

Original Research

Influence of Steel, Nylon, and Hybrid Fibers on the Mechanical and Flexural Performance of Self-Compacting Concrete T-Beams

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Abstract

In this work, the effect of steel, nylon and hybrid steel-nylon fibers on the fresh, mechanical and structural flexural behavior of self-compacting concrete (SCC) containing 11% silica fume as a supplemental cementitious material has been experimentally investigated. Ten mixes were studied, one reference SCC without reinforcement and nine fiber-reinforced composites with steel, nylon, or hybrid steel-nylon fibers at volume fractions of 0.2%, 0.3% and 0.4%. The fresh state response was characterized in terms of slump flow, T_{50} flow time, V-funnel, V-funnel after 5 min, and L-box tests as per EFNARC requirements. The hardened response was characterized after 28 days by compressive strength, splitting tensile strength, and four-point



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flexural testing of reinforced SCC T-beams. The statistical reliability and the factorial effects were analyzed by standard deviation, coefficient of variation, error bar analysis and two-way factorial ANOVA, taking into account the fiber type, the fiber dose and the interaction between them. The increase in the fiber percentage resulted in lower flowability and higher flow resistance, but the self-compacting properties of the studied mixes were still acceptable. The 0.4% steel fiber mixture exhibited the best mechanical and structural behavior, with the increase in compressive strength from 40.8 to 45.1 MPa, splitting tensile strength from 3.90 to 4.81 MPa and ultimate flexural load from 53.0 to 68.7 kN, with improvements of 10.5%, 23.3% and 29.6%, respectively. The 0.4% hybrid mixture had a compressive strength of 43.4 MPa, a splitting tensile strength of 4.25 MPa and an ultimate load of 65.2 kN, offering a balanced combination of strength and deformation performance. Two-way ANOVA demonstrated significant effects of fiber type and dose on all three responses, while their interaction was significant for compressive and splitting tensile strengths, but not for final flexural load. Specifically, the flexural interaction exhibited an F-value of 0.716 and a p-value of 0.592, showing that the hybrid system did not result in statistically evident synergistic augmentation of peak flexural capacity.

Keywords

Hybrid fiber; self-compacting concrete; flexural strength; T-beam; fiber-reinforced concrete

1. Introduction

Concrete remains the most widely used building material worldwide due to its versatility, convenience, and low cost [1]. It has excellent compressive strength and formability, which are essential for modern cutting-edge infrastructure; its inherent low tensile strength, which leads to brittle failure, remains a major limiting factor in structural practice [2, 3]. Such defects are likely to form cracks, and if unchecked, lead to eventual loss of durability and longevity. To prevent these disadvantages, researchers have suggested various reinforcement types, including conventional steel reinforcement, fiber-reinforced polymers (FRP), and discrete fibers [4, 5]. Fiber reinforcement is now recognized as an effective and versatile way for enhancing the mechanical features and cracking resistance of cementitious products [6-8].

The use of fibers in SCC has gained increasing interest because of their influence on fresh and hardened properties. SCC, which flows and compacts under its own gravity without external vibration, has also changed how concrete is placed in highly reinforced or complex-shaped structural elements [9]. However, the presence of fibers alters the rheological features of SCC, thereby modifying its workability, passing ability, and segregation resistance. Various studies have shown that the shape, aspect ratio, and volume fraction of fibers significantly affect the fresh and mechanical features of SCC [10, 11]. In a well-designed mixture, FRSCC can exhibit a better post-cracking response and greater ductility than conventional vibrated concrete, making it more attractive for structural members subjected to dynamic or impact loads [12].

Steel fibers have been actively investigated for structural applications over the past 20 years because of their high stiffness, tensile strength, and crack-bridging capacity. The use of steel fibers

has been reported to substantially improve the flexural toughness, modulus of rupture, and splitting tensile strength of SCC [13, 14] in many experimental studies. The contribution of fibers to improving shear resistance is also recognized in several design rules (ACI 318 [15] and fib Model Code [16]) that permit the partial replacement of traditional stirrups with steel fibers. However, the performance of steel fibers relies on the volume fraction and dispersion of the steel fibers in a matrix. Moderate increases might be anticipated to improve the structural behavior. However, too many fibers would reduce workability. This is expressed as longer V-funnel flow durations and lower slump-flow values, which would be followed predictably by a slower rate of compressive-strength development in SCC [17, 18]. Steel fibers are further vulnerable to corrosion, and their high density limits their practical applicability, e.g., in harsh environments and lightweight construction [19].

Because of these issues, polymeric fibers are becoming increasingly attractive as substitutes, especially polypropylene (PP) and nylon. These fibers offer chemical stability, corrosion resistance, and hydrophobicity, ensuring long-term service life even under harsh conditions [20, 21]. Moreover, they can reduce shrinkage cracking, increase toughness, and improve impact resistance. Sun and Xu [22] showed that adding polypropylene fibers up to 0.15% has an insignificant effect on compressive strength. In contrast, higher contents, such as 0.45%, improved the ductility of high-strength concretes without a significant loss in strength [22]. However, the amount of such synthetic fibers should be strictly limited because an excessively high proportion may reduce workability and even clog in overcrowded reinforcement during flow. To this end, Khayat et al. [23, 24] suggested optimizing the mortar-to-aggregate ratio and using (VMA) to maintain homogeneity and stability of FRSCC. They found that when polypropylene fiber dosage was less than 0.75% and the steel fiber dosage was less than 0.5%, optimal SCC flowability and anti-segregation performance could be achieved.

While researchers have extensively studied single-fiber-reinforced concrete, hybrid fiber reinforcement, combining steel and synthetic fibers, has gained increasing attention as a way to exploit the complementary characteristics of different fiber types and improve the mechanical and structural performance of concrete. The hybridization methodology leverages the stiffness and strength of steel fibers and the flexibility and crack-distribution characteristics of polymeric fibers, thereby enhancing post-cracking ductility, energy absorption, and fatigue performance. Nevertheless, few studies have systematically investigated how steel fibers, nylon fibers, and hybrid fiber reinforcement interact in SCC with a T-shaped beam cross-section, which better simulates practical structural components such as slabs and bridge girders. This study is focused on the experimental investigation of hybrid steel-nylon fiber-reinforced self-compacting concrete (FRSCC) for realistic full-scale T-beams, which have rarely been studied in the literature. The incorporation of 11% silica fume with different fiber fractions influences the rheological and mechanical behavior of the mixtures, providing complementary effects on strength and ductility while maintaining satisfactory flowability. The investigation addresses both fresh-state behavior and structural-scale flexural response, indicating that hybrid fiber reinforcement can provide a balance between stiffness and deformability. Such an integrated design principle offers a new perspective on the development of high-strength, ductile SCCs appropriate for advanced. The uniqueness of the current work is the development of an integrated experimental and statistical framework to assess the influence of fibers (steel, nylon, and hybrid steel-nylon) on the fresh, mechanical, and structural performance of self-compacting concrete containing 11% silica fume. Fresh-state characterization was performed by employing the slump flow, T_{50} flow duration, V-funnel, V-funnel after 5 min and

L-box tests. At the same time, the hardened properties were assessed by the compressive and splitting tensile strengths and the full-scale flexural testing of reinforced SCC T-beams. The experiment examines three fiber systems (steel, nylon and 50:50 hybrid steel-nylon) at volume fractions of 0.2%, 0.3% and 0.4% systematically evaluate the individual impacts of fiber type and dose. However, the statistical analysis now includes standard deviation, coefficient of variation, error-bar evaluation, one-way ANOVA and two-way factorial ANOVA with partial eta-squared effect sizes to distinguish the independent effects of fiber type and dosage from their interaction, unlike the previous formulation. The two-way ANOVA showed significant fiber type $\times$ dosage interactions for compressive and splitting tensile strengths.

2. Experimental Program

2.1 Materials

2.1.1 Cement

Ordinary Portland cement (OPC) of the locally produced Iraqi brand Kirkuk (Type I) was employed in this study. The chemical and physical features of the cement were found to comply with the Iraqi Standard Specification (IQS No. 5/1984) and are presented in Table 1.

Table 1 Chemical and physical features of cement.

Oxides composition	Amount %	Limit of Iraqi specification No. 5/1984
CaO	60.45	-
Al ₂ O ₃	4.65	8% Max
SiO ₂	20.11	21% Max
Fe ₂ O ₃	3.62	5% Max
MgO	4.1	5% Max
SO ₃	2.33	2.5% Max
Loss on Ignition (L.O.I)	2.72	4% Max
Insoluble material	1.33	1.5% Max
Lime Saturation Factor (L.S.F)	0.89	(0.66-1.02)
Physical features	Test findings	Limit of Iraqi specification No. 5/1984
Specific surface area (Blaine method), (m ² /kg)	308	(230 m ² /kg) lower limit
Setting time (vacate apparatus)		
Initial setting, (hrs:min)	2 hrs 15 min	Not less than 45 minutes
Final setting, (hrs:min)	4 hrs 10 min	Not more than 10 hrs
Compressive strength (kg/cm ²)		
For 3-day	288	Not less than 150 kg/cm ²
For 7-day	342	Not less than 230 kg/cm ²

2.1.2 Fine Aggregate

Fine aggregate was utilized as natural river sand from the Tuz area after thorough sifting. The part passing the sieve of 4.75 mm was chosen to satisfy the grading criteria of Iraqi Standard (IQS No. 45/1984), Zone III, as shown in Table 2. The specific gravity of the fine aggregate was 2.54, the

bulk density was 1600 kg/m³, the sulfate content was 0.22%, the clay and silt content was 1.01%, and the water absorption was 2.35%.

Table 2 The grading of fine aggregate.

Sieve size	Cumulative retained %	Cumulative passing %	Limit of IQS No. 45/1984 for zone No. (3)
4.75-mm (No.4)	9.05	90.95	90-100
2.36-mm (No.8)	13.38	88.62	85-100
1.18-mm (No.16)	21.45	78.55	75-100
600-μm (No.30)	33.04	66.96	60-79
300-μm (No.50)	83.26	16.74	12-40
150-μm (No.100)	95.66	4.34	0-10

2.1.3 Coarse Aggregate

The coarse aggregate was rounded natural river gravel from the Tikrit area with a maximum nominal size of 12.5 mm (M.A.S = 12.5 mm). The aggregate was carefully cleaned to remove impurities and clay particles. The particle size distribution met ASTM C33-01 specifications, as shown in Table 3. Specific gravity, bulk density, sulfate content, and water absorption were 2.60, 1600 kg/m³, 0.06%, and 0.8%, respectively.

Table 3 The grading of coarse aggregate.

Sieve size	Cumulative passing %	Limit of IQS No. 45/1984
12.5-mm	96.94	90-100
9.5-mm	90.82	85-100
4.75-mm	24.49	10-30
2.36-mm	0.00	0-10

2.1.4 Water

We used ordinary potable water free from deleterious substances for mixing and curing all specimens throughout the experimental program.

