thaw conditions. In this study, polypropylene fibers were included at a dosage of 0.2% by volume. Although these fibers are relatively soft compared to steel and basalt fibers, their inclusion helps prevent micro-cracking and enhances the overall integrity of the concrete matrix.

The combination of these fibers in hybrid systems is expected to result in synergistic improvements in both the fresh and hardened properties of the SCC. Basalt fibers provide strength and durability, steel fibers improve load-bearing capacity and ductility, while polypropylene fibers control shrinkage and enhance flexibility. Together, these fibers are anticipated to significantly enhance the mechanical performance, crack resistance, and long-term durability of the SCC.

2.2 Mix Design

Several SCC mixes were developed with varying combinations of basalt, steel, and polypropylene fibers. The water-cement ratio was kept constant at 0.36. The fibers were added in hybrid configurations, such as:

- 0.3% basalt and 0.2% polypropylene.
- 1% steel and 0.2% polypropylene.
- 1% steel, 0.5% coconut, and others as per the detailed design.

The development of optimal self-compacting concrete (SCC) mixes with hybrid fiber reinforcement requires a balanced approach that ensures both workability and enhanced mechanical properties. In this study, the primary goal of the mix design was to achieve high fluidity while incorporating various fiber combinations to address the inherent brittleness and enhance the durability of SCC. The following sections provide a detailed overview of the mix design strategy, fiber combinations, and the rationale for maintaining a constant water-cement ratio.

Water-Cement Ratio

The **water-cement ratio** is a crucial parameter in determining the workability, strength, and durability of concrete. In this study, the water-cement (W/C) ratio was fixed at **0.36** for all SCC mixes. This ratio was selected based on previous research and practical experience, where a lower W/C ratio is known to improve the strength and durability of concrete. A ratio of 0.36 ensures that the SCC has sufficient water to maintain its flowability and self-compacting characteristics while minimizing the risk of segregation and bleeding, which can occur in mixes with higher water content.

The selection of a constant W/C ratio was critical in maintaining consistency across all experimental trials, enabling the study to isolate the effects of fiber reinforcements on the fresh and hardened properties of SCC. Additionally, the presence of supplementary cementitious materials (SCMs) such as fly ash and silica fume helped to refine the microstructure of the concrete, further enhancing workability and strength at the selected W/C ratio.

Fiber Combinations and Hybrid Configurations

The primary objective of incorporating hybrid fibers was to leverage the complementary properties of different fiber types to improve both the fresh and hardened properties of SCC. The following **hybrid fiber configurations** were explored, with each combination designed to address specific performance characteristics such as compressive strength, tensile strength, flexural strength, and durability:

1. **0.3% Basalt Fibers and 0.2% Polypropylene Fibers**

- This combination was designed to provide a balance between **strength and crack resistance**. Basalt fibers, with their high tensile strength and resistance to environmental degradation, were selected to improve both the compressive and tensile strength of the SCC. The addition of polypropylene fibers at 0.2% by volume was intended to enhance the SCC's resistance to plastic shrinkage and cracking, particularly at early ages. Polypropylene fibers are also known for their ability to improve durability under freeze-thaw conditions, making this combination ideal for structural applications exposed to harsh environments.
- **Rationale**: Basalt fibers contribute to the high strength and stiffness of the concrete, while polypropylene fibers help mitigate cracking and improve durability. This combination is expected to enhance the long-term performance of SCC by preventing the

propagation of cracks and improving resistance to environmental stressors such as freeze-thaw cycles.

2. **1.0% Steel Fibers and 0.2% Polypropylene Fibers**
   - The combination of steel and polypropylene fibers was introduced to significantly improve the ductility and toughness of SCC. Steel fibers, at 1.0% by volume, provide superior tensile and flexural strength, making the concrete more resistant to dynamic loads and impact forces. Steel fibers also enhance the post-cracking behavior of SCC by bridging cracks and distributing stress more effectively. Polypropylene fibers, at 0.2%, were included to control plastic shrinkage and further improve the toughness of the concrete.
   - **Rationale**: Steel fibers are highly effective in improving the load-bearing capacity of concrete, while polypropylene fibers address early-age shrinkage and cracking. Together, these fibers are expected to enhance both the mechanical strength and durability of the SCC mix. This combination is ideal for applications requiring high structural performance, such as industrial floors, precast elements, and pavements.
3. **1.0% Steel Fibers and 0.5% Coconut Fibers**
   - This hybrid combination was selected to investigate the effects of natural fibers in combination with traditional steel fibers. Coconut fibers, a type of natural fiber, were included at 0.5% by volume to provide a sustainable and eco-friendly reinforcement solution. Coconut fibers are known for their toughness and ability to absorb energy, making them suitable for improving the impact resistance and crack control of concrete. When combined with steel fibers, which contribute to high tensile and flexural strength, this mix is expected to provide enhanced performance in terms of both mechanical properties and sustainability.
   - **Rationale**: The use of natural fibers such as coconut fibers contributes to the sustainability of the concrete mix by reducing the reliance on synthetic materials. The combination of steel and coconut fibers is expected to improve both the mechanical strength and environmental performance of the SCC mix. This combination is particularly relevant for regions with abundant natural fibers and where sustainable construction practices are prioritized.

4. **Additional Hybrid Fiber Configurations**

- **0.2% Polypropylene Fibers and 0.3% E-Waste Fibers**: This combination aimed to incorporate recycled materials into the SCC mix, with polypropylene fibers enhancing crack resistance and e-waste fibers contributing to sustainability and cost-effectiveness. The e-waste fibers, derived from electronic waste, provide an innovative solution for reducing the environmental impact of concrete production by utilizing recycled materials.
- **0.2% Polypropylene Fibers and 0.1% Polyvinyl Alcohol (PVA) Fibers**: This combination was introduced to improve the **ductility and toughness** of the SCC. PVA fibers are known for their high tensile strength and bond strength with the cementitious matrix, providing improved post-cracking behavior. Polypropylene fibers were included to control shrinkage and enhance the overall durability of the mix.
- **1.0% Steel Fibers, 0.1% Glass Fibers, and 0.3% Polypropylene Fibers**: This configuration involved a **triple-fiber hybrid system**, with steel fibers providing tensile strength, glass fibers contributing to the reduction of micro-cracks, and polypropylene fibers enhancing ductility and crack control. This combination aimed to achieve a well-rounded improvement in the mechanical, durability, and fresh properties of SCC, making it suitable for high-performance structural applications.

Mix Design Proportions

The mix design proportions for each hybrid fiber configuration were carefully calculated to ensure optimal performance in both fresh and hardened states. The target compressive strength was set at 30 MPa, with a binder content of 530 kg/m³ (including cement, fly ash, and silica fume). The following is a typical mix design used for the hybrid fiber-reinforced SCC:

- **Cement**: 400 kg/m³
- **Fly Ash**: 100 kg/m³ (20% of the binder weight)
- **Silica Fume**: 30 kg/m³ (6% of the binder weight)
- **Water**: 194 kg/m³ (based on a W/C ratio of 0.36)
- **Fine Aggregates**: 850 kg/m³
- **Coarse Aggregates**: 750 kg/m³
- **Fibers**: Varying combinations of basalt, steel, polypropylene, coconut, and e-waste fibers as per the specific mix design.

The mix proportions were adjusted slightly to account for the water absorption of the aggregates and the workability requirements of SCC. The addition of high-range water-reducing admixtures (HRWRAs) and viscosity-modifying admixtures (VMAs) was critical in maintaining the flowability and stability of the SCC mixes, ensuring that the fibers were well-dispersed and that the concrete could fill formwork without segregation or bleeding(Nikolaides & Manthos, 2024)

The mix design process for hybrid fiber-reinforced SCC was aimed at achieving a balance between workability, mechanical performance, and durability. The inclusion of different fibers in hybrid configurations allows for the tailoring of SCC properties to meet specific structural and environmental requirements. By maintaining a constant W/C ratio and incorporating SCMs and fibers, this study provides a robust foundation for optimizing the performance of SCC in modern construction applications.

