SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V11I10P106

Volume 11 Issue 10, 55-68, October 2024

Review Article

Impact of Synthetic Fibers on the Performance of High-Volume Fly Ash Self-Compacting Concrete

Mihir B Baldania[1], Mulesh K Pathak[2], Pratik B Somaiya[3], Bhargav H Jaiswal[4], Sahid A Patel[5], Dhaval P Advani[6]

[1,2]*Department of Applied Mechanics, L E College Morbi, Gujarat, India.*
[3]*Department of Applied Mechanics, GEC, Rajkot, Gujarat, India.*
[4,5]*Department of Civil Engineering, L E College Morbi, Gujarat, India.*
[6]*Department of Applied Mechanics, SSEC, Bhavnagar, Gujarat, India.*

[1]*Corresponding Author : mihir.baldania@gmail.com*

Received: 08 August 2024 Revised: 06 September 2024 Accepted: 07 October 2024 Published: 30 October 2024

Abstract *- This research investigates the impact of synthetic fibers on the mechanical and rheological properties of High-Volume Fly Ash Self-Compacting Concrete (HVFASCC). Class F fly ash was utilized to replace 50% and 55% of the cement, while Polyester (PO) and Polypropylene (PP) fibers were incorporated at dosages of 0.1% and 0.15% by weight. A comprehensive assessment of the properties of fresh concrete was carried out by employing the slump flow, V-funnel, L-box, and U-box tests to gauge workability and flowability. At 7, 28, and 56 days, the mechanical characteristics, including compressive, flexural, and tensile strength, were evaluated. Because of increased internal friction, introducing polypropylene fibers reduced flowability while improving workability. Polyester fibers, on the other hand, greatly improved mechanical properties. Optimal strength values were attained using a 50% fly ash blend and 0.15% polyester fiber, yielding enhanced compressive, flexural, and tensile strengths. This study explains how high-volume fly ash and synthetic fibers work together in self-compacting concrete, offering a way to balance fly ash and fiber dosage for better results. The findings also highlight the potential for reducing cement use in environmentally friendly building practices without sacrificing structural soundness.*

Keywords *- Self-compacting concrete, High volume fly ash, Polyester fiber, Polypropylene fibers.*

1. Introduction

Concrete is the predominant construction material owing to its affordability, widespread availability, load-bearing strength, and adaptability in structural uses. Although commonly utilized, standard concrete demonstrates poor tensile strength while possessing compressive solid strength. Self-Compacting Concrete (SCC) is engineered to overcome this constraint by possessing excellent flowability, enabling it to effortlessly occupy voids and navigate through dense reinforcement only under its own weight [1-5].

This problem can be alleviated by integrating short, discrete fibers into the concrete matrix. These fibres increase the post-softening residual stress in concrete compression through improved crack propagation behavior, energy dissipation, toughness, and pseudo-strain hardening. Several studies have examined how different Supplemental Cementitious Materials (SCMs) affect the mechanical characteristics of freshly mixed concrete [6–8].

Fibers, when added to SCC, further enhance the cured concrete’s characteristics. Incorporating fibers into concrete increases fracture energy reduces sudden failure, controls shrinkage, and improves toughness, flexural strength, and tensile strength [9, 10]. However, for fibers to effectively improve SCC, they must exhibit both high Tensile Strength and strong adhesion with the concrete matrix. Also, their flexibility is fundamental to increasing work flexural strength and energy-absorbing capacity [11-15].

Both the fresh and hardened characteristics of SCC may be affected by a number of variables, including fiber type, mass, length, and surface characteristics. For example, by increasing internal friction inside the concrete matrix, the increased surface area of microscopic fibers has a negative effect on workability [16–18].

Glass, basalt, charcoal, steel, polypropylene, polyester, nylon, jute, and coconut coir fibers are a few of the most often utilized fibers on the market. Fibers, especially preferred by the construction sector, have various advantages, including being cheap, easily purchased, long-lasting, high-tension capable, and anti-cracking. These fibers are used in guard rails, waterproof layers, tunnel linings, and sprayed concrete [19, 20]. Current research shows that new fibers –

polypropylene and polyester in particular – enhance the strength of concrete and impart increased mechanical performance. Polypropylene fibers are appreciated for reducing plastic shrinkage and preventing the formation of cracks that add capacity to lasting concrete structures [21, 22].

Likewise, the suitability of polyester fibers, such as high tensile strength and chemical resistance, makes them suitable for use in environments exposed to rigor or high temperatures [23]. Being synthetic fibers, they do not degrade with time, and durability is essential for their use in key infrastructural projects.

Synthetic fibers are beneficial in several applications, dealing with quality, equal dimensions, and shapes. Despite being reusable and biodegradable, natural fibres such as jute, sisal, and hemp have no fixed properties because they are bioproducts, making their mechanical features in concrete unpredictable [24].

Natural fibres absorb water in damp conditions, and hence, their bonding strength with the concrete matrix is reduced and, consequently, low durability [25]. For massive construction applications, synthetic fibers get better adhesion with concrete and do not pose this problem.

Although the manufacturing of synthetic fibers has an impact on the environment by utilizing non-renewable resources, natural fibers are much more beneficial to the environment. Natural fibers, characterized by their renewable and biodegradable properties, significantly reduce carbon footprints. Nonetheless, chemical treatments are frequently necessary to improve their performance in concrete, especially regarding moisture resistance and durability [26].

Recent findings indicate that hybrid fiber systems, which integrate natural and synthetic fibers, can provide a balanced solution by utilizing synthetic fibers' mechanical strength while capitalizing on the eco-friendliness of natural fibers. Considering the significance of sustainability, hybrid systems are important in the applications of geopolymer concrete [22].

Natural fibers are constantly outperformed by synthetic fibers like polyester and polypropylene regarding mechanical strength, durability, as well as resistance to cracking. The environmental advantages of natural fibers are significant, and continued research into hybrid fiber systems and enhanced treatments for natural fibers may improve their performance, rendering them more competitive with synthetic fibers in sustainable construction practices.

In recent years, using industrial byproducts as mineral admixtures instead of Portland cement has emerged as an efficient strategy to diminish cement content and carbon emissions in Self-Compacting Concrete (SCC). FA is among the most often utilized additional cementitious materials in SCC. Despite its potential, the lack of resources and awareness limits the widespread use of FA [27, 28]. Approximately 800 million tons of FA are generated every year, and a large amount of this is dumped in landfills, raising environmental issues [29–34].

Therefore, FA's potential to lower greenhouse gas emissions is a key component of supporting sustainable construction. However, incorporating synthetic fibers into the HVFASCC causes workability and flowability problems. The combination of fibres and higher FA content usually results in better interface friction and reduced workability; therefore, it is difficult to obtain a desirable level of mechanical properties and workability simultaneously. In order to determine the best combination for the appropriate and coherent flow properties, strength, and durability of SCC, extensive study is anticipated to be necessary due to the combined effects of the fiber type, fiber dosage, and FA concentration.

This study evaluates HVFASCC with varying percentages of Polyester (PO) and Polypropylene (PP) fibers, considering how these fiber proportions affect the mechanical and fresh qualities of SCC. The difficulties of adding fibers to HVFASCC are addressed in this paper, which also provides important information on the mechanical characteristics and workability of SCC. The construction industry can use the information obtained from the results to implement high-performance, sustainable SCC using less cement. The synergy of fibers and FA favors waking up an environmentally liberal conscience that ensures the affordability of green constructions that conform to world sustainable standards.

2. Materials and Methods

2.1. Cement and Fly Ash

Cement and FA were utilized as cementitious materials. 53-grade OPC is conforming to BIS 12269-1999, which has been employed. Class-F FA from Wanakbori Thermal Power Station, Gujarat, adhering to BIS 3812-2013, has been utilized in this experiment. Figure 1 shows its SEM image. Table 1 presents the chemical components of OPC and fly ash.