2.1.5 Fibers

The fresh, mechanical, and structural features of the composite were investigated by combining SCC mixes with 2 kinds of fibers as illustrated in Figure 1, hooked-end steel fibers (HESF) and crimped nylon fibers, in separate and combination forms. Hooked-end steel fibers (Dramix® ZP305, Bekaert, Belgium) of 30 mm length and 0.55 mm diameter were utilized because of their greater tensile strength and crack-bridging capacity. The fibers were bundled with a water-soluble glue, which was fully dissolved during mixing to promote uniform dispersion in the concrete matrix and minimize fiber agglomeration. Additionally, crimped nylon fibers with a nominal length of 45 mm were added to improve crack management and fiber-matrix interfacial bonding, owing to their enhanced surface area and mechanical anchoring.

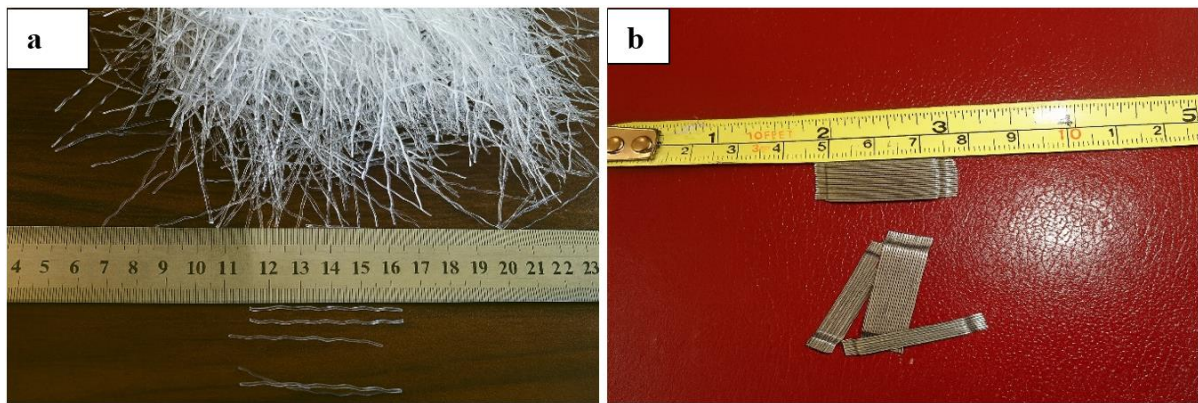


Figure 1 Fibers utilized in the present study: (a) nylon and (b) Steel.

The fiber was added at volume fractions of 0.2%, 0.3% and 0.4% of the total concrete volume. Three reinforcement combinations were investigated: steel fibers only (100:0), nylon fibers only (0:100) and hybrid steel-nylon fibers (50:50). The fiber content was limited to 0.4% to study the effect of the fiber dosage while maintaining the rheological properties required for SCC. It was found in previous studies that the increase in percentage of fiber volume can significantly increase the internal friction between aggregate particles and the viscosity of the fresh matrix and thus reduce the slump flow, passing ability, and filling ability. For fiber dosages higher than ~0.5 vol.%, in particular for steel fibers, the workability is sometimes significantly reduced and the SCC mixture may not satisfy the EFNARC fresh-state performance parameters due to fiber interlocking and increased flow resistance [25]. The selected fiber volume fractions are in a practical, technically feasible range, producing useful improvements in fracture resistance, tensile response and flexural behavior without changing the self-compacting properties or EFNARC guidelines for SCC [26].

2.1.6 Silica Fume

Addition of micro-silica (MEYCO® MS610) as a supplementary cementitious material. The material is an ultrafine solid residue from thermal reactions used to produce silicon metal from quartz and ferrosilicon in submerged electric arc furnaces. It is mainly composed of amorphous silicon dioxide (SiO_2) particles, which are approximately 100 times smaller than cement particles, thereby providing a very large specific surface area and pozzolanic reactivity. Silica fume addition increases compressive strength, cohesion, and abrasion resistance, while generally reducing permeability, thereby protecting steel reinforcement from corrosion. The pozzolanic activity and chemical composition of silica fume are listed in Table 4.

Table 4 Chemical analysis of silica fume.

Chemical decomposition of oxides	Findings %	Limit of ASTM C1240-03	Pozzolanic activity
L.O.I	3.89	105%	121.5%
SiO_2	91.03	85% Min	
Al_2O_3	4.02	-	
Fe_2O_3	0.32	-	
SO_3	0.73	-	

The dosage of 11% replacement of silica fume was used because this dosage gives a good balance between fresh and hardened properties of SCC. The silica fume improves the particle packing and the pozzolanic reaction with calcium hydroxide leads to the formation of additional C-S-H gel which ultimately results in denser microstructure and improved mechanical properties. However, its ultrafine particles and very high specific surface area mean that increasing the content of silica fume beyond about 10-15% significantly increase the water demand and paste viscosity, and reduce the slump flow, filling ability and passing ability. Thus, higher replacement levels usually necessitate higher dosages of superplasticizer to obtain SCC performance [26]. However, 11% replacement level was selected as the optimum practical one to improve strength and durability while meeting the workability requirements defined for SCC. This selection is also in agreement with previous studies on SCC, in which it was reported that the best overall combination of fresh and hardened characteristics was obtained with approximately 10-11% silica fume [27, 28].

2.1.7 Superplasticizer

A high-range water-reducing admixture (HRWR), *Structuro 502*, was utilized to achieve the desired flowability and cohesiveness of SCC. This admixture enhances both early and long-term strength development without containing chlorides or other corrosive compounds. It was added at dosages of 3.3% to 4.5% by weight of cement, depending on the amount of fiber.

2.1.8 Reinforcing Steel

Deformed steel bars with a nominal diameter of 8 mm were utilized as the main longitudinal reinforcement. In contrast, 6 mm bars were utilized for stirrups and top longitudinal ties to complete the reinforcement cage. Table 5 presents the mechanical properties of the reinforcing steel.

Table 5 Mechanical features of reinforcing steel bars.

Bar diameter (mm)	Yield strength, f_y (MPa)	Ultimate strength, f_u (MPa)	Elongation (%)
8	653.00	798.50	7.5
6	636.93	683.92	6.5

2.2 Mix Design for Self-Compacting Concrete

The SCC mix design was based on volume weight, per the EFNARC [29] guidelines. This method allows for better manipulation of the rheological balance of the paste and aggregates. The total powder content ranged from 400 to 600 kg/m³ (160-240 L/m³), and the W/P ratio was approximately 0.8-1.1 (vol.). Coarse aggregate contents ranged from about 28% to 35% of the total volume of all mixtures, and a maximum water content of 200 L/m³ was imposed. The filler or fine-aggregate fraction was adjusted to achieve the desired volumetric balance, ensuring a continuous matrix. A conservative design approach was taken to ensure novelty was preserved despite changes in raw material features (e.g., moisture content and particle size distribution). Therefore, VMA and HRWR (superplasticizer) were employed to help maintain consistent flow and offset potential variations in sand gradation or aggregate moisture.

Once the blend was developed, trial castings were conducted to assess the composition's adequacy and determine the necessary changes to achieve the desired workability and mechanical

performance. Trial batches that did not meet standards were modified. The adjustments included the addition of numerous fillers to boost cohesiveness, optimization of the fine-to-coarse aggregate ratio, and, if necessary, dosing with a plasticizer admixture and a superplasticizer. In other blends, a more closely matched superplasticizer was used, and the water content or the water-to-powder ratio was adjusted to achieve optimum workability without separation, as shown in Table 6. Rheological tests indicated that the modified blend met the EFNARC performance limits [29].

Table 6 Mix proportions of the reference SCC mixtures (without fiber).

Mix	Silica fume %	S.P %	Quantities of Mix Ingredients (Kg/m ³)							
			water (Kg)	Powder		w/cm ratio	F.A	C.A	S.P (Kg)	Density Kg/m ³
				Silica fume (Kg/m ³)	cement (kg)					
SCC	11%	3.3%	170	49.5	450	0.34	900	750	16.48	2335.98

Eight SCC mixes were presented with various filler quantities, aggregate content, cement content, and superplasticizer dose after the optimization procedure. The flowability of the slurry was tested, and the viscosity balance was evaluated by the slump-flow and T₅₀ time for each combination. The 7-day compressive strength of the level materials cubes from the three kits was tested, and the optimal component combination was found. The SCC mixture that gave the highest compressive strength without loss of SCC workability criteria was selected as the reference SCC mixture. The study also tested compliance with EFNARC guidelines [29] using the V-funnel and L-box tests. The selected reference mix with a 7-day compressive strength of 32.75 MPa was adjusted by adding steel, nylon, and hybrid (steel-nylon) fibers at volume fractions of 0.2%, 0.3%, and 0.4%. To offset the loss of workability caused by the inclusion of fibers, the amount of superplasticizer was increased from 3.3% in the reference mixture to 4.5% by cement weight in the fiber-reinforced mixtures. This adjustment was necessary to maintain the self-compacting characteristics of the concrete. However, the higher superplasticizer dosage may have partially influenced both the fresh and hardened properties. Therefore, the observed improvements should be interpreted as resulting from the combined effect of fiber incorporation and the modified superplasticizer content, rather than being attributed solely to the fibers.

2.3 Mixing, Casting, and Curing Procedures

Before casting, we thoroughly cleaned all models and coated them with a thin film of release oil to facilitate demolding after setting. The steel reinforcing cages were accurately positioned in the T-section molds in accordance with the structural design details. The mixing was performed in a controlled manner to maintain uniform material distribution and prevent fiber agglomeration. Half of the coarse aggregate and a small amount of water were added to the mixer first. Steel, nylon, or hybrid fibers were then slowly added while mixing to prevent balls from forming. Thereafter, half of the fine aggregate and cementitious materials (Portland cement & silica fume) were added then mixed for one minute. The remaining water and the full amount of superplasticizer were then added, and mixing continued for a further two minutes. Last, the remaining aggregates and cementitious materials were added, and mixing was continued for an additional 3 minutes to obtain a homogeneous flowable mixture.

Upon mixing, fresh concrete was tested to validate its rheological characteristics in accordance with the EFNARC specifications [29]. The molds were filled with two layers, 50 mm each, without mechanical compaction, as SCC. After casting, the prisms were covered with a polyethylene sheet and stored at laboratory temperature for 24 h before demolding. The demolded samples were then placed in a water curing tank and submerged for 27 days to ensure full hydration.

A total of ten SCC mixes were cast, and thirty reinforced beams (T-beams), thirty 150-mm cubic specimens, and thirty 150 × 300 mm cylindrical specimens were obtained. The mixtures included compressive, tensile, and flexural strength specimens, which were used to investigate the effects of fiber type and volume content on the mechanical and structural performance of SCC.