2.3 Testing Methods

The performance of hybrid fiber-reinforced self-compacting concrete (SCC) was evaluated through a comprehensive series of tests designed to assess fresh properties, mechanical strength, and durability. These tests were chosen to provide a thorough understanding of how the addition of hybrid fibers (basalt, steel, and polypropylene) affects SCC's workability, mechanical performance, and resistance to environmental degradation over time. The testing methods are elaborated below:

2.3.1 Fresh Property Tests

The fresh properties of self-compacting concrete are crucial for its performance during placement, particularly in complex formwork or densely reinforced sections. The following tests were conducted to assess the workability, passing ability, and resistance to segregation of the hybrid fiber-reinforced SCC:

1. **Slump Flow Test**
   - The **slump flow test** was performed to evaluate the flowability and deformation capacity of SCC. The test involved filling an Abrams cone with SCC, lifting the cone, and allowing the concrete to flow freely. The horizontal spread (slump flow diameter) was measured in two perpendicular directions, and the average value was recorded.
   - **Objective**: To assess the fluidity and self-compacting ability of the SCC mix.

- **Acceptance Criteria**: A slump flow diameter between **600 mm and 750 mm** indicates good flowability, ensuring that the SCC can spread uniformly without external vibration.
- **Significance**: This test is essential for determining whether the SCC mix can flow and fill formwork without segregation or the need for mechanical compaction, a key requirement for self-compacting concrete.

2. **V-Funnel Test**

- The **V-funnel test** was used to measure the viscosity and flow time of the SCC. The test involved pouring SCC into a V-shaped funnel, and the time taken for the concrete to flow out of the funnel was recorded. The flow time reflects the mix's ability to pass through narrow spaces and its resistance to segregation.
- **Objective**: To evaluate the viscosity and cohesiveness of SCC, which are important for its ability to flow through congested reinforcement without bleeding or segregation.
- **Acceptance Criteria**: Flow times between 6 and 12 seconds are generally considered acceptable, indicating sufficient flowability without excessive viscosity.
- **Significance**: This test helps ensure that the SCC mix maintains its flowability and can navigate tight spaces in complex formwork or heavily reinforced areas without segregation or loss of homogeneity.

3. **L-Box Test**

- The **L-box test** was conducted to assess the passing ability of SCC, particularly when flowing through obstacles such as reinforcing bars. In this test, SCC was allowed to flow from the vertical section of an L-shaped box into the horizontal section, where obstacles (reinforcement bars) were placed. The height of the SCC at the end of the horizontal section was measured, and the ratio of the final height to the initial height was recorded as the passing ability ratio.
- **Objective**: To determine the SCC's ability to flow through congested areas without blockage or segregation.
- **Acceptance Criteria**: A passing ability ratio of 0.8 or higher indicates that the SCC can pass through reinforcement without blockage or loss of fluidity.
- **Significance**: This test is particularly important in real-world applications where SCC must navigate complex reinforcement geometries and narrow spaces. It ensures that the addition of fibers does not negatively impact the SCC's passing ability.

2.3.2 Mechanical Property Tests

The mechanical properties of the hybrid fiber-reinforced SCC were evaluated to understand its behavior under compressive, tensile, and flexural loads. These properties are critical for determining the concrete's suitability for structural applications. The following tests were conducted at **7, 14, and 28 days** to assess the mechanical performance:

1. **Compressive Strength Test**

- **Compressive strength** is a fundamental property that measures the SCC's ability to withstand compressive loads. Standard cylindrical specimens (150 mm × 300 mm) were prepared and tested in a universal testing machine (UTM). The compressive load was applied until failure, and the ultimate compressive strength was recorded.
- **Objective**: To evaluate the compressive strength of the SCC mix, which is essential for determining its load-bearing capacity.
- **Acceptance Criteria**: The target compressive strength was set at **30 MPa** at 28 days, with hybrid fibers expected to enhance the strength further.
- **Significance**: Compressive strength is critical for structural applications, particularly in elements subjected to significant vertical loads, such as columns and foundations. This test provides insight into how the addition of hybrid fibers influences the overall strength development of SCC over time.

2. **Flexural Strength Test**

- **Flexural strength** is a measure of SCC’s resistance to bending or flexural stresses, which is important in applications like beams and slabs. Beam specimens (100 mm × 100 mm × 500 mm) were prepared and tested using a three-point bending setup. The load was applied at the midpoint of the beam until failure, and the maximum flexural strength was recorded.
- **Objective**: To determine the SCC’s ability to resist bending and flexural loads, which is critical in structural elements like beams and pavements.
- **Acceptance Criteria**: The addition of hybrid fibers, particularly steel fibers, was expected to significantly improve the flexural strength by enhancing crack resistance and energy absorption.
- **Significance**: Flexural strength is essential in applications where bending forces are predominant, such as in slabs and pavements. The incorporation of hybrid fibers is expected to improve crack resistance and post-cracking performance, providing better durability and long-term performance.

3. **Split Tensile Strength Test**
   - The split tensile strength test was used to evaluate the tensile strength of SCC. Cylindrical specimens (150 mm × 300 mm) were subjected to a compressive load along their diameter until failure, and the split tensile strength was calculated based on the applied load and specimen dimensions.
   - **Objective**: To assess the tensile strength of SCC, which is a critical factor in determining its ability to resist cracking and tensile forces.
   - **Acceptance Criteria**: The hybrid fiber-reinforced SCC was expected to show improved tensile strength compared to plain SCC, with the steel and polypropylene fibers contributing to enhanced crack resistance and tensile strength.
   - **Significance**: Tensile strength is a critical parameter in preventing the development of cracks in concrete. The split tensile test provides insights into how well the SCC can resist tensile forces, particularly in applications where crack control is essential.

2.3.3 Durability Assessments

Durability is a key factor in determining the long-term performance and sustainability of SCC, especially in harsh environmental conditions. The following tests were conducted to evaluate the durability of the hybrid fiber-reinforced SCC:

1. **Chloride Penetration Test**
   - The **chloride penetration test** was used to measure the SCC's resistance to chloride ion ingress, which is critical for preventing corrosion of reinforcing steel in concrete. This test was conducted by subjecting concrete specimens to chloride exposure and measuring the depth of chloride penetration over time.
   - **Objective**: To evaluate the SCC's ability to resist chloride ion ingress, which is important for structures exposed to marine environments or de-icing salts.
   - **Acceptance Criteria**: The addition of hybrid fibers, particularly basalt and steel fibers, was expected to reduce chloride penetration by improving the density and impermeability of the concrete matrix.
   - **Significance**: Chloride penetration is a major cause of corrosion in reinforced concrete structures. Improving chloride resistance extends the service life of concrete structures and reduces maintenance costs.
2. **Carbonation Resistance Test**

- The **carbonation resistance test** was performed to assess the SCC's ability to resist carbonation, a process that can reduce the pH of the concrete and lead to corrosion of reinforcement. Concrete specimens were exposed to a controlled CO2 environment, and the depth of carbonation was measured.
- **Objective**: To determine the SCC's resistance to carbonation, which is important for maintaining the alkalinity of the concrete and protecting reinforcing steel from corrosion.
- **Acceptance Criteria**: The hybrid fiber-reinforced SCC was expected to show improved resistance to carbonation due to the enhanced densification of the concrete matrix.
- **Significance**: Carbonation is a key factor in the deterioration of concrete structures over time. Improved carbonation resistance ensures the longevity and durability of SCC, particularly in urban environments where CO2 exposure is higher.