Table 1. Chemical & physical properties of cement and flyash

Chemical Properties		
Constituent	**Cement**	**Fly ash**
CaO	66.2	4.8
SiO_2	18.3	57.2
Al_2O_3	4.2	26.3
Fe_2O_3	3.26	6.2
SO_3	3.92	0.34
K_2O	0.7	1.2
MgO	1.4	0.5
LOI	1.2	2.8
Physical Properties		
Specific gravity	3.15	2.43
Density (kg/m^3)	3140	1710

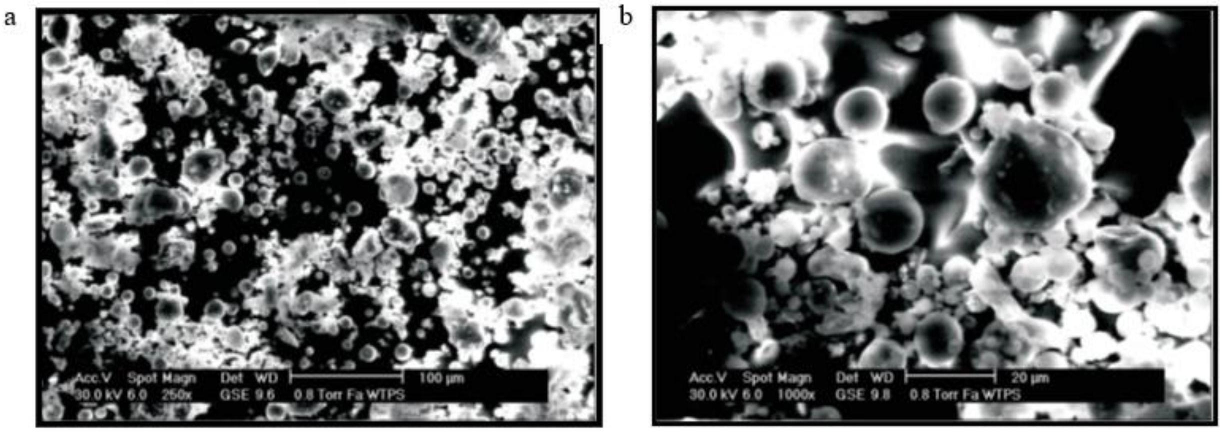

Fig. 1 SEM of Fly ash (a) Spot 1, and (b) Spot 2.

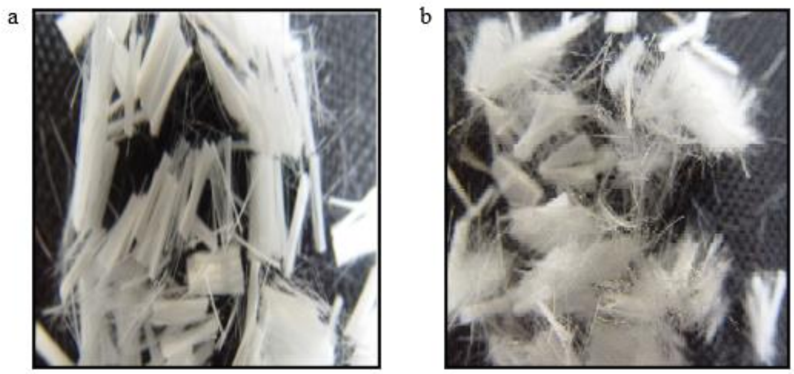

Fig. 2 Images of (a) Polyester Fiber, and (b) Polypropylene fiber.

2.2. Coarse and Fine Aggregate

Locally available Particle sizes <4.75mm are considered coarse aggregates, whereas those smaller than 4.75mm have been considered fine aggregates. The coarse aggregates that have been utilized in the current research are divided into two sizes: 10mm and 20mm. Table 2 displays the essential features that both FA and CA must possess. The materials satisfied all the requirements given in IS 383:2016.

Table 2. Properties of aggregates

Properties	CA		FA
	20mm	10mm	-
Specific Gravity	2.78	2.78	2.63
Water Absorption (%)	0.32	0.32	0.74
Crushing Value (%)	18.23	-	-
Impact Value (%)	21.66	-	-
Abrasion Value (%)	16.68	-	-
Flakiness Index (%)	16.26	-	-
Elongation Index (%)	18.89	-	-
FM	6.87	5.34	3.29
Density (kg/m^3) (SSD)	1626	1548	1692

2.3. Fibers

Figure 2 illustrates the two types of Virgin triangular monofilament fibers employed in the production of HVFASCFRC. Table 3 displays the characteristics of the fibers.

2.4. Superplasticizer and Viscosity Modifying Agent

To achieve optimal workability and flowability while minimizing the amount of water and powder utilized, the polycarboxylic-based Superplasticizer (PC) Sika Viscocrete 2100 and the Viscosity Modifying Agent (VMA) Sika Stabilizer-4 R were employed. These additives were chosen to prevent bleeding and segregation and enhance the mixture's cohesiveness.

2.5. Mix Composition

Ten different SCC mixture compositions were developed for this study. By replacing 50% and 55% of the total cementitious material by weight, Fly Ash (FA) was utilized in place of cement. Conversely, Polyester (PO) and Polypropylene (PP) fibers were added to the fiber-free control concrete mix at volume percentages of 0.1% and 0.15%, respectively. Following preliminary testing, the ideal workability was attained by optimizing the superplasticizer content to 1.3% of the cementitious material. This proportion was adjusted in subsequent mix designs, increasing in line with higher fiber content. Viscosity Modifying Agents (VMA) were added at a dosage of 10% of the superplasticizer volume to enhance mixture cohesion and prevent segregation. The purpose of these changes in fly ash substitution, fiber content, and additives was to assess how they affected the fresh and hardened qualities of SCC. The precise composition ratios for each combination are shown in Table 4.

2.6. Mix Procedure

The mixing process was carefully organized to guarantee consistency and repeatability. FA is a supplementary cementitious material that is frequently utilized in SCC. The

Table 3. Properties of fiber

Property	Recron 3S Polyester Fiber	Recron 3S Polypropylene Fiber
Chemical Composition	Made from Polyethylene Terephthalate (PET)	Made from polymerized propylene
Length(mm)	12	12
Effective Diameter (μ)	20-40	25-40
Specific Gravity	1.34	0.90
Elongation (%)	30 to 50	65 to 90
Thermal Properties (°C)	260	175
Tensile Strength (GPa)	>4	3-4
Elasticity (GPa)	>5	>4
Moisture Absorption	Low moisture absorption	Deficient moisture absorption, hydrophobic
Alkaline Stability	Good	Good
Dispersion	Excellent	Excellent

Materials were combined in a dry state for 2 minutes to ensure proper homogenization. The fibers (if applicable) were then added after 80% of the total water. The VMA (Sika Stabilizer-4R) and superplasticizer (Sika Viscocrete 2100) were progressively added to the remaining 20% water. Fibrous mixtures were mixed for five minutes instead of four minutes for non-fibrous mixtures to ensure fiber distribution in the concrete matrix.

2.7. Testing Methodology

Within fifteen minutes after adding water to the mixture, the testing procedures were carefully completed to assess the rheological characteristics and workability of SCC with and without fibers. This controlled timeframe ensured that the fresh concrete properties were assessed before any significant hydration could occur, preserving the accuracy of the results.

According to Ref. [35], the U-Box, slump flow, L-Box, V-funnel, Slump Flow T50, as well as V-funnel T5 tests were the main tests used in this investigation. These tests are well known for determining SCC's flowability, passing ability, and viscosity, ensuring a thorough analysis of its novel qualities. Figures 3 and 4 show photographs of testing equipment.

The study investigated how adding Polyester (PO) and Polypropylene (PP) fibers affected the mechanical characteristics and workability of SCC, particularly when FA had been employed in place of some of the cement. Fifty percent FA and fifty-five percent FA were used to prepare two sets of SCC samples. Three different fiber content variations were included in each set: 0%, 0.1%, and 0.15%. This made it possible to compare the performance gains generated by adding fibers. The SCC's uniformity and workability were evaluated using the slump flow test. After filling a conventional slump cone containing freshly mixed SCC free of vibration and compaction on a level, smooth base plate, the cone was elevated vertically to disperse concrete. To assess the SCC's flowability and homogeneity, the spread diameter was measured twice perpendicularly, and the average of these measurements was computed. To gain information into the viscosity of SCC, the time it needed for concrete to reach a 50cm diameter was also recorded (Slump Flow T50).