2.4 Concrete Testing Program

2.4.1 Fresh Concrete Tests

The fresh-state characteristics of SCC mixes were evaluated to assess flowability, passing ability through clogged reinforcement, and segregation resistance in the absence of external vibration. The experiments were carried out in accordance with EFNARC guidelines [29] and consisted of slump flow, T_{50} flow duration, V-funnel, V-funnel at 5 min, and L-box. These complementary rheological experiments were utilized to characterize the filling ability, flowability, viscosity, passage ability, and segregation resistance of the SCC mixes. The slump flow test was conducted to assess the horizontal spread of new concrete under its own weight, and the related T_{50} time (the time taken for the concrete to attain a spread diameter of 500 mm) was recorded as an indication of plastic viscosity and flow rate. The larger slump-flow diameters associated with lower T_{50} values indicate better filling ability and lower internal flow resistance. The V-funnel test was used to evaluate the viscosity and flow properties of SCC through a constrained opening, providing an indirect measure of its cohesiveness and resistance to segregation. Stability and tendency to particle settling of the mixes were also tested by V-funnel measurement after 5 min of rest. Increases in discharge time were indicative of instability. Also, L-box test was performed to determine the passage capacity of SCC through simulated reinforcement bars by measuring the blocking ratio (h_2/h_1). Values of the ratios close to 1 denote good passing ability, with little obstruction or segregation and confirm the acceptability of the mixes for highly reinforced structural members.

2.4.2 Hardened Concrete Tests

The hardened properties of SCC mixes were studied after 28 days of water curing, to ensure complete hydration and uniform strength development. The experimental program was carried out to investigate the effect of fiber type and volume fraction on the mechanical and structural performance of SCC using compressive strength, splitting tensile strength and flexural performance tests. The compressive strength was measured by testing the cube specimens of 150 × 150 × 150 mm in uniaxial compression using a Wekob universal compression testing machine of 2500 kN according to BS 1881 [30]. To assess the load-bearing capacity and overall mechanical performance of the concrete, the average compressive strength of three specimens for each combination was utilized. Splitting tensile strength was determined according to ASTM C496 [31] using specimens of 150 mm diameter and 300 mm height. We applied diametral compressive loading to the specimens until failure and computed the tensile strength from the associated failure load. The average value

from three specimens for each combination was utilized to evaluate the performance of the various fiber systems in improving fracture resistance, tensile capacity, and post-cracking behavior. The structural performance of the fiber-reinforced SCC was further investigated by performing four-point flexural tests on reinforced T-beams to evaluate the load-carrying capacity, stiffness, ductility, crack propagation characteristics, and overall flexural behavior under static loading. The entire testing program enabled a systematic assessment of the fresh rheological features and the hardened mechanical performance of SCC reinforced with steel, nylon, and hybrid fibers.

2.4.3 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was used for qualitative examination of local fiber-matrix interfaces. After 28 days of water curing, small fragments were taken from hardened specimens containing a visible steel-fiber or nylon-fiber interface.

2.4.4 Flexural Strength Test of T-Beams

The flexural behavior of reinforced T-cross-section SCC beams was examined under two-point loading. All beams were monolithically cast to avoid discontinuity joints at the flange and web. The profile of the beams is shown in Figure 2, with a steel span length of 1000 mm and a clear span between supports of 900 mm. Specimens were supported, and two concentrated loads, separated by 200 mm, were utilized to model the pure bending in the central area. The flexural tests were performed with a Universal Testing Machine (SANS) having a capacity of 5000 kN at a controlled loading rate of 1.5 mm/min. Three units of the same cross-section for each mix were tested at an age of 28 days. The mean load-deflection behavior of the three specimens was utilized to construct a typical curve that shows the influence of fiber type and volume fraction on beam flexural strength, stiffness, and ductility.

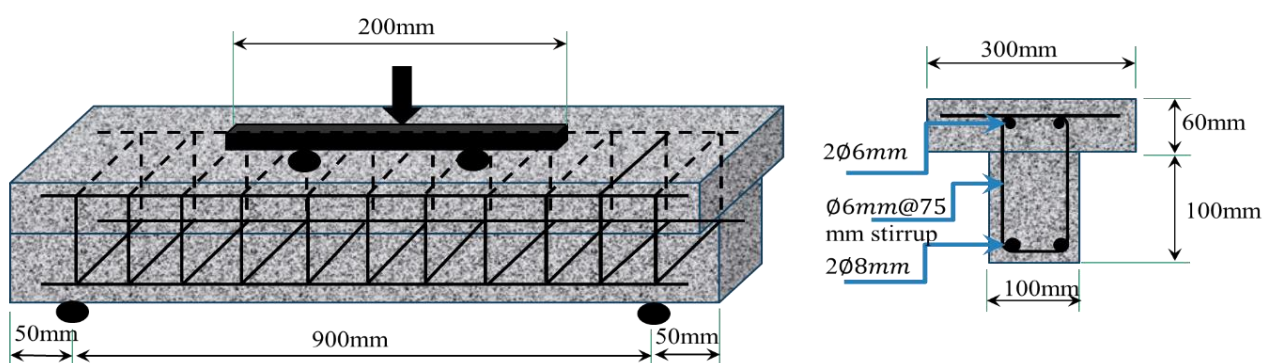


Figure 2 Detailed schematic of the reinforced concrete T-beam and loading configuration.

Reinforcement Calculation:

(1) Dimensions: For isolated (T-Beam)

Take: $b_w = 100 \text{ mm}$ & $h_w = 100 \text{ mm}$

$h_f \geq (b_w/2)$, $60 \geq ((100)/2)$, o.k

$\therefore h_f = 60 \text{ mm}$: Check

$b_f \leq 4b_w$, $300 \leq 4(100)$, o.k

$\therefore b_f = 300 \text{ mm}$

(2) Design of Flexural

$f_{cu} = 40.8 \text{ MPa}$, $f'_c = 32.6 \text{ MPa}$, $f_y = 653 \text{ MPa}$, Length of beam = 1000 mm

$\rho_{min} = \frac{1.4}{f_y}$, $\frac{1.4}{653} = 0.002144$, $\rho_{max} = 0.75$, $\rho_b = 0.85 * B1 * \frac{f'_c}{f_y} * \frac{600}{600+f_y} = 0.012954$

Take: $\rho_{min} \leq \rho \leq \rho_{max}$

$\therefore \rho = 0.0028$

$h = 160 \text{ mm}$, C.C = 26 mm, $d = 160 - 26 - 8 - 6 = 120 \text{ mm}$

$A_s = \rho * b * d$, $A_s = 0.0028 * 300 * 120 = 100.8 \text{ mm}^2$

Using $\phi 8 \text{ mm}$, A_s for $\phi 8 \text{ mm} = 50.24 \text{ mm}^2$

Number of bars (n) = $\frac{100.8}{50.24} = 2.00$

$\therefore$ use 2 $\phi 8 \text{ mm}$

(3) Checking the load:

- For Flexural

$a = 17.4 \text{ mm}$, $d = 120 \text{ mm}$, $f_y = 653 \text{ MPa}$, $A_s = 50.24 * 2 = 100.48 \text{ mm}^2$

$M_u (\phi Mn) = 0.9 * A_s * f_y * (d - a/2) = 6.572 \text{ kN} \cdot \text{m}$

$M_u (\text{applied}) = (P_1/2) * 0.45 - (P_1/2) * 0.1$, $M_u (\text{applied}) = 0.175 P_1$

$P_1 = 37.55 \text{ kN}$ (For Flexural Failure at mid-span)

- For Shear

$f'_c = 32.6 \text{ MPa}$, $f_y = 636.93 \text{ MPa}$, $d = 120 \text{ mm}$, $b_w = 100 \text{ mm}$, $s = 75 \text{ mm}$

$A_v = 2 * 28.26 = 56.5 \text{ mm}^2$

$V_c = 0.17 * \sqrt{f'_c} * b * d = 11.65 \text{ kN}$

$V_s = (A_v * f_y * d)/s = 57.58 \text{ kN}$

$V_u = 0.85(V_c + V_s) = 58.85 \text{ kN}$

$V_u = P_2/2$, $P_2 = 117.69 \text{ kN}$ (For Shear Failure)

$(P_2) \text{ Shear} > (P_1) \text{ Flexural}$

$\therefore$ Flexural Failure

(4) Design of shear:

For stirrups: Using $\phi 6 \text{ mm}$, A_s for $\phi 6 \text{ mm} = 28.26 \text{ mm}^2$, $V_s = 57.58 \text{ kN}$

$S^o = \frac{A_v * f_y * d}{V_s} = \frac{2 * 28.26 * 636.93 * 120}{57.58} = 75.02 \text{ mm}$

$\therefore$ use $\phi 6 \text{ mm}$ @ 75 mm

3. Statistical Analysis

The observed responses of compressive strength, splitting tensile strength, and ultimate flexural load were subjected to a comprehensive statistical analysis to assess the reliability, reproducibility, and statistical significance of the experimental data. The values provided are the averages of three separate samples produced and measured under identical conditions. The experimental results were expressed as mean $\pm$ standard deviation (SD) and the coefficient of variation (CV). The

statistical significance of the differences among the studied SCC mixtures was determined using a one-way analysis of variance (ANOVA) at the 95% confidence level ($\alpha = 0.05$). In addition, error bars indicating ± 1 standard deviation were included in all applicable figures to show the variability and reproducibility of the experimental results. The mean of the experimental observations was estimated as:

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

where:

$\bar{x}$ represents the arithmetic mean,

x_i represents the measured value of the i^{th} specimen, and n represents the total number of replicate specimens.

The sample standard deviation was utilized to quantify the variability of the experimental results:

$$SD = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}} \quad (2)$$

where: SD represents the standard deviation of the measured data.

The coefficient of variation (CV) was calculated to allow comparison of the experimental variability of several measured features:

$$CV(\%) = \frac{SD}{\bar{x}} \times 100 \quad (3)$$

The coefficient of variation reflects how spread the measurements are around the corresponding mean. The lower the CV, the more precise the experiment and the more repeatable the testing technique.

Statistical significance of differences among the SCC combinations was tested using one-way analysis of variance (ANOVA) based on the F-statistic:

$$F = \frac{MS_{between}}{MS_{within}} \quad (4)$$

where:

$$MS_{between} = \frac{SS_{between}}{k - 1} \quad (5)$$

and

$$MS_{within} = \frac{SS_{within}}{N - k} \quad (6)$$

in which:

$SS_{between}$ = sum of squares between groups

SS_{within} = sum of squares within groups

$MS_{between}$ = mean square between groups

MS_{within} = mean square within groups

k = number of experimental groups

N = total number of observations

The sums of squares were determined from:

$$SS_{between} = \sum_{j=1}^k n_j (\bar{x}_j - \bar{x})^2 \quad (7)$$

$$SS_{within} = \sum_{j=1}^k \sum_{i=1}^{n_j} (x_{ij} - \bar{x}_j)^2 \quad (8)$$

where:

n_j is the number of specimens in the j^{th} group

$\bar{x}_j$ is the mean value of the j^{th} group

$\bar{x}$ is the overall mean of all observations

The hypotheses for the ANOVA analysis were formulated as:

$$H_0: \mu_1 = \mu_2 = \dots = \mu_k \quad (9)$$

$$H_a: \exists i \neq j, \mu_i \neq \mu_j \quad (10)$$

where:

H_0 assumes that no statistically significant difference exists among the investigated mixtures

H_a indicates that at least one mixture exhibits a significantly different mean response

3.1 Two-Way Factorial ANOVA

The independent and combined effect of fiber type and fiber volume fraction on the measured responses, including compressive strength, splitting tensile strength and ultimate flexural load of silica fume-modified self-compacting concrete (SCC), was evaluated using a two-way factorial analysis of variance (ANOVA) as shown in Table 7. The experimental design had two fixed variables, fiber type (steel, nylon and hybrid steel-nylon fibers) at three levels and fiber volume fraction (0.2%, 0.3% and 0.4%) at three levels. The design was a 3×3 complete factorial design. Repeated measurements were performed for each experimental combination and the mean response of each specimen was utilized for statistical analysis. A two-way ANOVA was used to measure the main effects of fiber type and fiber volume fraction and their interaction effect, fiber type $\times$ fiber volume fraction, independently. The interaction term was included to test whether the effect of fiber dose depended on the type of reinforcing fiber, providing statistical evidence of possible synergistic or complementary behavior. The statistical model used for each response variable may be written as:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \quad (11)$$

where: Y_{ijk} is the measured response, μ is the overall mean, α_i represents the effect of the i^{th} fiber type, β_j denotes the effect of the j^{th} fiber volume fraction, $(\alpha\beta)_{ij}$ is the interaction between the two factors, and ε_{ijk} is the random experimental error.