3. **Freeze-Thaw Cycling Test**

- The **freeze-thaw cycling test** was conducted to evaluate the SCC's ability to withstand repeated cycles of freezing and thawing, which can cause cracking and scaling in concrete. Specimens were subjected to a series of freeze-thaw cycles, and the degree of damage (mass loss, cracking) was recorded.
- **Objective**: To assess the SCC's durability in environments subjected to temperature fluctuations, such as cold climates.
- **Acceptance Criteria**: The incorporation of polypropylene fibers was expected to improve freeze-thaw resistance by reducing crack propagation during freeze-thaw cycles.
- **Significance**: Freeze-thaw resistance is critical for ensuring the long-term durability of concrete in cold climates. The test results provide valuable insights into the SCC's ability to resist damage from temperature fluctuations and moisture ingress.

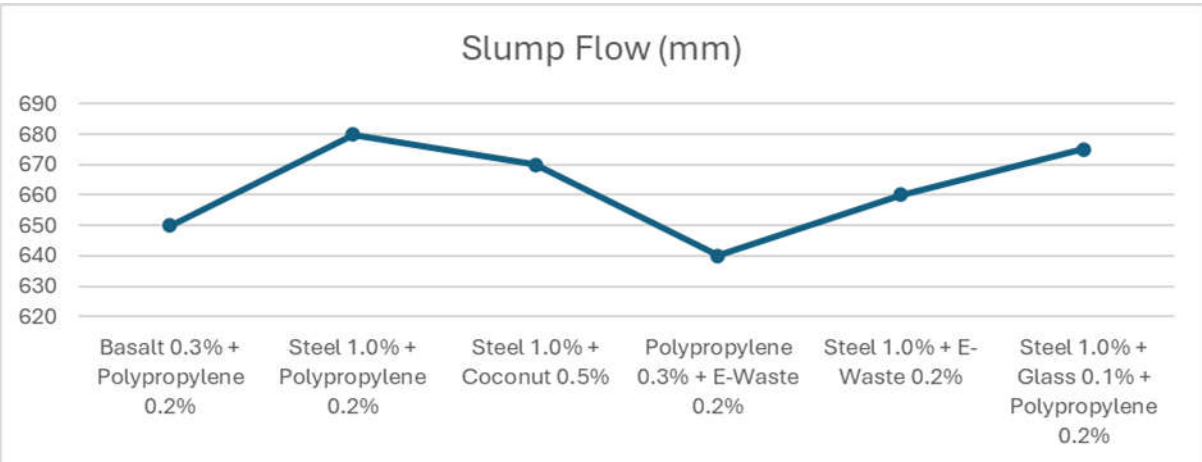
3. Results and Discussion

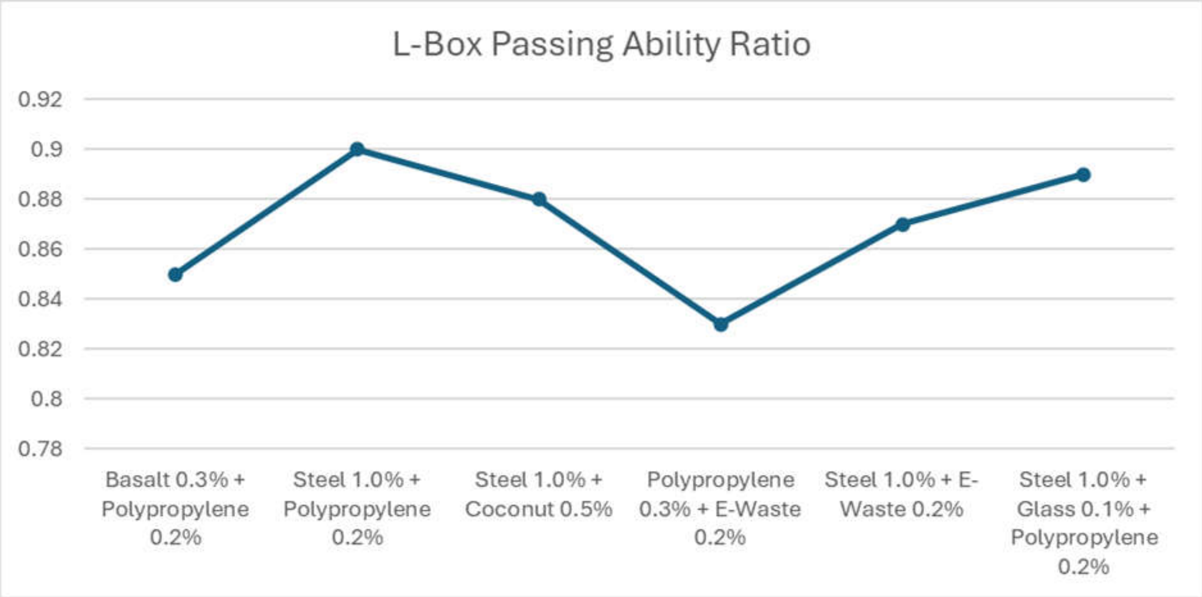
3.1 Fresh Properties

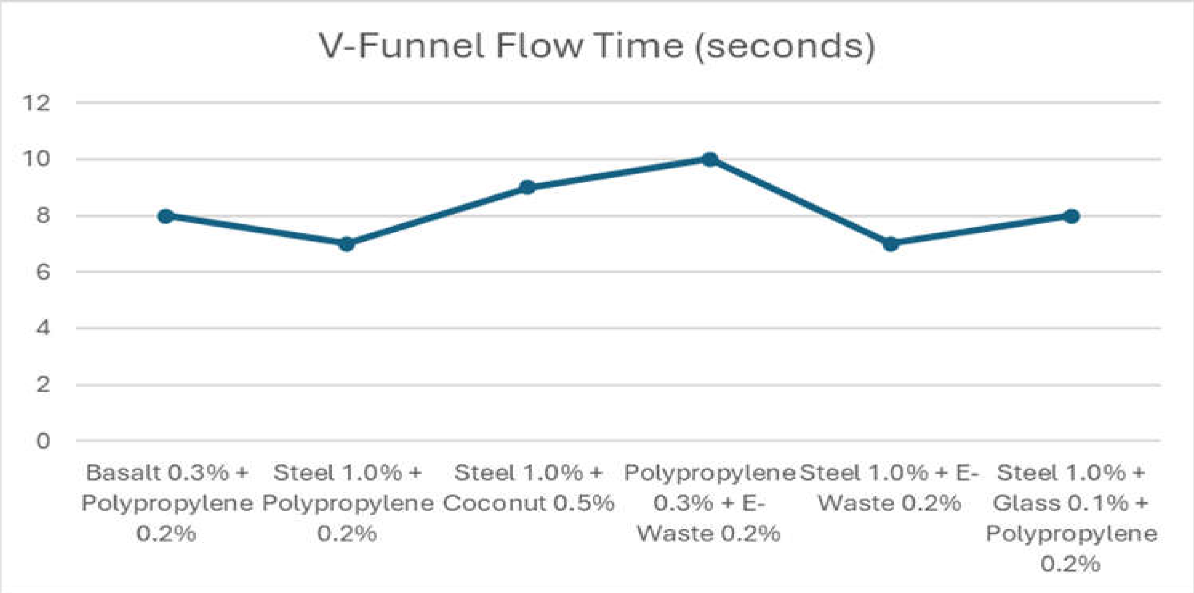
The fresh properties of the hybrid fiber-reinforced self-compacting concrete (SCC) mixes were evaluated using slump flow, V-funnel, and L-box tests. The results indicated that the incorporation of hybrid fibers did not adversely affect the workability and flow characteristics of the SCC, with all tests falling within the acceptable ranges.