Table 4. Details about concrete mix proportions (one cubic meter)

	M25									
	50 % Fly Ash					55 % Fly Ash				
	0 %	Polyester Fiber		Polypropylene Fiber		0 %	Polyester Fiber		Polypropylene Fiber	
		0.1 %	0.15 %	0.1 %	0.15 %		0.1 %	0.15 %	0.1 %	0.15 %
Cement (kg/m³)	239					215.1				
FA (kg/m³)	239					262.9				
“Fine Agg. (kg/m³)	896					912				
Coarse Agg. (kg/m³)	772					788				
Water (kg/m³)	188					188				
SP (l/m³)”	6.21	6.69	6.93	6.69	6.93	6.21	6.69	6.93	6.69	6.93
VMA (l/m³)	0.62	0.66	0.69	0.66	0.69	0.62	0.66	0.69	0.66	0.69
Fiber (kg/m³)	-	0.48	0.72	0.48	0.72	-	0.48	0.72	0.48	0.72

Fig. 3 Slump flow test

The flow properties of SCC were evaluated by employing the V-funnel test. Freshly mixed SCC was poured into the V-funnel immediately after mixing, allowing it to flow into the funnel's upper half. The bottom hole was opened once everything was complete, and the time it took for the concrete to pass through it had been accurately noted. The duration—also known as the V-funnel flow time—offered a simple evaluation of the SCC's flowability.

To evaluate the concrete's segregation resistance, the V-funnel T5 test entailed filling the funnel with SCC and leaving it undisturbed for five minutes. The bottom hole was opened after the five-minute break, and the time it took for concrete to pass through was noted. In order to ensure stability and resistance to segregation, the T5 test assesses concrete's capacity to retain its flow characteristics over time.

The fluidity and passing capabilities of SCC were evaluated using the U-Box test. The process included pouring self-compacting concrete into one half of a U-shaped container. After filling the compartment, the gate separating the two sections was raised, allowing the SCC to move into the adjacent compartment. After a period of 10 seconds, the height of the concrete in each compartment was documented. The height variation between the two sections underscored the fluidity and passing capability of the SCC, with a more negligible difference indicating enhanced flow. It minimized obstructions in the movement of the concrete.

The SCC's filling capacity had been evaluated by employing the L-box test. The SCC was quickly moved into the vertical portion of the L-shaped formwork after the mixing procedure was finished. After the vertical segment was filled, the gate between the vertical and horizontal sections was raised to allow concrete to flow into the horizontal section. At the beginning (H1) and end (H2) of the horizontal stretch, concrete height measurements were taken.

The filling capacity of the SCC was established by computing the ratio of the two heights (H2/H1). The ratio serves as an indicator of the SCC's capability to flow unobstructedly and adequately fill the mould, where an increased ratio signifies enhanced filling capacity.

Fig. 4 L box test

Standard concrete specimens were cast and allowed to cure for 7, 28, and 56 days to assess their compressive, flexural, and Tensile Strength. Cube specimens of 150mm×150mm×150mm were used in compressive strength testing in compliance with IS: 516.

These specimens were exposed to a constant compressive load until they failed. In accordance with IS: 5816, flexural strength tests had been conducted on beam specimens of 100mm×100mm×500mm. A three-point bending configuration was used, and the load was placed at the midpoint of the beam. The split-cylinder method described in IS: 516 was used to test cylindrical specimens of 150mm in diameter and 300mm in height for Tensile Strength. In order to determine the material's resistance to tensile stresses, these specimens were subjected to a diametral compressive load until splitting occurred along the vertical plane.

The laboratory environments were continuously monitored during the tests. It was observed that the temperature ranged from 27°C to 30°C, and the humidity ranged between 65% and 75%.

3. Result and Discussion

3.1. Slump Flow

It refers to the capacity of concrete to flow within different constructions. Furthermore, the duration for concrete to spread across a 50 cm circumference accurately reflects its capacity to move effortlessly and without separation. Figure 5 and Table 5 display HVFASCC slump flow measurements with and without Fibers. When both PO and PP fibers are added to concrete mixtures, the slump flow is significantly reduced, indicating a decrease in workability. Higher fiber doses (0.15%) because a more pronounced decline compared to smaller dosages (0.1%). The decrease in flow happens due to the fibers enhancing internal friction inside the mixture impending its movement and extensive surface area of the fibers. Concrete's fresh and rheological qualities are adversely affected by a broad surface area, which causes the concrete to spread over a vast region and hinders its movement.

Table 5. Relative change in SCC workability and flowability with different fibers and fly ash content

Property	Fly Ash Content	0% Fiber	0.1% PO Fiber	0.15% PO Fiber	0.1% PP Fiber	0.15% PP Fiber
Slump Flow (mm)	50% FA	703	681 (-3.13%)	663 (-5.69%)	660 (-6.11%)	648 (-7.82%)
	55% FA	678	665 (-1.92%)	652 (-3.83%)	670 (-1.18%)	643 (-5.16%)
T_{50cm} Slump Flow (sec)	50% FA	4	4.5 (+12.50%)	4.7 (+17.50%)	4.1 (+2.50%)	4.9 (+22.50%)
	55% FA	3.9	4.9 (+25.64%)	4.3 (+10.26%)	4.6 (+17.95%)	5.6 (+43.59%)
V Funnel (sec)	50% FA	9.5	9.8 (+3.16%)	11.1 (+16.84%)	10.3 (+8.42%)	12.9 (+36.32%)
	55% FA	10.4	10.2 (-1.92%)	12.5 (+20.19%)	11.3 (+8.65%)	14.2 (+36.54%)
V Funnel $T_{5\ min}$ (Sec)	50% FA	10.8	12.1 (+12.04%)	13.3 (+23.15%)	13.7 (+26.85%)	14.2 (+31.48%)
	55% FA	11.6	12.3 (+6.03%)	14.6 (+25.86%)	13.8 (+18.97%)	16.6 (+43.10%)
L-Box	50% FA	0.893	0.873 (-2.24%)	0.846 (-5.26%)	0.859 (-3.80%)	0.827 (-7.39%)
	55% FA	0.832	0.839 (+0.84%)	0.823 (-1.08%)	0.830 (-0.24%)	0.801 (-3.73%)
U-Box	50% FA	11.2	11.3 (+0.89%)	12.1 (+8.04%)	14.6 (+30.36%)	15.8 (+41.07%)
	55% FA	9.9	9.8 (-1.01%)	13.3 (+34.34%)	13.9 (+40.40%)	14.4 (+45.45%)

*Note: Figures in parentheses show the relative change compared to the 0% fiber mix.

The impact of the 55% FA mixture is more noticeable than that of the 50% FA mixture, demonstrating that including fibers exacerbates the decline in workability.

The slump flow is most significantly reduced when using a dosage of 0.15% PP fiber, indicating a more substantial effect on diminishing workability. These findings corroborate the findings of earlier researchers [36].

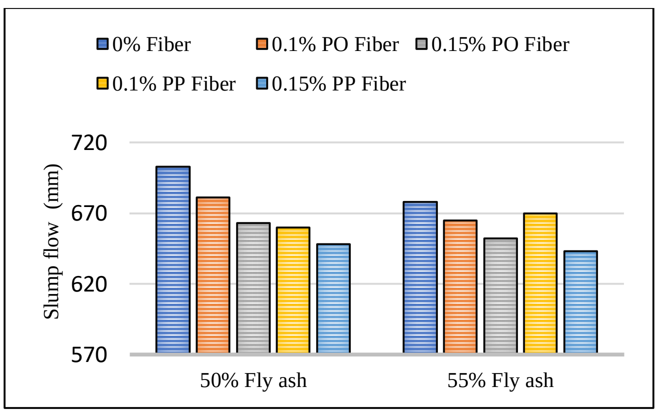

Fig. 5 Slump flow test results of the concrete with various fiber content

The slump flow T_{50cm} data for HVFASCC with and without fibers is presented in Figure 6. Both PO and PP fibers significantly increased the slump flow time (T50cm) when added to concrete mixtures, suggesting a decrease in workability. Higher fiber doses (0.15%) yield a more substantial increase compared to lower dosages (0.1%).