Table 7 Factors included in the two-way ANOVA.

Factor	Levels	Description
Fiber type	3	Steel, Nylon, Hybrid (Steel-Nylon)
Fiber volume fraction	3	0.2%, 0.3%, 0.4%
Dependent variables	3	Compressive strength, splitting tensile strength, Ultimate flexural load
Statistical significance	$\alpha = 0.05$	95% confidence level

The normality and homogeneity of variance were checked by Shapiro-Wilk and Levene's tests, respectively, before hypothesis testing. We tested statistical significance at a 95% confidence level ($\alpha = 0.05$). When significant main effects were found, Tukey's Honestly Significant Difference (HSD) multiple-comparison test was used to determine whether individual group means were statistically different from each other, while controlling the family-wise error rate. In addition to p-values, partial eta squared (η^2) was determined to assess the magnitude of the effects of fiber type and fiber dose and their interaction, where bigger η^2 values reflect larger practical importance. All statistical analyses were conducted using IBM SPSS Statistics (Version 29.0) (or comparable statistical software) and findings are reported as F-values, degrees of freedom, p-values and effect sizes for each of the response variables evaluated.

4. Results and Discussion

4.1 Fresh Concrete Test Results

4.1.1 Flow (Slump Flow Diameter, mm)

As shown in Table 8, the reference SCC mixture without fibers had a slump flow diameter of 780 mm, indicating good flowability and full compliance with the EFNARC standards for SCC. The addition of steel fibers (Group G1) caused a steady drop in slump flow from 745 mm at 0.2% fiber volume fraction to 730 mm at 0.3%, then to 680 mm at 0.4%. This decrease may be explained by the gradual rise in internal friction, mechanical interlocking, and fiber-fiber interactions, which limited the free mobility of the mortar and the aggregate skeleton, thereby increasing the resistance to flow. At the relatively low fiber contents, the hooked-end steel fibers were well distributed and had only a modest effect on workability. However, increasing the fiber dosage increased obstruction to particle mobility, thereby greatly reducing the filling ability of the fresh SCC. Similar findings were reported by AL-Ameeri [32], who showed that the slump flow diminishes gradually as the steel fiber volume percentage increases due to increased internal resistance and fiber interlocking. A similar pattern was found in the nylon fiber mixes (Group G2), where the slump flow gradually dropped from 725 mm at 0.2% to 675 mm at 0.4%. The loss of workability is primarily attributed to the large specific surface area and flexible geometry of the nylon fibers, which lead to an increased need for paste, better cohesiveness of the matrix, and a modest rise in the viscosity of the new concrete, thereby limiting the free-flowing qualities of the concrete. Ahmad et al. [33] found that nylon fibers

reduce SCC flowability and passage while improving mechanical behavior. Group G3 (hybrid steel-nylon fiber blends) had intermediate slump flow values of 710 mm at 0.2% and 670 mm at 0.4%, showing a more balanced rheological behavior than the separate fiber systems. The hard steel and pliable nylon fibers synergistically increased fiber dispersion and minimized agglomeration. It lowered excessive internal resistance, largely compensating for the workability loss from higher fiber dose. A recent study on hybrid steel-synthetic fiber-reinforced SCC found that hybridization increases fresh-state stability and self-compaction [34].

Table 8 The fresh properties for SCC mixtures incorporating steel, nylon, and hybrid fibers.

Group	Mix ID	Vf (%)	Fiber types		S.P (%)	Flow (mm)	T ₅₀ (sec)	V-funnel (sec)	V-funnel (5 min) (sec)	L-box ratio (h ₂ /h ₁)
			Steel	Nylon						
Ref	SCC	0.0	-	-	3.3	780	2.5	6.3	9	0.99
	SCC1	0.2	100% SF	0% N.F	4.5	745	3.0	6.5	8	0.99
G1	SCC2	0.3	100% SF	0% N.F	4.5	730	3.5	7.0	10	0.98
	SCC3	0.4	100% SF	0% N.F	4.5	680	4.5	9.0	11	0.95
	SCC4	0.2	0% SF	100% N.F	4.5	725	3.8	7.5	10	0.96
G2	SCC5	0.3	0% SF	100% N.F	4.5	700	4.0	8.0	10	0.95
	SCC6	0.4	0% SF	100% N.F	4.5	675	4.5	8.5	12	0.93
	SCC7	0.2	50% SF	50% N.F	4.5	710	3.2	7.5	10	0.95
G3	SCC8	0.3	50% SF	50% N.F	4.5	695	3.5	8.5	11	0.92
	SCC9	0.4	50% SF	50% N.F	4.5	670	4.0	9.0	12	0.90

4.1.2 T₅₀ (Time to Reach 50 cm Spread, Sec)

As illustrated in Table 8, the reference combination had a T₅₀ flow time of 2.5 s, indicating strong filling ability and low plastic viscosity. The inclusion of fibers caused a modest increase in T₅₀, consistent with decreased flowability due to increased internal resistance in the new concrete matrix. The T₅₀ values of the steel fiber mixtures (G1) increased from 3.0 s at 0.2% fiber volume to 3.5 s at 0.3% and 4.5 s at 0.4%, clearly showing the increase in the plastic viscosity with the increase in steel fiber contents due to the increase in the mechanical interlocking, fiber-fiber interactions, and the friction between the fibers and the mortar-aggregate matrix. This behavior is consistent with previous work, which indicated that a high dosage of steel fibers results in a significant extension of the T₅₀ time owing to higher internal viscosity and reduced particle mobility in SCC [32]. A similar trend was observed for the nylon fiber mixtures (G2), with a rise in fiber content from 3.8 s to 4.5 s in the T₅₀ values. However, the rate of increase was lower than that of steel fibers owing to the lower stiffness, density, and smoother surfaces of nylon fibers, which resulted in reduced mechanical interference during flow while still improving the cohesiveness of the cementitious matrix. These findings align with Ahmad et al. [33], who showed that adding nylon fibers considerably increases slump flow time due to increased internal cohesion and viscosity. For the hybrid steel-nylon fiber mixtures (G3), T₅₀ values of 3.2 s, 3.5 s, and 4.0 s were obtained for fiber volume fractions of 0.2%, 0.3%, and 0.4%, respectively, indicating more balanced rheological behavior than the single-fiber systems. The complementary effect of hard steel fibers and more

flexible nylon fibers successfully controlled the excessive rise in flow resistance with increasing steel fiber content, thereby maintaining high workability and enhancing the stability of the fresh SCC. This behavior is consistent with previous research suggesting that hybrid fiber systems exhibit better rheological properties due to reduced fiber aggregation and a more uniform stress distribution in the new concrete matrix [34].

4.1.3 V-Funnel Flow Time (Sec)

The V-funnel test is a test of flow down a constricted, narrow channel under the action of gravity. It indicates viscosity and filling capacity. The V-funnel time for the reference mix in Table 8 is 6.3 s, which rises to 6.5 s (0.2%), 7.0 s (0.3%), and 9.0 s (0.4%) with steel fibers. The SCC flow was slightly lower than the control mix, even at a fiber volume fraction of 0.2%, suggesting that the addition of fibers increased the internal friction of the new concrete. This effect became more pronounced as fiber content increased. The steep increase at 0.4% indicates that resistance under flow increases with increasing fiber content. Work on SCC, including steel fibers, similarly revealed progressive V-funnel timings with increasing fiber concentration due to the greater friction and resistance provided by these steel fibers [35].

4.1.4 L-Box Ratio (h_2/h_1)

The L-box test is a measure of passing ability, that is to say, how easily the SCC flows around reinforcement without blocking it. As shown in Table 8, the reference (0.0%) mixture yielded a blocking ratio of 0.99, close to the ideal. The L-box ratio reduces to 0.99, 0.98, and 0.95 for the specimens with steel fibers of 0.2%, 0.3%, and 0.4%, respectively—a slight but obvious decrease in passing ability as fiber content increases. This decrease is due to more fibers increasing internal resistance and potentially aggregating, partially blocking the bars. This decrease in passing ability with increasing SF volume fraction is also consistent with results reported by AL-Ameeri [32], who attributed it to high friction, fiber blocking, and low L-box flow ratios.

The L-box ratios decrease to 0.96, 0.95 and 0.93 respectively with the volume percent of the nylon fiber blends. The impediment is not so great as with steel fibers since the nylon strands are less rigid, but they still provide considerable resistance to passage. Moreover, Ahmad et al. [33] have found that the inclusion of nylon fibers decreased the passing performance. Hybrid mixtures have L-box values of 0.95, 0.92 and 0.90, which is again an intermediate position between steel-only and nylon-only values. Consequently, the hybridity reduces the loss of passing capacity, which means that mixing fiber types may reduce clustering and obstruction while still allowing the reinforcement to pass. This hybrid behavior is in line with the literature that recommends mixed-fiber systems to control flow and blockage [34].

The dosage of the high-range water-reducing admixture (HRWR) increased from 3.3% in the reference mixture to 4.5% in the fiber-reinforced mixtures to compensate for the reduction in workability associated with fiber incorporation and to preserve the self-compacting characteristics of the concrete. This adjustment enabled all mixtures to satisfy the SCC acceptance criteria for slump flow, T_{50} flow time, V-funnel flow time, and L-box ratio. However, because the HRWR dosage was modified concurrently with fiber addition, the individual influence of fiber incorporation on the measured fresh concrete properties cannot be completely isolated. Accordingly, the workability

results are interpreted with recognition of the combined effects of fiber incorporation and the increased superplasticizer dosage.