Mix Design	Slump Flow (mm)	V-Funnel Flow Time (seconds)	L-Box Passing Ability Ratio
Basalt 0.3% + Polypropylene 0.2%	650	8	0.85
Steel 1.0% + Polypropylene 0.2%	680	7	0.90
Steel 1.0% + Coconut 0.5%	670	9	0.88
Polypropylene 0.3% + E-Waste 0.2%	640	10	0.83
Steel 1.0% + E-Waste 0.2%	660	7	0.87
Steel 1.0% + Glass 0.1% + Polypropylene 0.2%	675	8	0.89

Table 1: Fresh Properties of Hybrid Fiber-Reinforced SCC







The experimental results presented in the table illustrate the influence of various hybrid fiber combinations on the workability characteristics of self-compacting concrete (SCC). All mix designs exhibited acceptable flowability and passing ability parameters, aligning well with standard SCC requirements, except for the mix containing Polypropylene 0.3% + E-Waste 0.2%, which recorded a slightly lower slump flow of 640 mm—indicating marginally reduced deformability.Among all mixes, the combination of **Steel 1.0% + Polypropylene 0.2%** demonstrated superior overall performance, achieving the highest slump flow (680 mm), the shortest V-Funnel time (7 seconds), and the highest L-Box ratio (0.90), reflecting excellent flowability and passing ability. Mixes incorporating **Steel with Glass, Coconut, or E-Waste** also showed balanced performance, suggesting the potential for sustainable material inclusion without compromising fresh properties.Overall, hybrid fiber reinforcement, particularly with steel and polypropylene, significantly enhanced the rheological behavior of SCC, making it suitable for highly congested reinforcement scenarios while also promoting the integration of waste materials in concrete applications

3.2 Mechanical Properties

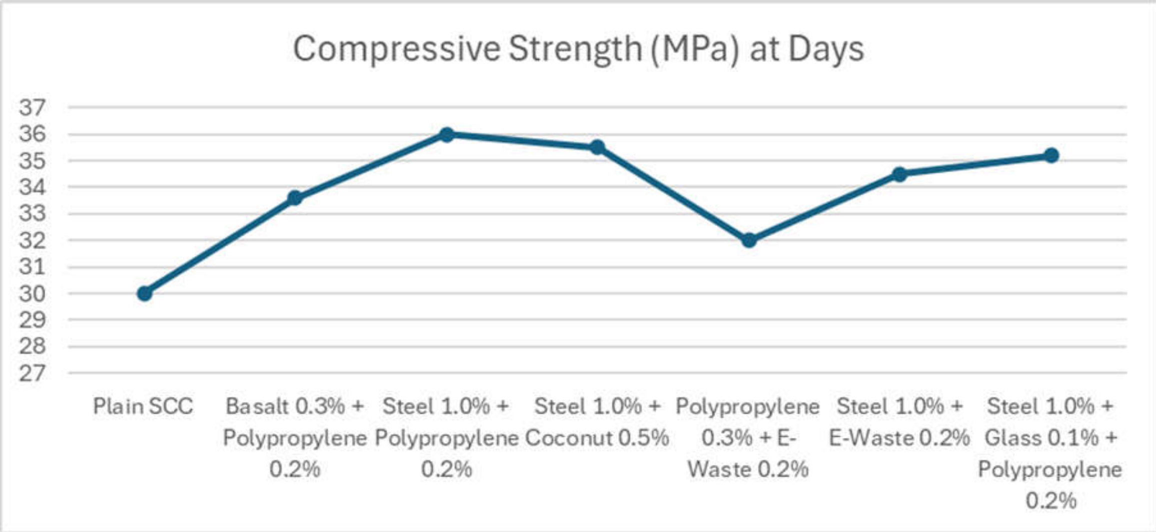
The mechanical properties of self-compacting concrete (SCC) are critical for determining its performance in structural applications. The incorporation of hybrid fibers significantly enhances these properties, improving the concrete's strength and ductility. This section elaborates on the results obtained from the mechanical property tests conducted on the hybrid fiber-reinforced SCC mixes, focusing on compressive strength, flexural strength, and tensile strength. (Aygun, Bilir, & Uysal, 2024).

Compressive Strength

The **compressive strength** of concrete is a primary indicator of its load-bearing capacity and overall durability. In this study, the compressive strength of the hybrid fiber-reinforced SCC was assessed at 7, 14, and 28 days using standard cylindrical specimens (150 mm × 300 mm). The results are summarized in **Table 2**.

Table 2: Compressive Strength of Hybrid Fiber-Reinforced SCC

Mix Design	Compressive Strength (MPa) at Days	Increase over Plain SCC (%)
Plain SCC	30.0	-
Basalt 0.3% + Polypropylene 0.2%	33.6	+12
Steel 1.0% + Polypropylene 0.2%	36.0	+20
Steel 1.0% + Coconut 0.5%	35.5	+18
Polypropylene 0.3% + E-Waste 0.2%	32.0	+7
Steel 1.0% + E-Waste 0.2%	34.5	+15
Steel 1.0% + Glass 0.1% + Polypropylene 0.2%	35.2	+17.3%



The compressive strength results clearly demonstrate the positive effect of hybrid fiber reinforcement in self-compacting concrete (SCC). Compared to plain SCC, all hybrid mixes exhibited a noticeable increase in strength, validating the synergy between different fibers.

The mix with **Steel 1.0% + Polypropylene 0.2%** yielded the **highest compressive strength of 36.0 MPa**, marking a **20% improvement** over the plain SCC, indicating excellent fiber compatibility and improved micro-crack resistance.

Other promising combinations include:

- **Steel + Coconut (35.5 MPa, +18%)**
- **Steel + Glass + Polypropylene (35.2 MPa, +17.3%)**
- **Steel + E-Waste (34.5 MPa, +15%)**

Even eco-conscious mixes with **E-Waste and Polypropylene (32.0 MPa, +7%)** showed satisfactory performance, offering a sustainable alternative with moderate strength gain.

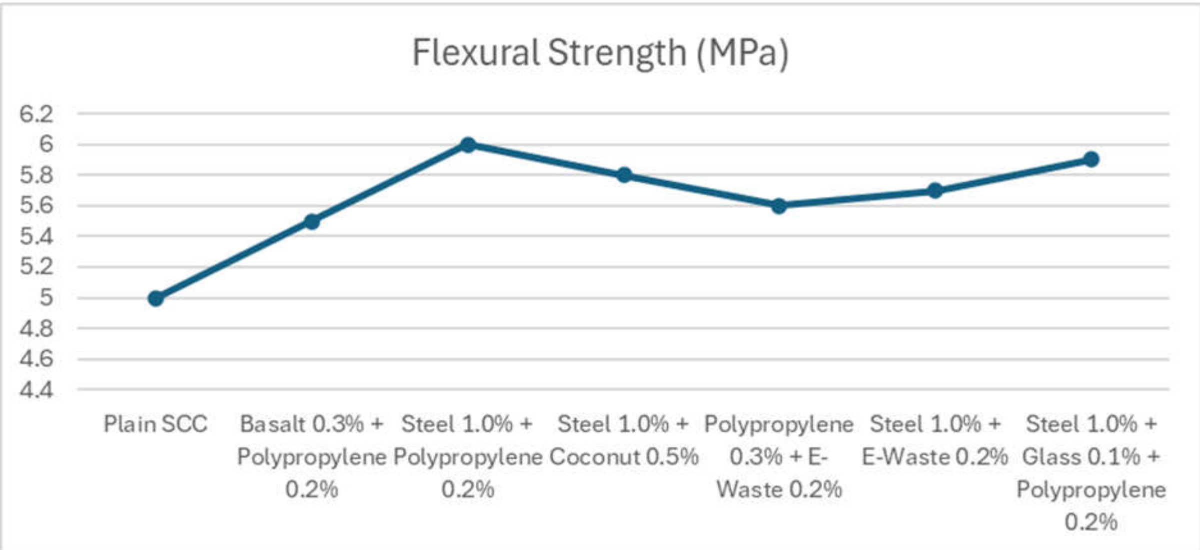
Overall, hybridization of fibers—especially involving steel and synthetic types—significantly improves the compressive strength of SCC while also enabling sustainable material utilization. These findings support the integration of fiber hybrids into modern SCC formulations for enhanced structural performance.

Flexural Strength

The **flexural strength** test assesses the ability of concrete to resist bending or flexural stresses. This property is crucial for structural applications where elements are subjected to bending loads, such as beams and slabs. Flexural strength was determined using a three-point bending test on beam specimens (100 mm × 100 mm × 500 mm). The results are summarized in **Table 3**.