Greater internal friction, impeding the concrete mix's flow. Slump flow time increases most significantly when a dosage of 0.15% PP fiber is added. The 55% fly ash effect is more noticeable than the 50% mixture, suggesting that adding fibers exacerbates the workability loss [1].

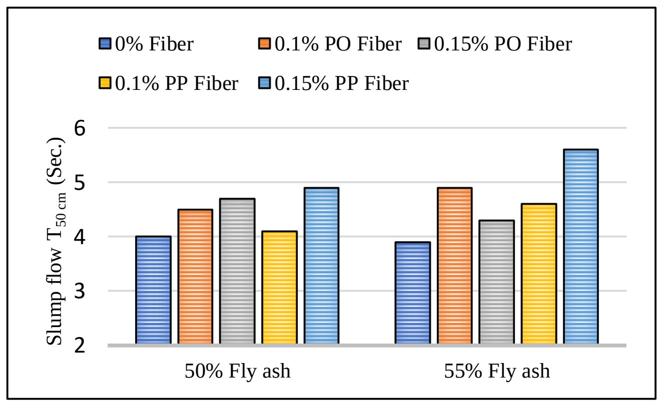

Fig. 6 $T_{50\ cm}$ slump flow test results of the concrete with various fiber content

3.2. V-Funnel Tests

SCC V-Funnel test findings demonstrate that fibers affect flow time, with 0.1% PO Fiber and 0.1% PP Fiber performing best. At 50% fly ash, 0.1% PP Fiber has the shortest flow time (10.3 seconds), whereas 0.1% PO Fiber has the shortest at 55%. These fibers increase mix viscosity and reduce blockage, improving flow. Fly ash content increases flow times by 55% compared to 50%. Higher fly ash content reduces mix cohesiveness, slowing V-Funnel flow.

Fibers improve the mix's structural integrity, although excessive fiber concentration slows the flow at higher dosages (0.15%). All HVFASCC combinations' V-funnel outcomes were evaluated at 9-14 seconds. Figure 7 shows that fiber type affected findings. Fiber-containing concrete moves more slowly through the V-funnel outlet. Due to the fibres' large surface area, fresh concrete passes slower—the flow times of all HVFASCC combinations, as measured by the V-funnel $T_{5\ min.}$ The test ranged from 11 to 17 seconds. These flow times were observed to be affected by both the fiber used, as depicted in Figure 8. The most extended amount of time was required for the concrete to pass through the V-funnel's outlet when PP fibers were added. This is explained by the fiber's larger surface area, which slows the flow of newly mixed concrete [13].

3.3. U Box Tests

The U-Box test results for SCC illustrate the impact of fiber content, fiber type, and fly ash content on passing ability (H2-H1). The addition of fibers improves passing ability, with 0.15% PP Fiber showing the highest enhancement, followed by 0.1% PP Fiber and 0.15% PO Fiber. Polypropylene (PP) fibers are more effective than Polyester (PO) fibers in improving workability. Comparatively, SCC with 50% fly ash demonstrates higher passing ability than SCC with 55% fly ash, indicating better workability at the lower fly ash content. Increased fly ash content negatively affects passing ability, suggesting a trade-off between fiber addition and fly ash content for optimal workability. Figure 9 these results highlight how crucial fiber type and dosage are to maximizing the performance of SCC. Table 5 also represents the relative change in SCC workability and flowability with different fibers and fly ash content.

3.4. L Box Tests

Figure 10 displays the L-box values of samples. Adding Polyester (PO) and Polypropylene (PP) fibers consistently reduces the passing ratio compared to the control mix with 0% fiber. Higher fiber concentrations (0.15%) outcomes in a more significant decline in the passing ratio than lower concentrations (0.1%), indicating decreased flowability and workability due to increased internal friction. Polypropylene fibers have slightly more impact flowability than polyester fibers, especially at higher concentrations. Furthermore, compared to SCC with 55% fly ash, SCC with 50% FA shows a greater passing ratio, indicating that a higher FA content further diminishes workability.

3.5. Impact of Fly Ash Content and Fiber on Workability

Also, the amount of fly ash replacement significantly influences SCC's workability. As the fly ash content increases to 55%, the flowability of the mix decreases due to increased internal friction within the concrete matrix. FA particles have a greater surface area than cement particles due to their finer size, which increases the amount of water needed and reduces the free flow of the mixture. Furthermore, a combination with a larger fly ash percentage tends to be less cohesive, which increases its susceptibility to segregation and slows down flow rates.

The test results demonstrate this with SCC containing 50% fly ash continuously exhibiting superior fluidity and quicker flow rates compared to the 55% fly ash mix. The 50% fly ash mix retains better workability because it maintains an optimal balance between particle size, cohesiveness, and flowability, improving ease of placement and reducing segregation.

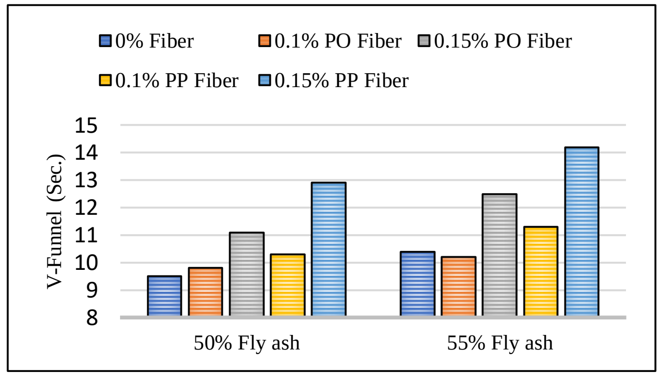

Fig. 7 V funnel test results of the concrete with various fiber content

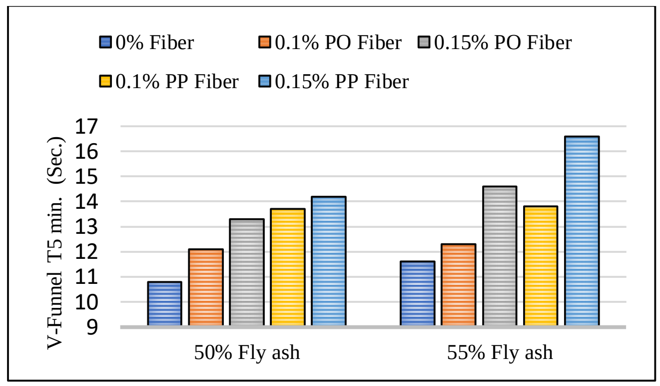

Fig. 8 V funnel T_{5min} test results of the concrete with various fiber content

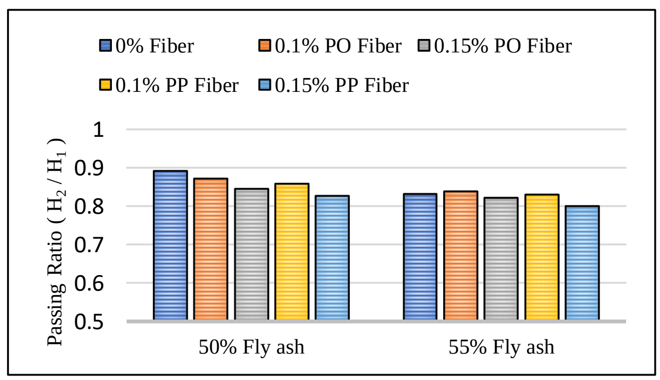

Fig. 9 U-box test results of the concrete with various fiber content

According to the outcomes of slump flow, T50, as well as V-funnel experiments, the inclusion of Polypropylene (PP) fibers in SCC decreases flowability. The fibers' greater internal friction within the concrete matrix is the reason for this drop in flowability. PP fibers' stiffness and rise in hydrophobic nature resistance during flow, limiting the concrete’s ability to spread or pass through congested areas. The large surface area of the fibers further reduces fluidity by enhancing internal friction. Prior research has shown that fibers decrease workability by restricting the movement of the mix [11]. Higher fiber dosages exacerbate this effect. Increased fiber volume leads to more internal entanglement, further hindering flowability, consistent with other studies [13, 36].