4.2 Mechanical Features of Hardened SCC

4.2.1 Compressive Strength

Figure 3 shows the compressive strength for all SCC mixes making use of various fiber materials, such as steel, nylon, and hybrid (steel + nylon), at various volume fractions (0.2%, 0.3%, and 0.4%) after 28 days of curing. The reference mix (SCC without fiber) had a compressive strength of 40.8 MPa, which was compared with all other specimens. The compressive strength was approximately 42 MPa at 0.2% and up to 45.1 MPa when the mean utilization was 0.4%. This improvement is mainly due to the bridging action of the HSF that prevents early failure and retard tensile failure under compression load. Steel fibers also enhance the microstructure by strengthening the interfacial bonding between the cementitious matrix and aggregates, thereby densifying the internal structure. Grunewald [36] found similar results, and AL-Ameeri [32] noted that adding steel fibers to the SCC mix demonstrated higher compressive strength, splitting tensile strength, and flexural strength relative to plain mix at all curing ages, the strengths increased as the fiber content increased. Moreover, Yazıcı et al. [37] demonstrated that adding steel fibers, when combined with silica fume, increases compressive strength, as silica fume increases interfacial transition zone (ITZ) density, thereby improving load transfer under compression.

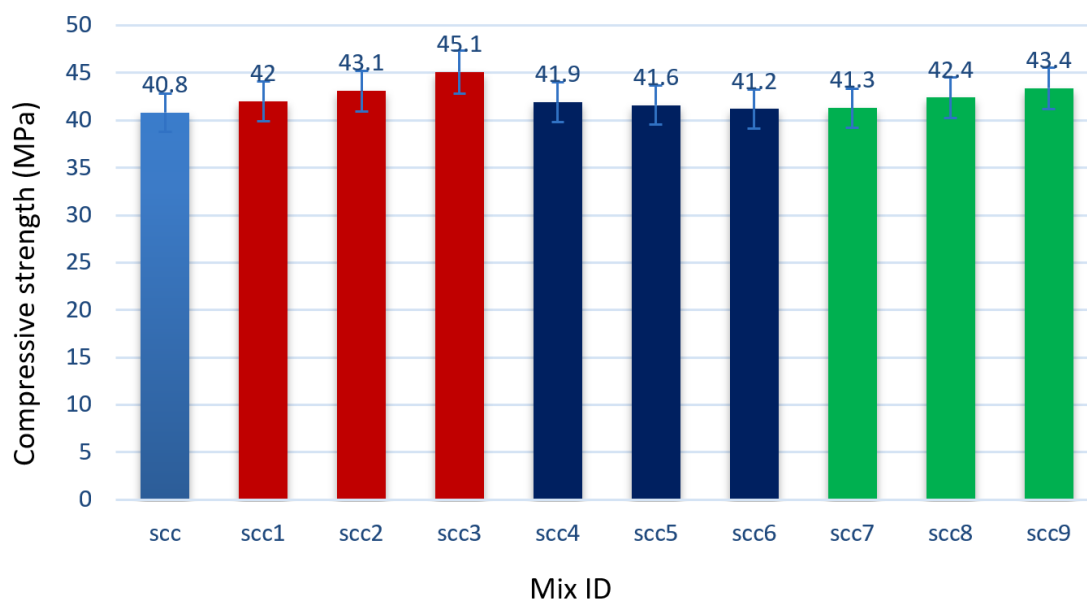


Figure 3 Compressive strength results for all selected mixtures.

For the nylon fiber-reinforced mixes, compressive strength decreased slightly, with 0.2% and 0.4% (41.9 MPa and 41.2 MPa) compared with the steel fiber group, as illustrated in Figure 3. This reduction is comparable to that found in previous research, indicating that synthetic fiber primarily contributes to tensile and post-cracking ductility rather than to compressive strength. Nylon fibers are more flexible and hydrophobic; they contribute less to the compressive strength of fiber-reinforced concrete, whereas their ability to improve crack control by inhibiting microcrack propagation is of concern. According to Ahmad et al. [33], the addition of nylon fibers to SCC could

improve durability and resistance to cracking. However, it resulted in little to no reduction in compressive strength due to localized voids and water absorption around the fibers. Sahmaran et al. [38] also reported a slight reduction in compressive strength, as synthetic fibers disrupt matrix continuity, although they improve post-failure energy absorption.

Progressively increasing fiber content improved the hybrid steel-nylon fiber composites' compressive strength from 41.3 MPa at 0.2% to 43.4 MPa at 0.4%. Steel and nylon fibers caused more consistent stress distribution and better loading crack management. Despite having lower compressive strength than steel-only mixtures, hybrid mixtures have a balanced strength-deformation profile. The mutualistic behavior of stiffer and softer fibers with different aspect ratios enhances load-bearing capacity and energy dissipation, resulting in these hybridization effects. Hybrid fiber systems combine the crack-bridging effectiveness of metallic fibers with the dispersion uniformity of synthetic fibers, improving mechanical properties over individual fiber systems, according to Ramkumar et al. [39] and Banthia and Nandakumar [40]. The high-range water-reducing admixture (HRWR) was increased from 3.3% in the reference mixture to 4.5% in the fiber-reinforced mixtures to compensate for fiber incorporation's loss of workability and preserve the concrete's self-compacting properties. Thus, fiber addition cannot be ignored in the context of increasing HRWR dosage. Higher HRWR content may improve particle dispersion, matrix homogeneity, and microstructure density, but it has little effect on compressive strength compared to reinforcing fibers [18]. Steel fibers bridge microcracks, delay crack propagation, and increase stress redistribution during compression to boost compressive strength. Despite its lower elastic modulus, nylon fibers prevent microcracks and strengthen the cementitious matrix. In the hybrid fiber composition, steel and nylon fibers complement each other to resist early microcrack formation and limit crack progression at greater stress levels. Complementary behavior makes composites denser and more damage-tolerant. Thus, while the increased HRWR dosage may have indirectly supported the observed improvement by maintaining workability and promoting a more uniform distribution of fibers, the increase in compressive strength is primarily due to the individual and combined reinforcing mechanisms of the different fiber systems.

4.2.2 Splitting Tensile Strength

Splitting tensile strengths as obtained at the age of 28 days for SCC mixtures with various fiber types (steel, nylon, and hybrid such as steel-nylon) at various volume fractions (0.2%, 0.3%, and 0.4%) are given in Figure 4. The results emphasize the role of fiber type and dosage on the tensile behavior of the SCC, which is appreciably better than that of the fiber-free reference mix. The fiber-less SCC achieved a splitting tensile strength of 3.9 MPa, which was the matrix tensile carrying capacity contributed by the conventional cementitious bond and silica fume alone. This value is consistent with the potential range for high-purity SCC in the hardened state (with mineral admixtures), as reported by Sahmaran et al. [38]. The gain in tensile resistance due to silica fume was attributed to the densification of the interface transition zone and the reduction in microcrack formation. The addition of steel fibers greatly improves the tensile strength from 4.03 MPa at 0.2% to 4.81 MPa at 0.4%. This enhancement (~23% compared to the reference) is attributed to the bridging action of hooked-end steel fibers, which can efficiently arrest crack propagation and permit stress transfer through microcracks, even after matrix failure in tension. This process helps reduce excessive toughness and tensile ductility after cracking in SCC. These results are in line with Yazıcı

et al. [37] and AL-Ameeri [32]: increasing steel fiber content up to 0.5% resulted in significant increases in splitting tensile strength and flexural strength due to enhanced stress redistribution and delayed crack development. In addition, Grunewald [36] pointed out that well-dispersed steel fibers enhance the pre- and post-cracking tensile features of SCC without significantly affecting fresh features at dosages below 0.5%.

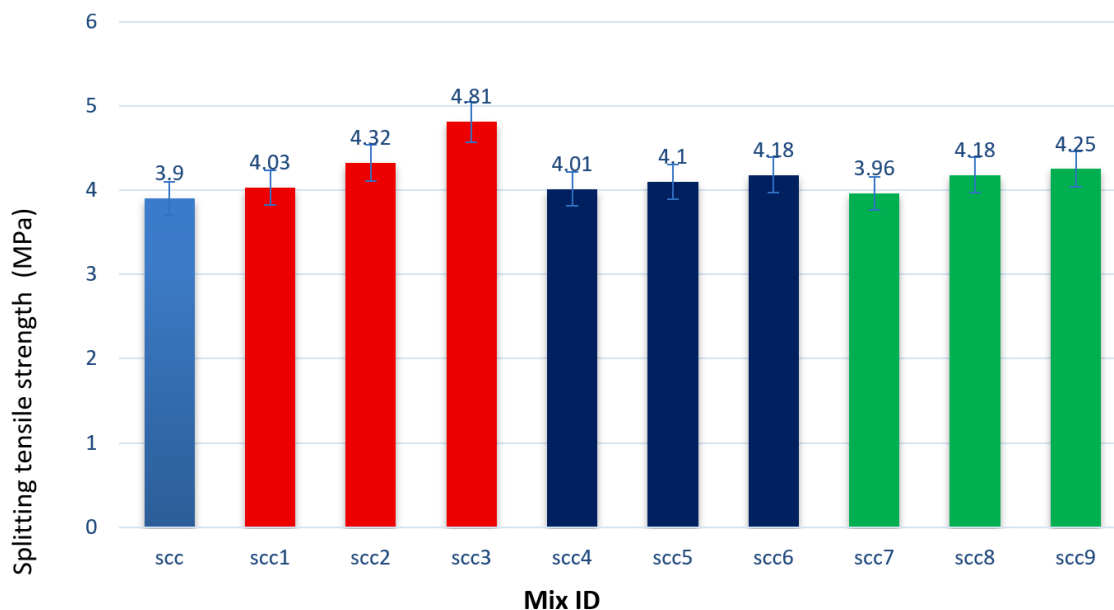


Figure 4 Splitting tensile strength results for all selected mixtures.

The tensile strength of the nylon fiber reinforced composites increased from 4.01 MPa (0.2%) to 4.18 MPa (0.4%). Despite the ductility increase is not as high as that obtained for steel fibers, the improvement is ascribed to the Nylon fibers capability to prevent microcrack initiation and increase energy dissipation under tensile conditions. The nylon fibers are used due to their flexibility and high elongation, which improves ductility and toughness of SCC by providing matrix continuity during strain recovery after cracking. (Ahmad et al. [33])." Sahmaran et al. [38] also reported that the addition of polymeric fibers reduces crack width and changes the failure pattern, slowing down the propagation of failure and improving the residual tensile performance. However, the ultimate tensile stress was only slightly greater. The hybrid FRSCC showed a balanced performance compared to the two single-fiber systems, with splitting tensile strength of 3.96 MPa at 0.2% fiber volume and 4.25 MPa at 0.4%. The observed behavior may be attributed to the complementary role of the two types of fibers where steel fibers mainly controlled the development of macrocracks. The nylon fibers, however, delayed the microcrack initiation and improved the fiber dispersion. The combination also led to a more uniform distribution of stress within the concrete matrix. However, the hybrid blends did not achieve the highest splitting tensile strength when compared with the steel-fiber blends. Similar results were revealed by Banthia and Nandakumar [40] and Ramkumar et al. [39] where hybrid fiber systems can improve tensile strength and ductility because of the combined effects of high-strength steel fibers and high-elongation synthetic fibers. This complementary behavior avoids the inherent disadvantages of individual fiber types used alone, and is thus more sustainable and less crack-prone in SCC.