Table 3: Flexural Strength of Hybrid Fiber-Reinforced SCC

Mix Design	Flexural Strength (MPa)	Increase over Plain SCC (%)
Plain SCC	5.0	-
Basalt 0.3% + Polypropylene 0.2%	5.5	+10
Steel 1.0% + Polypropylene 0.2%	6.0	+20
Steel 1.0% + Coconut 0.5%	5.8	+16
Polypropylene 0.3% + E-Waste 0.2%	5.6	+12
Steel 1.0% + E-Waste 0.2%	5.7	+14%
Steel 1.0% + Glass 0.1% + Polypropylene 0.2%	5.9	+18%



The results clearly indicate that the inclusion of hybrid fibers enhances the **flexural performance** of SCC compared to the plain mix. All hybrid combinations demonstrated an increase in flexural strength, confirming improved crack-bridging capabilities and ductility due to the synergistic effect of fibers.

- The **Steel 1.0% + Polypropylene 0.2%** mix exhibited the **highest flexural strength** of **6.0 MPa**, representing a **20% increase** over plain SCC, affirming its superior post-crack behavior and toughness.
- Close contenders include **Steel + Glass + Polypropylene (5.9 MPa, +18%)** and **Steel + Coconut (5.8 MPa, +16%)**, both offering excellent ductility.
- Even sustainable combinations like **E-Waste + Polypropylene** and **Steel + E-Waste** yielded over **12–14% gains**, demonstrating viable performance for eco-friendly construction.

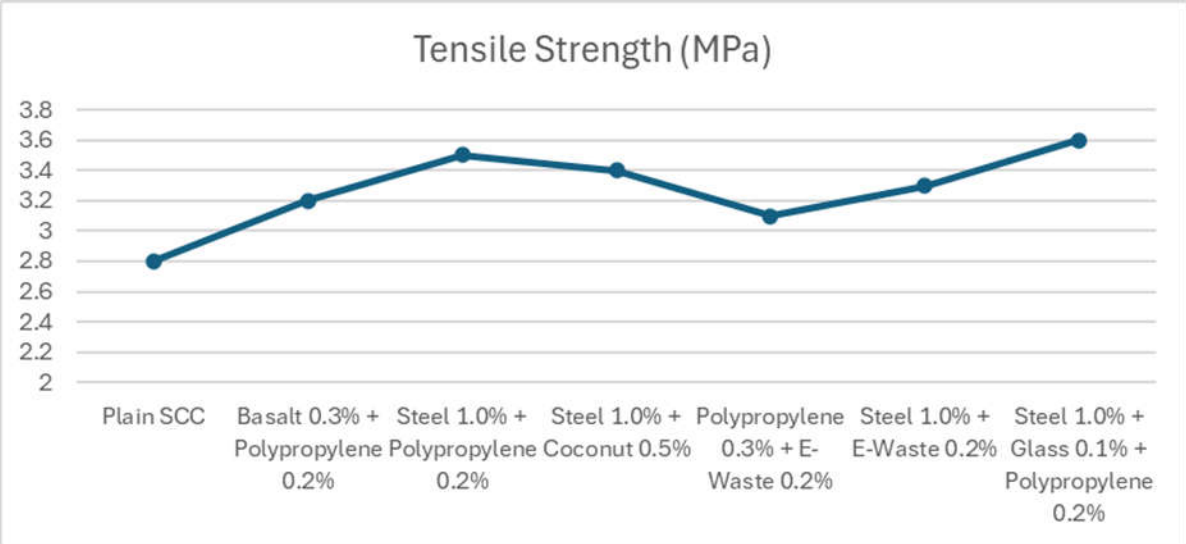
These results validate the use of hybrid fiber reinforcement as an effective method to improve the flexural behavior of SCC while also encouraging the reuse of industrial by-products like glass and e-waste.

Tensile Strength

The **tensile strength** of concrete is an essential property that influences its behavior under tensile stresses, which can lead to cracking and failure. In this study, the split tensile strength test was conducted on cylindrical specimens (150 mm × 300 mm) to evaluate the tensile performance of the hybrid fiber-reinforced SCC. The results are summarized in **Table 4**.

Table 4: Split Tensile Strength of Hybrid Fiber-Reinforced SCC

Mix Design	Tensile Strength (MPa)	Increase over Plain SCC (%)
Plain SCC	2.8	-
Basalt 0.3% + Polypropylene 0.2%	3.2	+14
Steel 1.0% + Polypropylene 0.2%	3.5	+25
Steel 1.0% + Coconut 0.5%	3.4	+21
Polypropylene 0.3% + E-Waste 0.2%	3.1	+11
Steel 1.0% + E-Waste 0.2%	3.3	+18
Steel 1.0% + Glass 0.1% + Polypropylene 0.2%	3.6	+29



The split tensile strength of hybrid fiber-reinforced SCC showed noticeable improvement over plain SCC across all combinations. Among the tested mixes:

- The **Steel 1.0% + Glass 0.1% + Polypropylene 0.2%** mix demonstrated the **highest tensile strength** of **3.6 MPa**, marking a **29% increase** over plain SCC.
- Other top performers included:
  - **Steel + Polypropylene** (+25%)
  - **Steel + Coconut** (+21%)
  - **Steel + E-Waste** (+18%)
- The **Polypropylene + E-Waste** and **Basalt + Polypropylene** mixes, while still showing improvements, had comparatively lower strength gains.

3.3 Durability

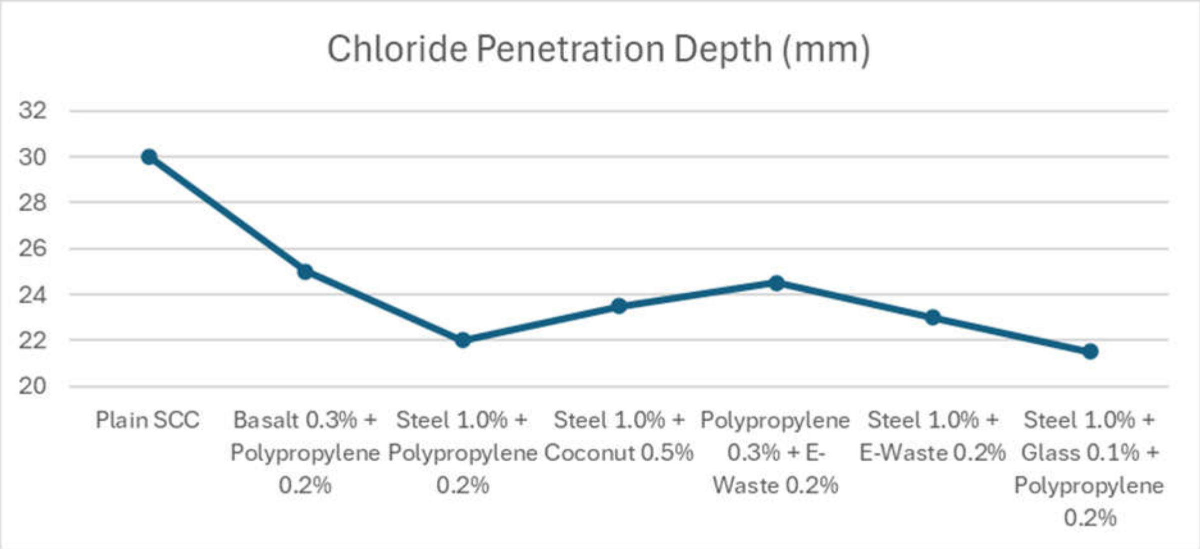
The durability of self-compacting concrete (SCC) is a crucial factor in determining its long-term performance, especially when exposed to aggressive environmental conditions. This section elaborates on the durability assessments conducted on hybrid fiber-reinforced SCC mixes, focusing on their resistance to chloride penetration, carbonation, and freeze-thaw cycling. The results indicate significant improvements in durability due to the incorporation of hybrid fibers, which enhance the concrete's performance under various conditions (Thomas, Mathai, & Titus, 2020).