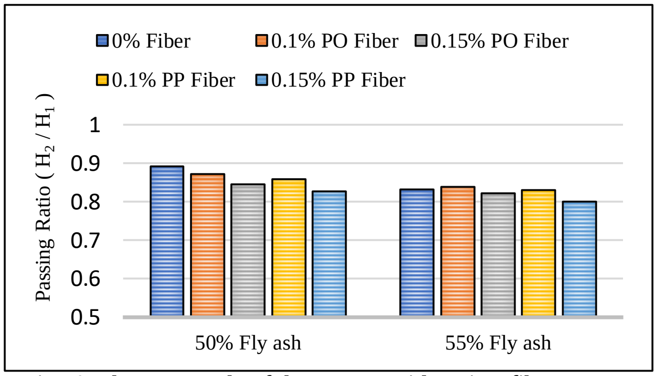

Fig. 10 L-box test results of the concrete with various fiber content

The mechanical qualities of SCC, including its tensile strength, flexural toughness, and crack resistance, are enhanced by PP fibers, despite the fact that they decrease flowability [13]. This trade-off between improved strength and decreased workability is crucial when creating SCC blends. In construction applications requiring high fluidity, such as heavily reinforced structures, careful calibration of superplasticizer dosages is necessary to maintain workability. Studies also emphasize optimizing fiber dosage and admixture content to balance fresh and hardened properties [23, 13].

3.6. Compressive Strength of Concrete

Figure 11 and Table 6 present the compressive strength of the samples with and without fibers at 7, 14, and 56-day test durations. The results of the 50% FA SCC samples demonstrate that adding fibers significantly increases compressive strength. After seven days, the samples with 0.1% and 0.15% PO fiber had compressive strengths that were roughly 4.12% and 6.41% higher than the fiber-free control sample. When PP fiber was added at quantities of 0.1% and 0.15%, there were corresponding increases of 2.00% and 4.77%, respectively. After 28 days, the compressive strength improvements have been more noticeable. The samples with 0.1% and 0.15% PO fiber exhibited increases of 7.03% and 11.39%, respectively. On the other hand, the samples with 0.1% and 0.15% PP fiber showed increases of 3.48% and 6.78%, respectively. The 0.15% PO fiber samples exhibited the maximum compressive strength after 56 days, with a 16.25% increase. The 0.1% PO fiber samples had a 12.64% increase in compressive strength. The PP fiber samples exhibited 5.04% and 14.48% enhancements for concentrations of 0.1% and 0.15%, respectively.

Similarly, as illustrated in Figure 12, fiber incorporation increased the compressive strength of the 55% fly ash SCC samples, albeit not as much as the 50% fly ash samples. After 7 days, the fiber samples with a concentration of 0.1% and 0.15% of PO showed increases of 1.31% and 1.37%, respectively. On the other hand, the fiber samples with a concentration of 0.1% of PP showed a little drop of 0.83%. While the samples with a concentration of 0.15% showed an Increase of 4.29%. After 28 days, the compressive strength of the 0.1% PO fiber samples grew by 2.79%, and the compressive strength of 0.15% PO fiber samples increased by 6.94%.

Similarly, the comparable PP fiber samples experienced a 1.47% rise in compressive strength for the 0.1% concentration and a 3.95% increase for the 0.15% concentration.

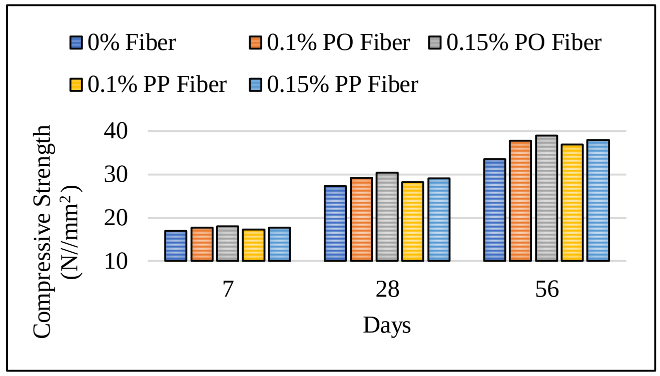

Fig. 11 Compressive strength results of the 50% fly ash with various fiber content

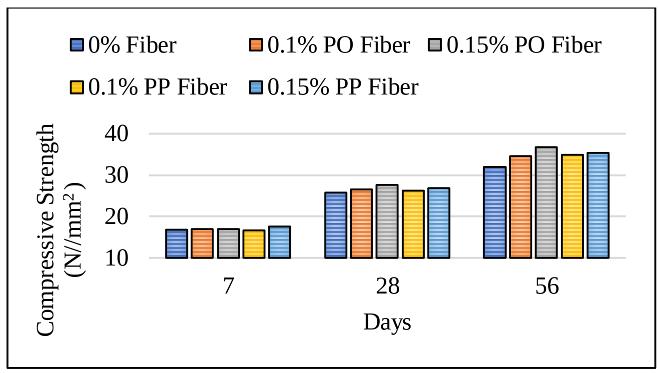

Fig. 12 Compressive strength results of the 55% fly ash with various fiber content

The compressive strength of the 0.15% PO fiber samples increased by 14.97% after 56 days, which was the greatest among all the samples. The 0.1% PO fiber samples showed a lower rise in compressive strength at 8.29%. The PP fiber samples exhibited enhancements of 9.00% and 10.79% for concentrations of 0.1% and 0.15%, respectively.

Also, it is widely acknowledged that fly ash has a slower reaction rate than regular Portland cement, leading to a delayed increase in strength in concrete. The delayed pozzolanic response is defined by the continuous process of hydration that continues after the initial curing phase, resulting in a gradual improvement in compressive strength over time. The findings of this study demonstrate this occurrence, as indicated by the notable enhancements in compressive strength over later stages (56 days) in contrast to the first stage (7 days). The incorporation of fibers seems to enhance the delayed reaction by offering more reinforcement and improving the microstructure of the SCC, resulting in more significant strength improvements at later stages of curing.

Table 6. Mechanical properties of HVFASCC with different fiber contents over time

Mech. Properties	Fly Ash Content	Days	Fiber Content				
			0% Fiber	0.1% PO Fiber	0.15% PO Fiber	0.1% PP Fiber	0.15% PP Fiber
Compressive Strength (N/mm^2)	50% Fly Ash	7	16.98	17.68	18.07	17.32	17.79
		28	27.26	29.18	30.37	28.21	29.11
		56	33.52	37.76	38.97	36.91	37.87
	55% Fly Ash	7	16.79	17.01	17.02	16.65	17.51
		28	25.82	26.54	27.61	26.2	26.84
		56	31.96	34.61	36.74	34.84	35.41
Flexural. Strength (N/mm^2)	50% Fly Ash	7	3.73	4.03	4.21	3.92	4.08
		28	4.52	5.03	5.3	4.96	5.15
		56	5.38	5.9	6.18	5.73	5.95
	55% Fly Ash	7	3.56	3.83	4.04	3.76	3.89
		28	4.25	4.66	4.91	4.63	4.78
		56	5.01	5.45	5.7	5.13	5.49
Tensile. Strength (N/mm^2)	50% Fly Ash	7	1.98	2.02	2.13	1.99	2.09
		28	3.21	3.26	3.29	3.22	3.25
		56	3.46	3.49	3.61	3.47	3.52
	55% Fly Ash	7	1.93	1.98	2.08	1.95	1.99
		28	3.13	3.19	3.21	3.14	3.17
		56	3.28	3.32	3.43	3.18	3.29

3.7. Flexural Strength of Concrete

When fibers have been added, as demonstrated in Figure 13 and tabular format Table 6, the flexural strength of the 50% FA SCC samples significantly increases. After a week, the samples with 0.1% and 0.15% PO fiber had flexural strengths of roughly 8.04% and 12.87% higher than the fiber-free control sample. When PP fiber was added at quantities of 0.1% and 0.15%, there were corresponding increases of 5.09% and 9.38%, respectively. After 28 days, the flexural strength improvements were more noticeable. The samples with 0.1% and 0.15% PO fiber exhibited increases of 11.28% and 21.24%, respectively.