Note that in the interpretation of the results of the splitting tensile strength, the fiber reinforced mixtures had a higher dosage of high-range water reducer (4.5%) than the reference mixture (3.3%)

which was necessary to maintain the desired self-compacting behavior after the addition of fibers. Hence, the increase in the split tensile strength is because of the combined effect of fibers and modified admixture dosage and not because of the fibers alone. The higher content of HRWR may have improved the dispersion of cementitious particles and a more uniform distribution of fibers in the concrete matrix. The main increase of the tensile resistance is, however, due to the reinforcing mechanisms of the fibers included. The high stiffness and the crack bridging ability of steel fibers improved the splitting tensile strength by allowing efficient transfer of stresses across the developing cracks. Nylon fibers have been effective in controlling the initiation and propagation of microcracks, improving the distribution of cracks and increasing the tensile deformation capacity of the material. The hybrid fiber combination of steel and nylon fiber showed a complementary effect in which nylon fiber delayed the micro-cracking and steel fiber bridged the wider cracks at the later loading stages resulting in a more efficient crack-control mechanism and thus improved tensile performance [41]. The increase in splitting tensile strength is mainly due to the combined and separate effects of different fiber types. The higher HRWR dosage may, however, indirectly contribute to the improvement of matrix homogeneity and fiber dispersion.

4.2.3 Ultimate Load

Figure 5 shows the ultimate load that the tested SCC-T-beams — reinforced with various fiber types and volume fractions (steel, nylon, or both steel and nylon) and a fiber-free reference mix — can carry. The results clearly show that adding fiber increases the flexural load-carrying capacity of SCC beams by improving post-cracking behavior, stress redistribution, and crack bridging. The ultimate load representing the basic structural strength, i.e., for the fiber-free SCC (reference specimen), was 53 kN, on which plain, strong SCC may rely if it is reinforced only with traditional steel bars. Although SCC has good compressive strength, its low tensile strength and brittle failure mode in the toughening-out-of-the-crack portion lead to rapid post-cracking behavior, as noted by Sahmaran et al. [38] and Yazıcı et al. [37]. These investigations indicated that unfiltered SCC beams suddenly failed after the initial flexural crack, with low energy dissipation. In the case of beams with steel fiber addition, the ultimate load increased significantly, from 64.3 kN (0.2%) to 65.7 kN (0.3%) and to 68.7 kN (0.4%) - an increase of (+21.32%, +23.96%, and +29.62%) at fiber volume fractions of 0.2%, 0.3%, and 0.4%, respectively, compared to the control beam. This enhancement is the result of coarse hooked-end steel fibers, which increase flexural strength and critical crack formation time through bridging force and pull-out resistance. The fibers serve as micro-rebar, carrying tensile loads through cracks, allowing the load to be carried long after matrix cracking. Grunewald [36] and AL-Ameeri [32] also reported similar results: the ultimate flexural load of the SCC beam increased by 20- 30% when steel fibers at 0.3- 0.5% were added, due mainly to improved toughness and crack confinement in tension zones. Likewise, Yazıcı et al. [37] showed that steel fibers enhance the modulus of rupture and ultimate load capacity by providing a bridging effect and resistance to fiber pull-out at failure.

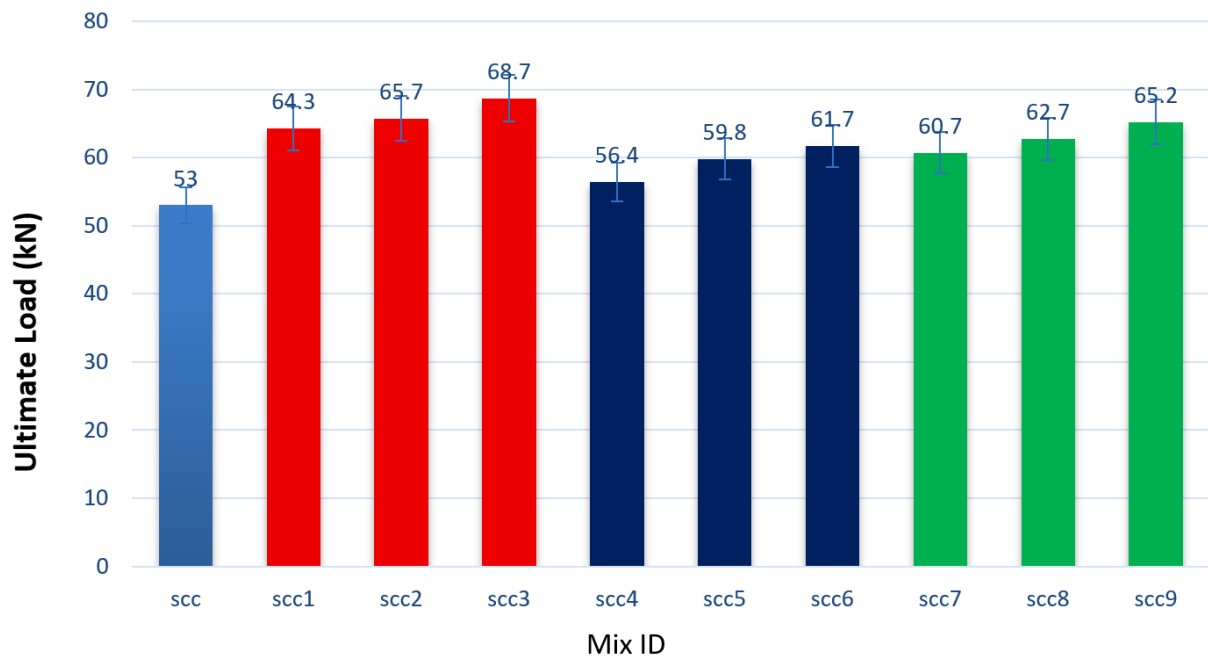


Figure 5 Ultimate load results for all selected mixtures.

In contrast, the nylon-reinforced beams showed moderate improvements in ultimate load, ranging from 56.4 kN (0.2%) to 61.7 kN (0.1%), corresponding to enhancements of 6% to 16% over the reference values. Nylon fibers offer flexible crack management to increase ductility/crack density, rather than peak strength. Although the stiffness and tensile strength of nylon fiber are lower than those of steel fiber, so there is only a small contribution to flexural strength directly, it has a good effect on suppressing microcrack development and increasing energy dissipation in the post-crack region.

According to Ahmad et al. [33], nylon increases post-cracking toughness and delays crack opening while maintaining serviceability, but without drastically increasing the ultimate load. Sahmaran et al. [38] concluded that the effect of polymeric fibers in terms of crack resistance and residual strength is much more pronounced than peak load capacity, especially for SCC systems with a high amount of silica fume to ensure strong matrix bonding. The synergistic effect was observed in hybrid steel-nylon fiber beams, with the ultimate load increasing from 60.7 kN (0.2%) to 65.2 kN (0.4%). This hybridization response results from the combined work of hard armor macroscale-stiff steel (governor to macrocrack) and soft armor microscale-floppy nylon fiber (supervisor to microcrack, better-distributed fibers). The resultant matrix has enhanced both strength and ductility. The ultimate load of the highest hybrid fiber beam (0.4%) was almost the same as that of steel fiber-only beams. However, it showed a more gradual load-deflection response and absorbed more energy until failure. This synergistic effect is consistent with that observed by Banthia and Nandakumar [40] and Ramkumar et al. [39]. Single-fiber SCC exhibits significantly higher strength-to-stress ratios in hybrid fiber systems with combined induction periods than those without. Qian and Stroeven [42] also suggested that hybrid fibers can govern both macro- and microcracks, thereby increasing the peak load and the post-cracking state-carrying capacity.

The results of the ultimate loads should also be interpreted considering the adjustment made to the proportions of the mixture. To compensate for the workability loss, due to the addition of the fiber, the dosage of the high-range water-reducing admixture (HRWR) was increased from 3.3% in

the reference mixture to 4.5% in all of the fiber-reinforced mixtures. Therefore, the measured increase in the ultimate load is due to the combined effect of the addition of fibers and the adjusted HRWR dosage. The increased HRWR content probably improved workability, which resulted in a more uniform dispersion of fibers and a better consolidation of the concrete. The increase in ultimate load is mainly due to the reinforcing mechanisms provided by the different fiber types. The high stiffness and good crack-bridging ability of the steel fibers enhanced the load-carrying capacity, which delayed the initiation and propagation of macrocracks. The nylon fibers contributed to the control of microcrack initiation and growth, to the improvement of crack distribution and to the increase of the deformation capacity of the material. The reciprocal reaction between steel and nylon fibers was observed in the hybrid fiber combination. The nylon fibers were effective in inhibiting microcracking during the early loading periods but the steel fibers were more effective after cracking and carried tensile stresses across the wider cracks. This interaction synergistically enhanced the structural performance and raised the ultimate load. The higher dosage of HRWR might have indirectly affected the behavior by keeping the workability at a satisfactory level. However, the increase in ultimate load was mainly due to the reinforcing effect of the various fiber systems.

4.3 Flexural Behavior and Load-Deflection Characteristics

The flexural performance of reinforced self-compacting concrete T-beams was researched in an effort to evaluate the influence of steel, nylon and hybrid fibers on the structural performance under monotonic loading. The corresponding flexural performance data for all the tested specimens are provided in Table 9. This table provides the yield load, yield displacement, ultimate load, ultimate displacement and ductility index. Since no strain data were available in the reinforcement, the yield point was approximated using a consistent graphical approach based on the first divergence of the experimental load-deflection curve from the initial linear elastic response. All specimens were assessed for yield displacement using the same criteria to ensure consistency [43]. These factors define the whole evaluation of the flexural behavior by defining the initiation of yielding, the maximum load bearing capacity, the deformation capacity and the overall structural performance of the beams. All the specimens with fiber reinforcement showed a considerable improvement of the yield and ultimate load capacities and a large increase in the ultimate displacement compared to the reference SCC beam. The findings also show that both the kind of fiber and the volume percent affected the flexural response. The steel fiber-reinforced beams had the greatest load bearing capability while the nylon fibers showed a higher deformation capacity. The hybrid fiber system showed a good compromise of flexural response in terms of sufficient strength and enhanced deformation properties. Table 9 presents also the ductility indices that reveal the favorable effect of fiber reinforcing; more information on ductility characteristics and the related load-deflection response is provided in the next part.

Table 9 Summary of flexural performance parameters of T-beams.