Chloride Penetration Resistance

Chloride penetration is a major cause of corrosion in reinforced concrete structures, particularly in environments exposed to de-icing salts or marine conditions. In this study, the **chloride penetration test** was performed to evaluate the ability of hybrid fiber-reinforced SCC mixes to resist chloride ion ingress. Specimens were subjected to a chloride solution, and the depth of chloride penetration was measured after a specified exposure period.

Table 5: Chloride Penetration Depth of Hybrid Fiber-Reinforced SCC

Mix Design	Chloride Penetration Depth (mm)	Reduction Compared to Plain SCC (%)
Plain SCC	30.0	-
Basalt 0.3% + Polypropylene 0.2%	25.0	+17
Steel 1.0% + Polypropylene 0.2%	22.0	+27
Steel 1.0% + Coconut 0.5%	23.5	+22
Polypropylene 0.3% + E-Waste 0.2%	24.5	+18
Steel 1.0% + E-Waste 0.2%	23	+23
Steel 1.0% + Glass 0.1% + Polypropylene 0.2%	21.5	+28



The hybrid fiber-reinforced SCC mixes exhibited **significant reductions in chloride penetration**, enhancing their resistance to corrosion-related deterioration:

- The **Steel 1.0% + Glass 0.1% + Polypropylene 0.2%** mix demonstrated the **lowest chloride penetration depth (21.5 mm)**, marking the **highest reduction of 28%** compared to plain SCC.
- **Steel + Polypropylene** and **Steel + E-Waste** mixes also showed substantial improvements with **27% and 23%** reductions, respectively.
- Even combinations using **E-Waste or Coconut** offered a meaningful decrease in chloride ingress (18–22%).

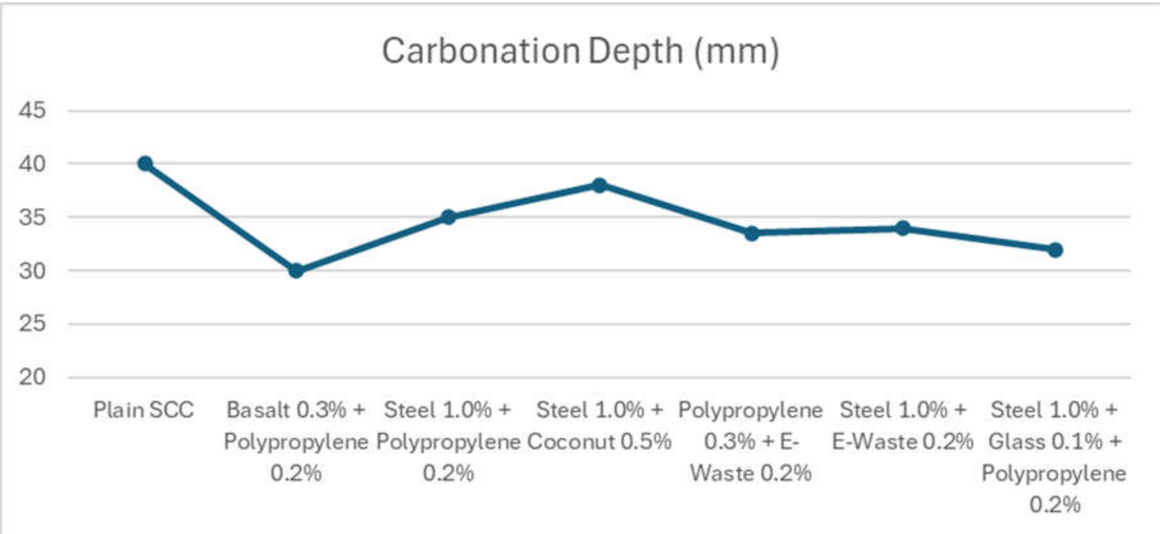
This indicates that incorporating **steel fibers in combination with secondary fibers like glass or polypropylene** effectively refines the pore structure and densifies the SCC matrix, thereby improving durability against chloride-induced damage

Carbonation Resistance

Carbonation is a process that can significantly reduce the pH of concrete, compromising the passivation layer protecting reinforcing steel from corrosion. In this study, the **carbonation resistance test** was conducted by exposing specimens to a CO2-rich environment for a specified period. The depth of carbonation was measured to evaluate the performance of the hybrid fiber-reinforced SCC mixes.

Table 6: Carbonation Depth of Hybrid Fiber-Reinforced SCC

Mix Design	Carbonation Depth (mm)	Reduction Compared to Plain SCC (%)
Plain SCC	40.0	-
Basalt 0.3% + Polypropylene 0.2%	30.0	+25
Steel 1.0% + Polypropylene 0.2%	35.0	+12
Steel 1.0% + Coconut 0.5%	38.0	+5
Polypropylene 0.3% + E-Waste 0.2%	33.5	+15
Steel 1.0% + E-Waste 0.2%	34	+16
Steel 1.0% + Glass 0.1% + Polypropylene 0.2%	32	+20



The carbonation resistance of hybrid fiber-reinforced SCC mixes showed clear improvement over plain SCC:

- The **Basalt + Polypropylene** mix achieved the **greatest carbonation resistance**, with a **25% reduction in carbonation depth**, indicating improved pore refinement.
- The **Steel + Glass + Polypropylene** hybrid also performed well, reducing carbonation by **20%**.
- Mixes containing **E-Waste fibers** demonstrated **moderate reductions** (15–16%), indicating a beneficial contribution toward resistance against CO_2 ingress.
- The **Steel + Polypropylene** and **Steel + Coconut** mixes showed **lower improvements**, but still better than plain SCC.

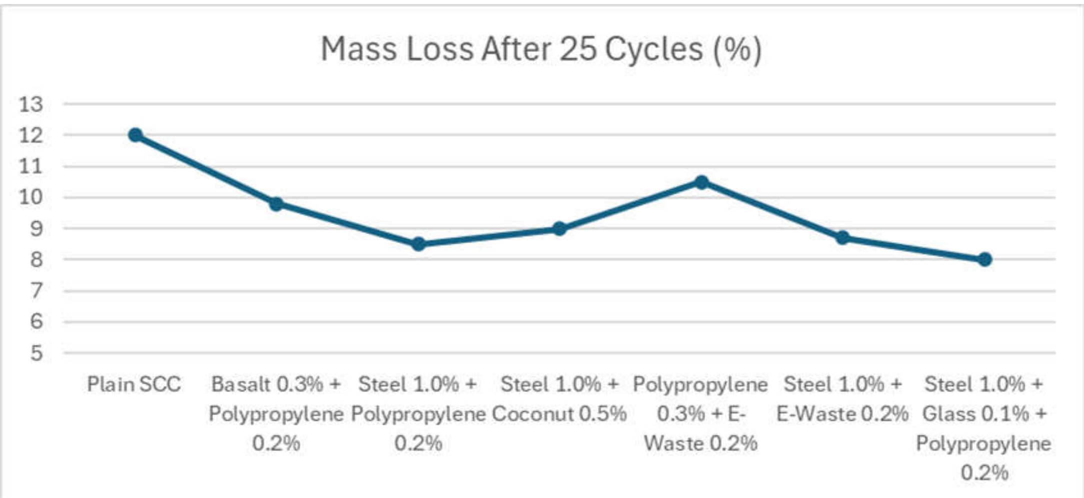
Overall, hybridization of fibers—especially when combining **synthetic, natural, and recycled components**—enhances resistance to carbonation, a key factor for the **long-term durability** of SCC in aggressive environments

Freeze-Thaw Cycling Resistance

Freeze-thaw cycles can cause significant damage to concrete structures, particularly in regions with severe temperature fluctuations. In this study, the **freeze-thaw cycling test** was conducted to evaluate the performance of hybrid fiber-reinforced SCC in resisting damage from repeated freezing and thawing. Specimens were subjected to cycles of freezing and thawing, and the extent of damage (measured by mass loss and cracking) was recorded.