On the other hand, the samples with 0.1% and 0.15% PP fiber showed increases of 9.73% and 14.04%, respectively. The 0.15% PO fiber samples exhibited the maximum flexural strength after 56 days, with a 14.87% increase. The 0.1% PO fiber samples had an 11.53% increase in flexural strength. The PP fiber samples exhibited enhancements of 6.50% and 10.60% for concentrations of 0.1 and 0.15%, correspondingly.

Similarly, Figure 14 Shows that fiber inclusion enhanced the flexural strength of the 55% fly ash SCC samples but to a slightly lesser degree than the 50% fly ash samples. Compared to the fibre-free control sample, the fiber samples with concentrations of 0.1% and 0.15% PO exhibited increases of 7.58% and 13.48%, respectively, after 7 days. Conversely, fiber samples containing 0.1% PP showed a 5.62% increase, and fiber samples containing 0.15% PP showed a 9.28% increase. After 28 days, the flexural strength of the 0.1% PO fiber samples grew by 9.65%, and the flexural strength of the 0.15% PO fiber samples increased by 15.53%.

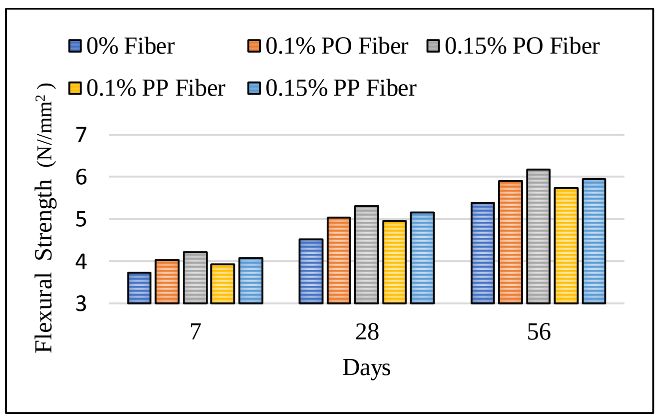

Fig. 13 Flexural strength results of the 50% fly ash with various fiber content

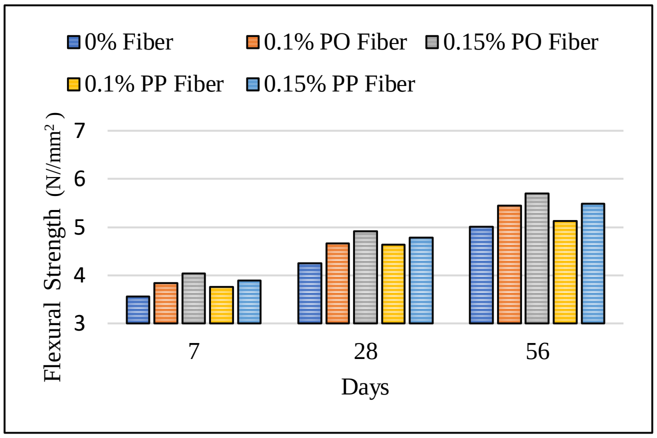

Fig. 14 Flexural strength results of the 55% fly ash with various fiber content

Similarly, the comparable PP fiber samples experienced an 8.94% rise in flexural strength for the 0.1% concentration and a 12.47% increase for the 0.15% concentration. The flexural strength of the 0.15% PO fiber samples increased by 14.17% after 56 days, which was the greatest among all the samples. The 0.1% PO fiber samples showed a rise in flexural strength of 8.78%. The PP fiber samples exhibited enhancements of 2.39% and 8.75% for concentrations of 0.1% and 0.15%, respectively.

3.8. Tensile Strength of Concrete

When fibers have been added, the Tensile Strength of the 50% FA SCC samples significantly increases, as seen in Figure 15 and tabular format Table 6. After 7 days, the tensile strength of the samples containing 0.1% and 0.15% PO fiber increased by about 2.02% and 7.58%, respectively, compared to the control sample without any fiber. When PP fiber was added at quantities of 0.1% and 0.15%, there were corresponding increases of 1.01% and 5.56%, respectively. The improvements in tensile strength became more apparent after 28 days. The increases in the samples containing 0.1% and 0.15% PO fiber was 10.28% and 4.96%, respectively. On the other hand, the samples with 0.1% and 0.15% PP fiber showed increases of 3.47% and 6.83%, respectively.

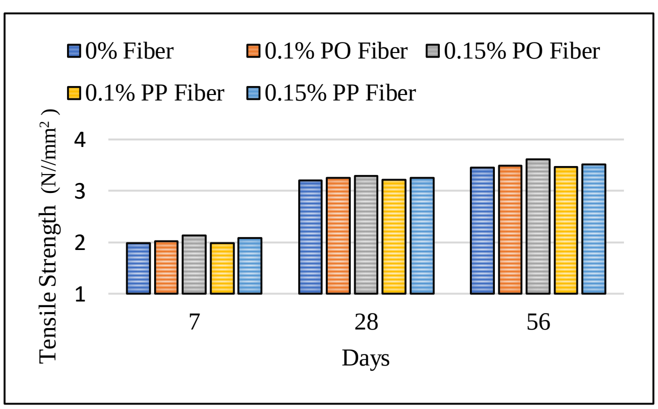

Fig. 15 Tensile strength results of the 50% fly ash with various fiber content

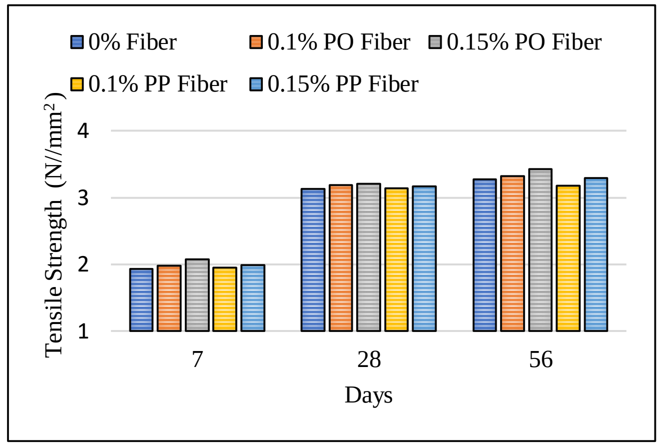

Fig. 16 Tensile strength results of the 55% fly ash with various fiber content

The 0.15% PO fiber samples exhibited the maximum tensile strength after 56 days, with a 7.29% increase. The 0.1% PO fiber samples had a 6.73% increase in tensile strength. The PP fiber samples exhibited enhancements of 5.46% and 7.81% for concentrations of 0.1% and 0.15%, respectively.

Similarly, Figure 16 shows that including fibers enhanced the tensile strength of the 55% fly ash SCC samples but slightly less than the 50% fly ash samples. Compared to the fiber-free control sample, the fiber samples with concentrations of 0.1% and 0.15% PO exhibited increases of 2.59% and 7.77%, respectively, after 7 days. On the other hand, the fiber samples with a concentration of 0.1% of PP showed an increase of 1.04%, while the samples with a concentration of 0.15% showed a rise of 3.11%. The 0.1% PO fiber samples' tensile strength improved by 2.00% after 28 days, while the 0.15% PO fiber samples' tensile strength increased by 7.21%. Likewise, the tensile strength of the similar PP fiber samples increased by 1.57% at 0.1% concentration and 5.80% at 0.15% concentration. The Tensile Strength of the 0.15% PO fiber samples increased by 4.57% after 56 days, which was the greatest among all the samples. The 0.1% PO fiber samples showed a rise in tensile strength of 3.18%. The PP fiber samples exhibited enhancements of 2.72% and 3.10% for concentrations of 0.1% and 0.15%, respectively.

3.9. Impact of Fly Ash Content & Fiber on Mechanical Properties

Similarly, the addition of synthetic fibers (polyester and polypropylene) improves the mechanical qualities of SCC, including its compressive, flexural, as well as tensile strengths. However, the amount of FA also has a significant effect on the total strength. Because of its improved matrix integrity and cohesiveness, SCC performs better mechanically with 50% fly ash than the 55% fly ash mix. At 50% replacement, the fly ash particles effectively fill voids and contribute to a denser matrix, enhancing both the pozzolanic reaction as well as the long-term strength of the concrete. In contrast, 55% fly ash mix, although still benefiting from fiber reinforcement, experiences a reduction in the binding efficiency between the particles, which can lead to a decrease in strength development, particularly at higher fiber dosages. This is because, specifically in the early curing stages, the increased fly ash content slows down the pozzolanic reaction, which leads to slower strength growth.