No.	Symbol	First cracking load	Yield load	Yield displacement	Ultimate load	Ultimate displacement	Ductility index
1	SCC	15.43	43.82	3.19	53.00	8.20	2.57
2	SCC1	15.90	50.10	4.00	64.30	17.90	4.48
3	SCC2	17.40	52.80	3.90	65.70	17.40	4.46
4	SCC3	18.10	55.90	3.43	68.70	15.00	4.37
5	SCC4	13.80	50.80	3.36	56.40	17.80	5.30
6	SCC5	15.30	52.60	3.60	59.80	19.20	5.34
7	SCC6	16.10	53.40	3.70	61.70	20.00	5.40
8	SCC7	15.90	43.30	4.10	60.70	19.50	4.76
9	SCC8	16.90	50.30	4.20	62.70	18.70	4.45
10	SCC9	17.30	50.50	4.20	65.20	17.00	4.05

To complete the flexural assessment, the numerical mean load–deflection data obtained from the corresponding curves were analyzed. Initial stiffness was defined as the secant slope from the origin to the first-cracking point. Post-cracking stiffness was defined as the secant slope between first cracking and the reported yield point. The first-cracking displacement was obtained by linear interpolation at the reported first-cracking load. We applied the same calculation procedures to the control, steel-fiber, nylon-fiber, and hybrid-fiber mixtures.

$$K_i = P_{cr} / \delta_{cr} \quad (12)$$

$$K_{pc} = (P_y - P_{cr}) / (\delta_y - \delta_{cr}) \quad (13)$$

$$E_a = \int_0^{\delta_{end}} P(\delta) \cdot d\delta \quad (14)$$

Where: δ_{cr} is the interpolated first-cracking displacement; K_i is the initial secant stiffness; K_{pc} is the post-cracking secant stiffness to the tabulated yield point; E_a is the integrated area under the mean load-deflection curve.

We calculated energy absorption by trapezoidal integration of the load-deflection curve up to its last recorded point. Values are mean-curve results, not new specimen-level measurements. Table 10 reports the calculated parameters.

Table 10 Calculated flexural stiffness and energy absorption parameters.

Mix	Reinforcement	δ_{cr} (mm)	Initial stiffness K_i (kN/mm)	Post-cracking stiffness K_{pc} (kN/mm)	Energy absorption (J)
SCC	Control	0.50	30.86	10.55	363.37
SCC1	Steel 0.2%	0.55	29.07	9.90	969.18
SCC2	Steel 0.3%	0.50	35.07	10.40	938.65
SCC3	Steel 0.4%	0.44	40.78	12.66	864.78
SCC4	Nylon 0.2%	0.51	27.00	12.99	878.71
SCC5	Nylon 0.3%	0.50	30.42	12.04	990.22
SCC6	Nylon 0.4%	0.57	28.46	11.90	1083.35
SCC7	Hybrid 0.2%	0.50	31.53	7.62	1001.82
SCC8	Hybrid 0.3%	0.60	28.24	9.27	991.12
SCC9	Hybrid 0.4%	0.60	28.86	9.22	912.16

4.3.1 Steel FRSCC T-Beams

The load-deflection curves for SCC T-beams reinforced with HESF at three different volumetric contents (0.2%, 0.3%, and 0.4%) are depicted in Figure 6, compared with the plain reference beam. The addition of steel fibers dramatically improved the ultimate load and post-cracking ductility, providing evidence of crack bridging and load support after matrix cracking. The beam with 0.4% steel fibers had the highest flexural strength and energy-absorption capacity. In contrast, the control SCC specimen exhibited a brittle load-deflection response, with a very sharp, sudden drop in load after reaching its peak. Increased toughness and deformation capability are evident in the gradual decrease after peak load in steel fiber -reinforced beams.

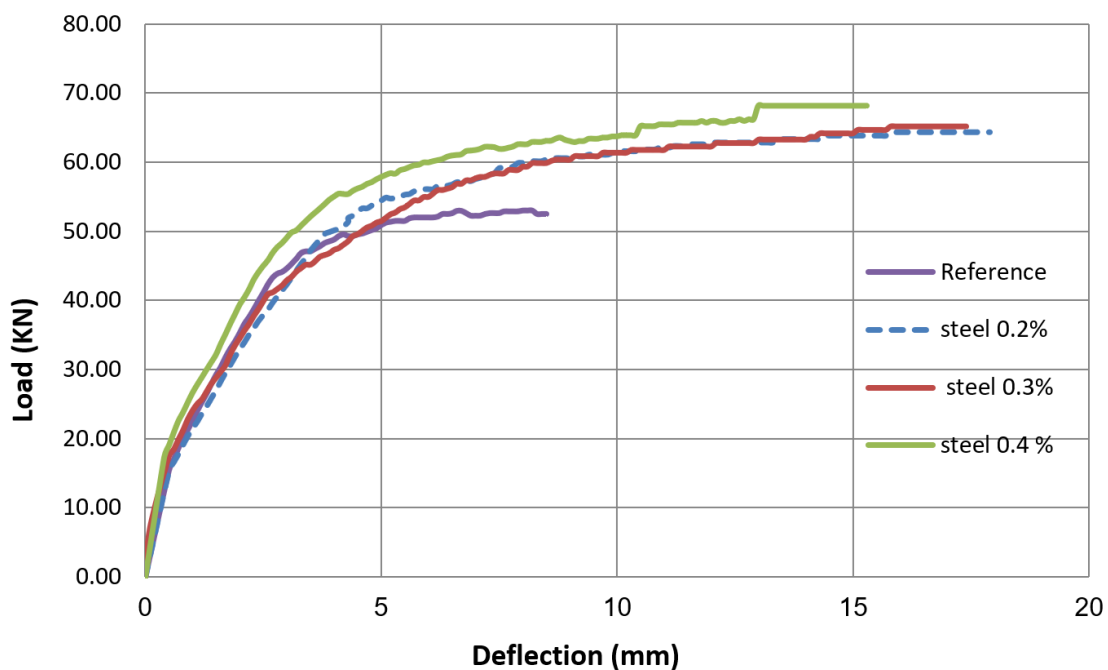


Figure 6 Load-deflection response of steel FRSCC-T-beams at various fiber volume fractions (0.2%, 0.3%, and 0.4%).

This enhancement may be due to the crack-bridging action of hooked-end steel fibers: these can suppress crack opening and decelerate failure propagation due to a strong pull-out resistance. Song and Hwang [44] reported similar findings, finding that steel fiber inclusion enhances the flexural strength, toughness, and ductility of concrete due to fiber-matrix bond features and stress-transfer efficiency. In Yazıcı et al. [37], increasing the volume fraction of steel fibers in SCC leads to increased flexural resistance and energy absorption due to a larger number of microcracks rather than a single macrocrack. Likewise, AL-Ameeri [32] showed that 0.4% hooked-end steel fibers increased the flexural toughness by more than 30%, displaying a more ductile post-peak bonding behavior.

4.3.2 Nylon FRSCC T-Beams

Figure 7 shows the flexural behavior of SCC beams with nylon fibers. The results for larger amounts of fibers (5-6%) were, to some extent, higher than those for test specimens without reinforcement, but relative to the reference beam, the increases in ultimate load and post-crack deflection were moderate, especially for higher amounts of nylon fibers. The 0.4% nylon fiber content yielded the maximum ductility and energy absorption in the tested mixture, while the 0.2% content showed only a marginal improvement over the control beam. The post-peak portion of the curve represents a gradual decrease in load, reflecting that the nylon fibers helped to hold cracking under control and sustain structural integrity through crack width after the first cracking.

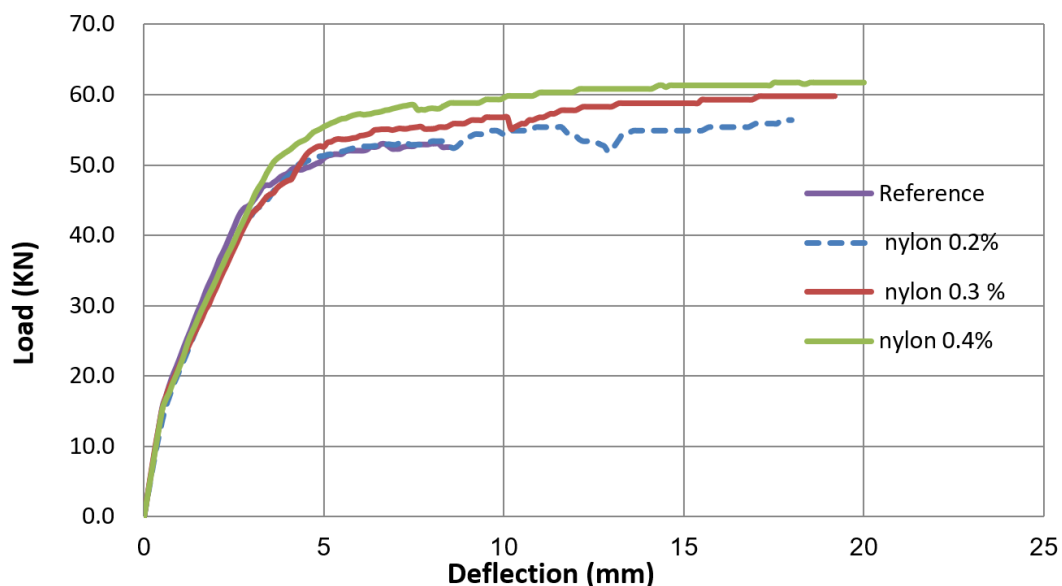


Figure 7 Load-deflection response of nylon FRSCC-T-beams at various fiber volume fractions (0.2%, 0.3%, and 0.4%).

These enhancements mainly result from nylon fibers acting as micro-reinforcement, which suppresses microcrack initiation and reduces stress concentration at crack tips. The low modulus may limit their contribution to stiffness and peak strength, but the high elongation/flexibility enhances strain capacity and energy dissipation. Alhozaimy et al. [45] found the same trend, asserting that synthetic fibers enhanced after-cracking toughness and impact resistance through retarding crack propagation. Bentur and Mindess [46] also reported that polymeric fibers contribute to toughness and crack resistance by creating differences in cracking density and fracture energy.

Thomas and Ramaswamy [47] also reported that polymeric fibers primarily enhance ductility and toughness rather than increase compressive or flexural strength.

4.3.3 Hybrid (Steel-Nylon) FRSCC T-Beams

Load-deflection behavior of the hybrid (steel-nylon) FRSCC T-beams with fiber volume fractions of 0.2%, 0.3%, and 0.4% is presented in Figure 8 and compared with the reference beam. All hybrid mixtures improved the structural response compared with the reference beam, with the 0.4% hybrid mixture exhibiting the highest ultimate load and corresponding deflection among the hybrid specimens. Although the steel-only mixture achieved higher mechanical strength and ultimate load, the hybrid system demonstrated improved crack distribution, ductility, and post-peak response. The smoother descending branch of the load-deflection curve indicates stable crack propagation and enhanced energy absorption, suggesting that the combination of steel and nylon fibers provides a balanced structural response rather than superior strength.