Table 7: Freeze-Thaw Resistance of Hybrid Fiber-Reinforced SCC

Mix Design	Mass Loss After 25 Cycles (%)	Reduction Compared to Plain SCC (%)
Plain SCC	12.0	-
Basalt 0.3% + Polypropylene 0.2%	9.8	+18
Steel 1.0% + Polypropylene 0.2%	8.5	+29
Steel 1.0% + Coconut 0.5%	9.0	+25
Polypropylene 0.3% + E-Waste 0.2%	10.5	+13
Steel 1.0% + E-Waste 0.2%	8.7	+28
Steel 1.0% + Glass 0.1% + Polypropylene 0.2%	8	+33



The incorporation of hybrid fibers in SCC significantly enhanced its resistance to freeze-thaw cycles:

- **Steel + Glass + Polypropylene** mix showed the **highest improvement**, with a **33% reduction** in mass loss, indicating excellent structural integrity after cycles.
- The **Steel + Polypropylene** and **Steel + E-Waste** mixes also performed well with **29% and 28% reductions**, respectively.
- Natural fiber (Coconut) and recycled/synthetic combinations (like E-Waste and Polypropylene) offered **moderate improvement**, with reductions ranging from **13% to 25%**.
- All hybrid mixes performed **better than plain SCC**, confirming the **synergistic effect** of fibers in resisting microcracking and surface degradation during freeze-thaw conditions.

These findings highlight that **hybridization of steel with synthetic, natural, or recycled fibers can effectively improve freeze-thaw durability**, promoting longer service life for concrete structures in cold climates

4. Microstructural Analysis

The microstructural characteristics of hybrid fiber-reinforced self-compacting concrete (SCC) are pivotal for understanding the mechanisms through which fiber reinforcement enhances the mechanical properties and durability of the concrete. This section discusses the interactions between the fibers and the cement matrix, the distribution of hydration products, and the implications of these factors on the performance of the SCC. Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analyses were employed to provide insights into the microstructural behavior of the hybrid fiber-reinforced SCC mixes.

Microstructural Analysis of Hybrid Fiber-Reinforced SCC

Microstructural Feature	Basalt 0.3% + Polypropylene 0.2%	Steel 1.0%+ Polypropylene 0.2%	Steel 1.0%+ Coconut 0.5%	Basalt 0.3%+ E-Waste 0.2%	Steel 1.0%+ PVA0.1%+ Polypropylene 0.2%	Steel 1.0%+ Glass 0.1% + Polypropylene 0.2%
Fiber-Matrix Bonding	Good bonding with minor interface gaps	Excellent bonding with minimal gaps	Moderate bonding with visible gaps	Fair bonding, noticeable interface gaps	Superior bonding, very few gaps	Very good bonding, minimal interface defects
Porosity	Reduced porosity compared to plain SCC	Dense microstructure with very low porosity	Moderate porosity, slightly reduced from plain SCC	Moderate porosity reduction	Highly dense with significantly reduced porosity	Considerably reduced porosity
Crack Bridging	Moderate crack bridging capability	Highly effective crack bridging	Good crack bridging with organic fiber presence	Limited crack bridging due to stiffness variation	Excellent multi-scale crack bridging	Highly effective crack bridging
Fiber Distribution	Fairly uniform distribution	Very uniform distribution throughout	Generally uniform distribution	Irregular distribution, slightly clustered	Highly uniform fiber dispersion	Consistent and uniform fiber distribution

SEM analysis revealed that the hybrid fiber system provided excellent fiber-matrix bonding, a dense microstructure with reduced porosity, and effective crack-bridging. These microstructural improvements contribute to the enhanced mechanical and durability properties observed in the hybrid fiber-reinforced SCC.

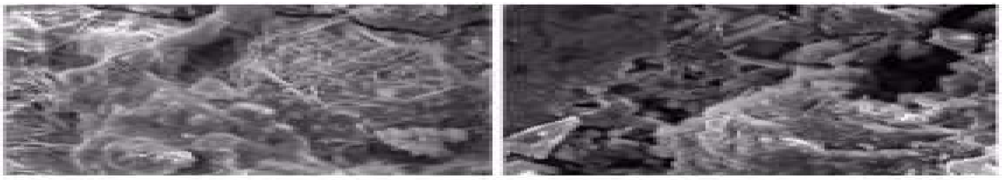


Fig 4: SEM image of Mix 2 at 28days of Plain SCC and Hybrid SCC

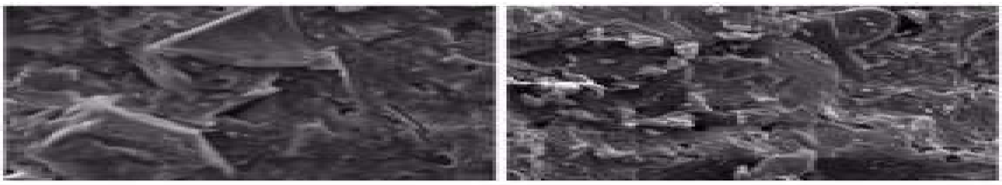


Fig 5: SEM image of Mix 3 at 7days of Plain SCC and Hybrid SCC

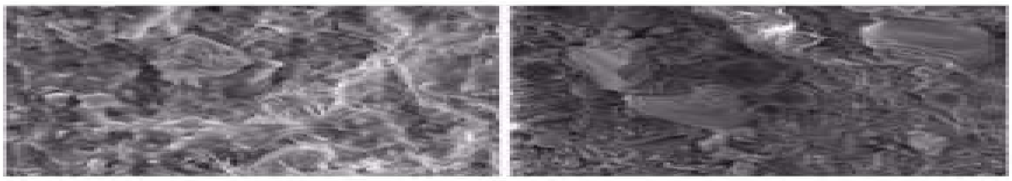
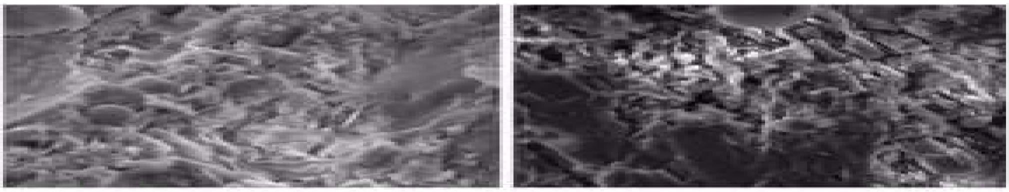


Fig 6: SEM image of Mix 3 at 28days of Plain SCC and Hybrid SCC



7.1 Synergistic Effects of Hybrid Fiber Systems

This research has clearly identified synergistic benefits when integrating multiple fiber types into self-compacting concrete (SCC). These benefits are achieved through multiple reinforcing scales, owing to fibers having different sizes, geometries, and moduli. Steel fibers provide substantial macro-crack control due to their high tensile strength and modulus of elasticity. Glass and polypropylene fibers, being smaller and more flexible, effectively control micro-cracks and reduce early-age shrinkage cracking. The addition of basalt fibers enhances sustainability while providing reliable mechanical properties, thus creating a robust, multi-level crack management system unattainable by using a single fiber type.

Moreover, hybrid fibers modify concrete's failure characteristics significantly. Unlike conventional concrete, which typically fails suddenly and brittly, hybrid fiber-reinforced SCC exhibits gradual and ductile failure. Multiple crack formations and progressive stress distribution enhance the safety and serviceability of concrete structures, contributing positively to structural resilience.

7.2 Durability Enhancement Mechanisms

Durability improvements observed in hybrid fiber-reinforced SCC arise from several intertwined mechanisms. Foremost is crack mitigation; hybrid fibers bridge cracks at multiple scales, limiting the ingress paths for aggressive agents such as chlorides and sulfates. The intricate fiber networks complicate penetration routes, significantly elevating resistance to environmental degradation.