Polyester fibers significantly enhance the mechanical performance of SCC by interacting with the cement matrix. These fibers engage with the cementitious material during the hydration process, facilitating efficient stress transfer from the matrix to the fibers. This bond is essential to increase the concrete's tensile and flexural strength and enable a more efficient load distribution throughout the material. Furthermore, polyester fibers act as elements that bridge cracks, managing the propagation of microcracks by strengthening the matrix and inhibiting the development of larger cracks. This mechanism enhances the overall toughness of SCC, allowing the material to maintain its integrity despite initial cracking.

Polyester fibers enhance post-cracking behavior by maintaining tensile loads across cracked areas, which in turn boosts the concrete's residual strength. Furthermore, these fibers contribute to the dissipation of stress energy during loading, thereby improving the fracture resistance and toughness of SCC. This characteristic is especially significant in scenarios that demand enhanced durability, like in constructions subjected to seismic forces or impact loads. Furthermore, polyester fibers reduce shrinkage cracking, which is crucial for ensuring long-term durability by lessening cracks that arise from drying shrinkage, especially in high-volume FA concrete.

4 Environmental Impact Analysis of Synthetic Fibers in HVFASCC

4.1. Raw Material Extraction and Production Impact

Polypropylene and polyester synthetic fibers are made from petroleum-based substances. Crude oil extraction and purification is even more energy-consuming than the polymerization needed to produce synthetic fibers. This technology lets out greenhouse gasses and exhausts non-renewable resources in later stages. The manufacturing of PP fibers emits approximately 1.7 kg CO_2 equivalent emissions per kilogram of the fiber; the high figure demonstrates manufacturing’s significant environmental effect. The manufacturing of polyester fibers needs a lot of energy.

These fibers greatly enhance HVFASCC in terms of mechanical properties, like crack resistance and tensile strength. Consequently, the durability of concrete structures is elongated, and repairs and replacements are fewer. Finally, improved efficiency reduces the early effects of fiber manufacturing on the environment by reducing the need for further resource use in the structure’s life cycle.

4.2. Use in Concrete Structures

The resulting material's TS, compressive strength, and overall performance are all improved by the synthetic fiber blend in HVFASCC. These advancements enable concrete structures to withstand increased mechanical strain, shrinkage, and cracking, reducing the need for frequent repairs and maintenance over the course of their usefulness. According to research, adding synthetic fiber, especially in the right amount, improves flexural hardness and compressive strength by 10% to 15%. Consequently, the advantages of the improved environmental situation are achieved by implementing the minimum consumption of materials and energy for repair works and the minimum amount of transportation of heavy equipment in connection with maintenance. Since the energy consumption and emissions from maintenance as well as reconstruction of concrete structures are decreased during the course of a concrete structure's lifecycle, the continuous decrease in resource utilization benefits the environment.

4.3. End-of-Life Considerations

Disposal is problematic whenever a concrete structure attains the end of its useful life, as synthetic fibers are not biodegradable. Polypropylene and polyester fibers are almost indestructible in the natural environment, raising concerns about accessory accumulation in landfills. The two primary problems of using concrete as aggregate in recycling relate to the synthetic fibers incorporated in the concrete: it turns out to be very easy to dispose of in the recycling process because pulling them out is very difficult. Harmful air pollutants like CO2, nitrogen oxides, and volatile organic compounds are released when synthetic fibres are burned for energy recovery. Therefore, a common practice like landfill disposal adds to the development of long-term waste management issues. This ecological assessment focuses on different types of recycling procedures for fiber-reinforced concrete and their implications for the environment, and it compares these procedures with further consequences for developing advanced sustainable disposal alternatives for these materials.

4.4. Lifecycle Assessment (LCA) Methodology

An LCA approach has been used to assess the environmental impacts associated with each synthetic fiber life cycle phase, from the extraction of raw materials to material processing, use of the material, and disposal point. Various dreadful indicators, such as global warming potential, energy, and resource use, were assessed as part of the impact. The energy conservation factor for polypropylene fiber production is about 120MJ per ton; this shows that energy significantly impacts the product's carbon footprint. Most noteworthy, the LCA also considers the benefits gained during the usage phase because HVFASCC offers excellent asset durability and a longer service time without requiring material repairs and resupply. As we will see in this detailed LCA study, the organization should weigh the benefits and costs of using synthetic fibers in HVFASCC regarding the life cycle cost on the one hand and the benefits to a sustainable environment on the other hand.

5. Conclusion

This study investigated the impact of various FA and synthetic fibers combinations on the mechanical and fresh characteristics of SCCs by analyzing experimental data.

This work examines two concentrations of FA replacement, which are 50% and 55% ID, and two fiber dosages, namely at 0.1% and 0.15% DV, to understand the characteristics of HVFASCC under various scenarios. The results show that 50 percent FA has better workability and mechanical properties than 55 percent FA. The consequent increase in FA content to 55% affected the workability; the fiber content and superplasticizer dosage needed to be calibrated accordingly to provide suitable flow characteristics.

Polyester (PO) and Polypropylene (PP) fibers were introduced to improve mechanical properties. PO fibers enhanced compressive, flexural, and tensile strengths more effectively than PP fibers, primarily through improved fiber-matrix interaction. On the other hand, while enhancing workability, PP fibers slightly improved flow properties but to a lesser extent in terms of strength improvement. The experimental results demonstrated that higher fiber content (0.15%) improved mechanical properties but negatively impacted workability due to increased internal friction. Meanwhile, lower fiber content (0.1%) provided a balanced enhancement in both mechanical properties and workability.

V-funnel, Slump flow, L-box, as well as U-box tests confirmed that increased fiber content and higher fly ash content reduced workability and passing ability. Compressive strength improvements were notable with PO fibers at 0.15%, with enhancements observed across all curing stages (7, 28, and 56 days). Fiber inclusion also benefited Flexural and tensile strengths, particularly with 0.15% PO fibers.

The study's novel contribution lies in demonstrating the balance required between fiber content and fly ash levels to optimize both workability and mechanical performance in SCC, thus advancing the understanding of sustainable construction materials. This research has the potential to significantly cut carbon emissions and the application of traditional cement in the manufacture of concrete by promoting high-volume FA as a partial cement replacement.

The long-term performance of HVFASCC in various climatic circumstances, including freeze-thaw cycles, chemical exposure, and prolonged mechanical loading, should be the primary focus of future research. Additionally, exploring alternative synthetic fibers, such as basalt, nylon, or hybrid fibers, may yield further improvements in workability and mechanical properties.

Acknowledgments

The researchers truly thank L.E. College for providing the resources and labour during the project. Additionally, every member of the technical and non-technical staff at the concrete laboratories has substantially contributed to the study and accomplishing the work's goal.

References

[1] Abdullah M. Zeyad, "Effect of Fibers Types on Fresh Properties and Flexural Toughness of Self-Compacting Concrete," *Journal of Materials Research and Technology*, vol. 9, no. 3, pp. 4147-4158, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[2] Mohammed Abed, Rita Nemes, and Bassam A. Tayeh, "Properties of Self-Compacting High-Strength Concrete Containing Multiple Use of Recycled Aggregate," *Journal of King Saud University - Engineering Sciences*, vol. 32, no. 2, pp. 108-114, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] Hajime Okamura, "Self-Compacting High-Performance Concrete," *Concrete International*, vol. 19, no. 7, pp. 50-54, 1997. [Google Scholar] [Publisher Link]

[4] M. Pająk, and T. Ponikiewski, "Flexural Behavior of Self-Compacting Concrete Reinforced with Different Types of Steel Fibers," *Construction and Building Materials*, vol. 47, pp. 397-408, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[5] Shahiron Shahidan et al., "Physical and Mechanical Properties of Self-Compacting Concrete Containing Superplasticizer and Metakaolin," *IOP Conference Series: Materials Science and Engineering, Global Congress on Construction, Material and Structural Engineering*, Johor Bahru, Malaysia, vol. 271, pp. 1-8, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[6] Abu Sayed Mohammad Akid et al., "Assessing the Influence of Fly Ash and Polypropylene Fiber on Fresh, Mechanical and Durability Properties of Concrete," *Journal of King Saud University - Engineering Sciences*, vol. 35, no. 7, pp. 474-484, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[7] Shi-Cong Kou, and Chi-Sun Poon, "Long-Term Mechanical and Durability Properties of Recycled Aggregate Concrete Prepared with the Incorporation of Fly Ash," *Cement and Concrete Composites*, vol. 37, pp. 12-19, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[8] Aseel Madallah Mohammed, Diler Sabah Asaad, and Abdulkader I. Al-Hadithi, "Experimental and Statistical Evaluation of Rheological Properties of Self-Compacting Concrete Containing Fly Ash and Ground Granulated Blast Furnace Slag," *Journal of King Saud University - Engineering Sciences*, vol. 34, no. 6, pp. 388-397, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] Døssland Åse Lyslo, "*Fibre Reinforcement in Load Carrying Concrete Structures: Laboratory and Field Investigations Compared with Theory and Finite Element Analysis*," Doctoral Theses, Faculty of Natural Sciences and Technology, NTNU, 2008. [Google Scholar] [Publisher Link]

[10] Anette Jansson, "*Effects of Steel Fibres on Cracking in Reinforced Concrete*," Theses, Chalmers University of Technology, Gothenburg, Sweden, pp. 1-50, 2011. [Google Scholar] [Publisher Link]

[11] Arabi N.S. Al Qadi, and Sleiman M. Al-Zaidyeen, "Effect of Fibre Content and Specimen Shape on Residual Strength of Polypropylene Fibre Self-Compacting Concrete Exposed to Elevated Temperatures," *Journal of King Saud University - Engineering Sciences*, vol. 26, no. 1, pp. 33-39, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[12] M.G. Alberti, A. Enfedaque, and J.C. Gálvez, "On the Mechanical Properties and Fracture Behavior of Polyolefin Fiber-Reinforced Self-Compacting Concrete," *Construction and Building Materials*, vol. 55, pp. 274-288, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[13] F. Aslani, and B. Samali, "Flexural Toughness Characteristics of Self-Compacting Concrete Incorporating Steel and Polypropylene Fibres," *Australian Journal of Structural Engineering*, vol. 15, no. 3, pp. 269-286, 2014. [Google Scholar] [Publisher Link]

[14] Yining Ding et al., "Study on Residual Behaviour and Flexural Toughness of Fibre Cocktail Reinforced Self Compacting High Performance Concrete After Exposure to High Temperature," *Construction and Building Materials*, vol. 26, no. 1, pp. 21-31, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[15] Chang Lin et al., "Influence of Fibre Type on Flexural Behaviour of Self-Compacting Fibre Reinforced Cementitious Composites," *Cement and Concrete Composites*, vol. 51, pp. 27-37, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[16] Alireza Khaloo et al., "Mechanical Performance of Self-Compacting Concrete Reinforced with Steel Fibers," *Construction and Building Materials*, vol. 51, pp. 179-186, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[17] Shariq Masood Khan, and Juned Ahmad, "Mechanical Properties of Steel Fiber Reinforced Self-Compacting Concrete: A Review," *International Research Journal of Engineering and Technology*, vol. 5, no. 3, pp. 951-956, 2018. [Google Scholar] [Publisher Link]

[18] Mustafa Sahmaran, Alperen Yurtseven, and I. Ozgur Yaman, "Workability of Hybrid Fiber Reinforced Self-Compacting Concrete," *Building and Environment*, vol. 40, no. 12, pp. 1672-1677, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[19] Aslı Boz et al., "Mechanical Properties of Lime-Treated Clay Reinforced with Different Types of Randomly Distributed Fibers," *Arabian Journal of Geosciences*, vol. 11, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] Saber Fallah, and Mahdi Nematzadeh, "Mechanical Properties and Durability of High-Strength Concrete Containing Macro-Polymeric and Polypropylene Fibers with Nano-Silica and Silica Fume," *Construction and Building Materials*, vol. 132, pp. 170-187, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[21] Jawad Ahmad et al., "Performance of Concrete Reinforced with Jute Fibers (Natural Fibers): A Review," *Journal of Engineered Fibers and Fabrics*, vol. 17, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[22] Marzena Kurpińska et al., "The Impact of Natural Fibers' Characteristics on Mechanical Properties of the Cement Composites," *Scientific Reports*, vol. 12, no. 1, pp. 1-14, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[23] Afonso R.G.de Azevedo et al., "Natural Fibers as an Alternative to Synthetic Fibers in Reinforcement of Geopolymer Matrices: A Comparative Review," *Polymers*, vol. 13, no. 15, pp. 1-21, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[24] Gobinath Ravindran et al., "Usage of Natural Fibre Composites for Sustainable Material Development: Global Research Productivity Analysis," *Buildings*, vol. 13, no. 15, pp. 1-16, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[25] Lin Chen et al., "Recent Developments on Natural Fiber Concrete: A Review of Properties, Sustainability, Applications, Barriers, and Opportunities," *Developments in the Built Environment*, vol. 16, pp. 1-17, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[26] Sreedhara B. Marulasiddappa et al., "Exploring the Potential of Arecanut Fibers and Fly Ash in Enhancing the Performance of Self-Compacting Concrete," *Journal of Engineering and Applied Science*, vol. 71, no. 1, pp. 1-23, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[27] Weiguo Shen et al., "Experimental Investigation on the High-Volume Fly Ash Ecological Self-Compacting Concrete," *Journal of Building Engineering*, vol. 60, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[28] Navdeep Singh, Pawan Kumar, and Paresh Goyal, "Reviewing the Behaviour of High Volume Fly Ash Based Self Compacting Concrete," *Journal of Building Engineering*, vol. 26, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[29] Reza Saleh Ahari, Tahir Kemal Erdem, and Kambiz Ramyar, "Thixotropy and Structural Breakdown Properties of Self Consolidating Concrete Containing Various Supplementary Cementitious Materials," *Cement and Concrete Composites*, vol. 59, pp. 26-37, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[30] Tomasz Ponikiewski, and Jacek Gołaszewski, "The Influence of High-Calcium Fly Ash on the Properties of Fresh and Hardened Self-Compacting Concrete and High Performance Self-Compacting Concrete," *Journal of Cleaner Production*, vol. 72, pp. 212-221, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[31] Gritsada Sua-Iam, and Natt Makul, "Utilization of High Volumes of Unprocessed Lignite-Coal Fly Ash and Rice Husk ash in Self-Consolidating Concrete," *Journal of Cleaner Production*, vol. 78, pp. 184-194, 2014. [CrossRef] [Google Scholar] [Publisher Link]

[32] P. Kumar Mehta, "Sustainable Cements and Concrete for the Climate Change Era – A Review," *Proceedings of the Second International Conference on Sustainable Construction Materials and Technologies*, Aneona, Italy, pp. 1-10, 2010. [Google Scholar] [Publisher Link]

[33] Prabir Sarker, and Luke McKenzie, "Strength and Hydration Heat of Concrete Using Fly Ash as a Partial Replacement of Cement," *Proceedings of the 24th Biennial Conference of the Concrete Institute Australia*, pp. 1-9, 2009. [Google Scholar] [Publisher Link]

[34] Navdeep Singh, M. Mithulraj, and Shubham Arya, "Utilization of Coal Bottom Ash in Recycled Concrete Aggregates Based Self Compacting Concrete Blended with Metakaolin," *Resources, Conservation and Recycling*, vol. 144, pp. 240-251, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[35] "*Specification and Guidelines for Self-Compacting Concrete*," EFNARC, pp. 1-32, 2002. [Publisher Link]

[36] L.G. Li et al., "Combined Effects of Water Film Thickness and Polypropylene Fibre Length on Fresh Properties of Mortar," *Construction and Building Materials*, vol. 174, pp. 586-593, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[37] M.G. Alberti, A. Enfedaque, and J.C. Gálvez, "The Effect of Fibres in the Rheology of Self-Compacting Concrete," *Construction and Building Materials*, vol. 219, pp. 144-153, 2019. [CrossRef] [Google Scholar] [Publisher Link]