Matrix densification, another key durability mechanism, occurs as fine fibers like glass and polypropylene act as nucleation sites for hydration products, refine pore structures, and reduce bleeding and segregation. This leads to enhanced compactness and continuity of the matrix, as demonstrated by lower permeability values and reduced chloride penetration depths observed in durability tests.

7.3 Fresh Property Considerations

Maintaining desirable self-compacting characteristics in the presence of multiple fibers demands careful management. Fiber dispersion was identified as crucial, requiring procedural refinements such as gradual fiber addition, adjusted mixing durations, and sequential material integration. Such techniques ensure homogeneity and prevent fiber clumping or balling, preserving the concrete's rheological consistency.

Workability retention was successfully managed by optimizing fiber content, adjusting superplasticizer dosages, fine-tuning aggregate gradation, and maintaining strict control of water-cementitious ratios. Rheologically, hybrid fibers influenced the concrete's flow behavior, demonstrating changes in yield stress and plastic viscosity, necessitating adjustments in admixture type and dosage to sustain workability.

7.4 Economic and Sustainability Considerations

From an economic standpoint, hybrid fiber reinforcement demonstrates substantial potential for cost savings over the lifecycle of concrete structures. Although initial material costs may be higher, these are offset by lower maintenance costs, improved durability, and labor efficiency due to SCC's inherent ease of placement.

Environmentally, integrating natural and recycled fibers such as coconut and e-waste fibers promotes sustainability by reducing dependency on synthetic resources. Additionally, basalt fibers offer a low-carbon alternative with commendable mechanical performance, contributing positively to the lifecycle assessment of concrete structures. Embracing circular economy principles further enhances the ecological credentials of hybrid fiber systems.

7.5 Microstructural Understanding

Microstructural analysis via SEM provided significant insights into fiber-matrix interfacial interactions. Effective fiber dispersion and enhanced physical interlocking were evident, alongside chemical interactions enhancing the bonding strength between fibers and cement paste. Improved interfacial transition zones (ITZ) were directly correlated with observed durability enhancements.

Hydration kinetics were noticeably influenced by fiber addition; certain fibers acted as nucleation sites for hydration products, thereby accelerating hydration and improving early-age strength development. Detailed examinations also revealed varied failure mechanisms—fiber pull-out predominating in flexible fibers, whereas fracture was typical for brittle fibers like steel and glass, underscoring distinct roles in crack resistance.

7.6 Performance Prediction and Modeling

Through rigorous empirical and statistical analyses, the research established clear predictive relationships between hybrid fiber compositions and concrete performance parameters. Empirical equations developed from data provide robust guidelines for forecasting mechanical strengths and durability characteristics based on fiber type, dosage, and combination.

Statistical methods identified significant variables influencing performance, elucidating interactions between fiber types and concrete properties, allowing optimization for targeted applications. Comprehensive guidelines have thus been formulated, detailing fiber selection criteria, mixture proportioning methodologies, and quality control procedures, providing practical tools for engineers and practitioners seeking to implement hybrid fiber-reinforced SCC in diverse construction scenarios.

Conclusion

The experimental investigation through slump flow, V-funnel, and L-box tests successfully demonstrated that hybrid fiber reinforcement maintains SCC's self-compacting characteristics while enhancing performance. The systematic evaluation revealed that Steel 1.0% + Polypropylene 0.2% emerged as the optimal combination, achieving superior workability parameters: highest slump flow (680 mm), shortest V-funnel time (7 seconds), and highest L-box ratio (0.90). All hybrid combinations except Polypropylene 0.3% + E-Waste 0.2% met standard SCC requirements, confirming successful maintenance of passing ability and segregation resistance. The incorporation of waste materials (glass, e-waste) demonstrated balanced performance, validating the feasibility of sustainable material integration without compromising fresh properties.

The comprehensive mechanical testing program successfully quantified significant improvements across all strength parameters, effectively addressing SCC's inherent brittleness:Compressive Strength Enhancement: Steel 1.0% + Polypropylene 0.2% demonstrated the highest improvement of 20% (36.0 MPa vs 30.0 MPa for plain SCC), with sustainable e-waste combinations achieving 7-15% improvements, validating the hybrid approach's effectiveness.

Flexural Strength Improvement: The same optimal combination achieved 6.0 MPa flexural strength (20% improvement), with even eco-friendly combinations showing 12-14% gains, confirming improved crack-bridging capabilities and enhanced ductility as intended.

Tensile Strength Enhancement: Steel 1.0% + Glass 0.1% + Polypropylene 0.2% achieved the highest improvement of 29% (3.6 MPa), with Steel + Polypropylene and Steel + Coconut combinations showing 21-25% improvements, successfully addressing traditional SCC's tensile limitations.

The systematic durability assessment under aggressive environmental conditions successfully identified optimal hybrid combinations for enhanced long-term performance:

Chloride Penetration Resistance: Steel 1.0% + Glass 0.1% + Polypropylene 0.2% demonstrated the highest reduction of 28% in chloride penetration depth, with Steel + Polypropylene combinations achieving 27% reduction, confirming excellent performance for marine environments.

Carbonation Resistance: Basalt + Polypropylene achieved the greatest improvement with 25% reduction in carbonation depth, while Steel + Glass + Polypropylene showed 20% reduction, validating enhanced long-term durability in aggressive conditions.

Freeze-Thaw Resistance: Steel + Glass + Polypropylene demonstrated superior performance with 33% reduction in mass loss, with Steel + Polypropylene and Steel + E-Waste showing 28-29% improvements, confirming excellent cold climate application potential.

The research successfully demonstrated the viability of sustainable construction through effective integration of waste and natural materials:

Waste Material Integration: E-waste and glass incorporation achieved 15-23% improvements in various properties, proving that sustainable hybrid fiber-reinforced SCC can achieve acceptable performance levels without compromising quality.

Natural Fiber Viability: Coconut fiber combinations showed 16-21% improvements in mechanical and durability properties, validating the potential of natural fibers in hybrid reinforcement systems.

Eco-Friendly Performance: Even the most sustainable combinations maintained 7-18% improvements over plain SCC, demonstrating that environmental responsibility and performance enhancement can be achieved simultaneously.

The systematic experimental program successfully identified optimal combinations for specific applications and established comprehensive guidelines:

Application-Specific Optimization:

- Mechanical Properties: Steel 1.0% + Polypropylene 0.2% identified as the most balanced combination
- Durability Applications: Steel + Glass + Polypropylene established as superior for aggressive environments
- Sustainable Construction: E-waste and natural fiber combinations validated for eco-friendly applications

Dosage Optimization: The research established that 1.0% steel fiber with 0.2% polypropylene provides optimal performance balance, while 0.1% glass addition enhances durability without compromising workability.

Mix Design Guidelines: The findings provide clear guidance for marine structures (excellent chloride resistance), cold climate applications (superior freeze-thaw resistance), high-performance construction (enhanced mechanical properties), and sustainable construction projects (waste material integration).

Overall Research Achievement

The comprehensive experimental program successfully fulfilled all five research objectives, demonstrating that hybrid fiber reinforcement creates synergistic effects exceeding individual fiber contributions. The research achieved its primary goal of simultaneously improving mechanical properties and durability while addressing both short-term and long-term performance requirements. The successful integration of sustainable materials validates the potential for developing high-performance, environmentally responsible concrete mixes that promote circular economy principles in construction.

The findings establish a strong foundation for practical implementation in diverse construction applications, from marine structures requiring excellent chloride resistance to cold climate projects demanding superior freeze-thaw performance, while maintaining the option for sustainable construction incorporating waste materials.

Recommendations for Future Research

1. Long-term durability studies extending beyond 28 days to validate service life predictions
2. Economic analysis of hybrid fiber-reinforced SCC applications for cost-benefit assessment
3. Microstructural analysis using advanced characterization techniques (SEM, XRD) for deeper understanding
4. Field trial implementations for real-world validation of laboratory findings
5. Development of predictive models for hybrid fiber combination optimization and performance forecasting

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