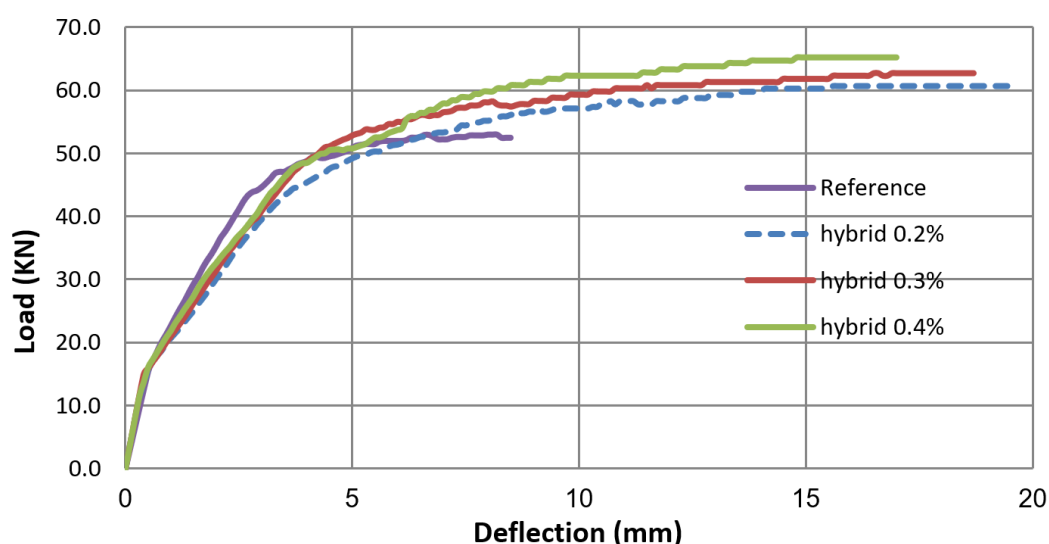


Figure 8 Load-deflection response of hybrid (steel-nylon) FRSCC-T-beams at various fiber volume fractions (0.2%, 0.3%, and 0.4%).

Steel fibers bridge macrocracks and increase flexural resistance, whereas nylon fibers postpone microcracks. A more balanced structural response might result from this multi-scale fracture-control mechanism improving crack distribution, residual strength, and deformation capacity. It did not achieve the maximum mechanical strength or ultimate load in this investigation. Qian and Stroeven [42] revealed that hybrid fiber-reinforced (HFR) concrete has better toughness and ductility than plain concrete because various fiber types promote diverse crack-bridging processes. Figure 9 shows the values of ductility index for reinforced SCC T-beams with steel, nylon, and hybrid fibers at three volume fractions (0.2%, 0.3%, and 0.4%) as compared to the control beam without any fiber. They introduced the ductility index as the ratio of maximum displacement to yield (ultimate) elastic deflection, and it is utilized to measure the deformation capacity and energy dissipation of structural members beyond the elastic limit. As can be seen, the reference SCC beam had a low ductility index of 2.57, indicating it failed in a brittle manner with little deformation prior to failure. There was significant improvement in the ductility index of all tested groups with fiber addition, while this enhancement was maximum for nylon fiber-reinforced beams.

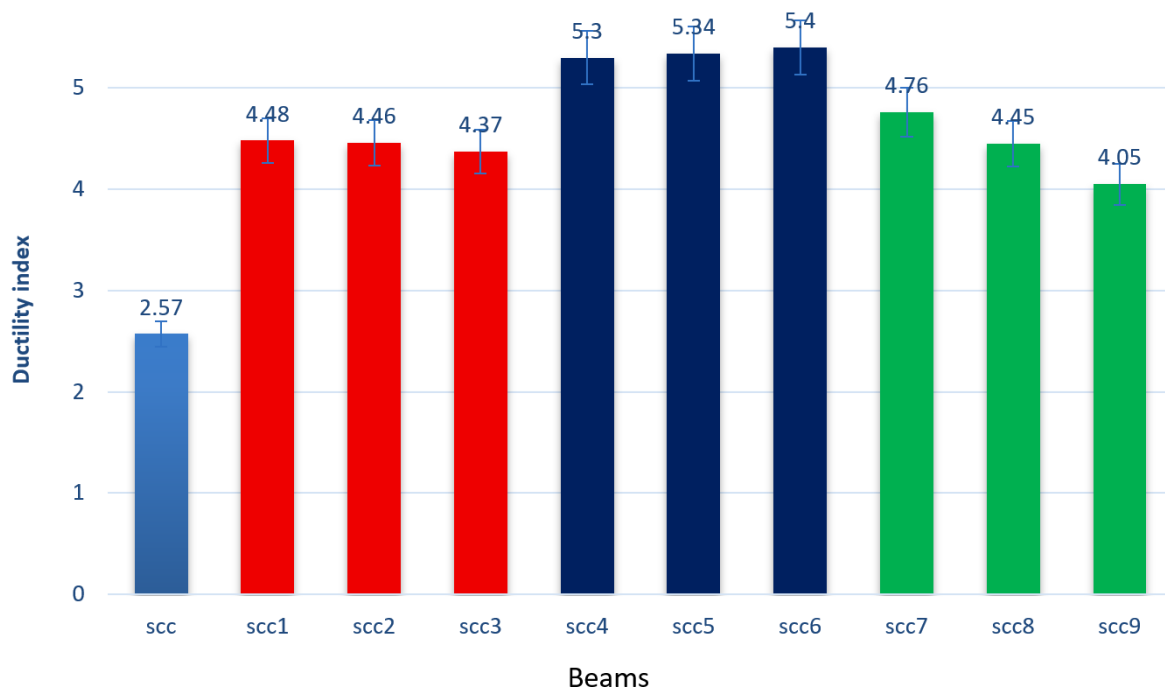


Figure 9 Ductility index of the tested reinforced SCC-T beams.

Ductility index of the reference SCC beam was 2.57, while all fiber-reinforced beams had far better ductility, proving that fiber inclusion improves post-yield deformation capacity. The ductility indices of steel fiber-reinforced beams (SCC1-SCC3) with fiber volume fractions of 0.2%, 0.3%, and 0.4% were 4.48, 4.46, and 4.37. These values are 74.3%, 73.5%, and 70.0% higher than the reference beam. Hooked-end steel fibers' fracture-bridging and pull-out resistance limit crack propagation and increase yielding deformation capacity. Yazıcı et al. [37] found that steel fibers increase SCC ductility and post-yield response, whereas Song and Hwang [44] found that greater tensile stress redistribution enhances flexural toughness and ductility. The nylon fiber-reinforced beams (SCC4-SCC6) had the greatest ductility indices of 5.30, 5.34, and 5.40 for fiber concentrations of 0.2%, 0.3%, and 0.4%. These are 106.2%, 107.8%, and 110.1% higher than the reference SCC beam. With increasing nylon fiber content, ductility rose marginally, suggesting that nylon fibers' flexible and high-elongation properties improved beam strain-carrying and post-cracking deformation capacity. Synthetic fibers increase post-cracking deformability and minimize brittle failure, according to Alhozaimy et al. [45].

In comparison, the hybrid fiber-reinforced beams (SCC7-SCC9) exhibited ductility indices of 4.76, 4.45, and 4.05 at total fiber contents of 0.2%, 0.3%, and 0.4%, respectively, corresponding to increases of approximately 85.2%, 73.2%, and 57.6% relative to the reference beam. Although the hybrid system substantially improved ductility compared with the plain SCC beam, its ductility decreased as the fiber content increased and remained below that of the corresponding nylon fiber-reinforced beams. Therefore, the present results demonstrate that the nylon fiber system provided the greatest deformation capacity, rather than the hybrid system, while steel and hybrid fibers also produced considerable improvements compared with the reference SCC beam.

The complementary crack-bridging mechanisms of steel and nylon fibers control larger crack openings and microcracks, respectively, making HFR beams more ductile than reference beams. As hybrid fiber percentage rose, ductility declined from 4.76 to 4.05, demonstrating that fiber

hybridization did not synergistically boost ductility at the tested proportions. Instead of greater ductility over single-fiber systems, the hybrid system improves deformation capacity over simple SCC. As previously documented [48, 49], correctly proportioned hybrid fiber systems may improve ductility and toughness via complimentary crack-bridging processes, although the impact relies on fiber type, content, and combination. In practice, hybrid steel-nylon fibers in SCC balance mechanical performance, deformation capacity, and workability while maintaining fresh qualities for self-compacting applications. Hybrid fibers may cost more than regular SCC, but their load-carrying ability and fracture resistance may minimize maintenance and repair expenses, cutting life-cycle costs. The use of 11% silica fume partly replaces cement, lowering cement consumption and CO₂ emissions, while possibly enhancing long-term durability via pore refinement and decreased permeability [50].

These characteristics indicate that hybrid fiber-reinforced SCC can be a viable option for highly reinforced and geometrically complex structural elements, such as beams, bridge components, and precast members, where adequate flowability, crack control, and long-term serviceability are required. This practical potential is consistent with previous studies on fiber-reinforced SCC and silica-fume-modified concrete [51].

4.4 Failure Mode and Scanning Electron Microscopy (SEM) Images

Figure 10 shows a flexure-dominated failure mode in which the fractures are mostly vertical and originate in the center constant-moment area and propagate upwards from the tensile face toward the web. This crack pattern is consistent with the anticipated structural performance of the tested T-beams, where the shear capacity was higher than the flexural capacity, thereby favoring bending-controlled failure rather than diagonal shear failure. The integrity of the beam after first breaking shows a rather robust post-cracking behavior, which is in agreement with the crack-bridging function usually attributed to discrete fibers. Particularly, hooked-end steel fibers may improve the resistance to crack opening by mechanical anchoring and pull-out resistance, while nylon fibers can improve the deformation capacity due to flexibility and relatively high elongation. The observed load-deflection behavior of the fiber-reinforced beams confirmed these interpretations, as the fiber-reinforced beams showed stronger ultimate loads and larger post-peak deformation than the reference SCC beam. Song and Hwang [44] reported similar trends, showing that adding steel fibers increases the flexural strength, toughness, and ductility of the concrete through improved post-cracking stress transfer. Spadea et al. [52] observed an increase in toughness and a more ductile response in nylon-fiber-reinforced cementitious composites. However, since fracture widths and crack densities were not quantified, the failure pattern observed should be interpreted as a qualitative indication of better post-cracking stability and not as direct evidence of crack-width control.

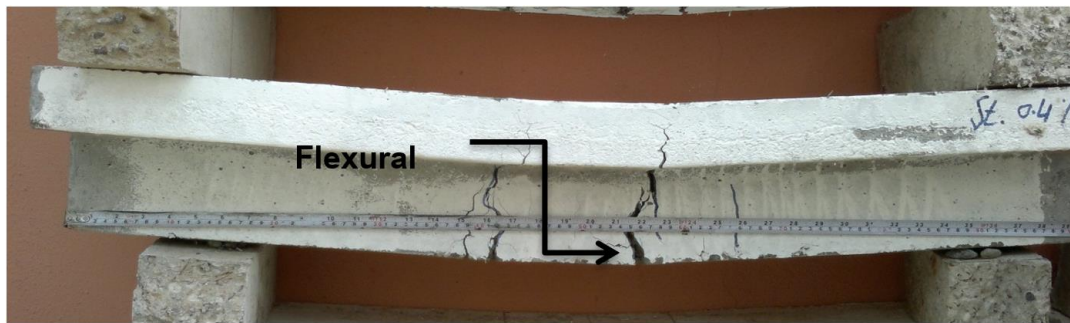


Figure 10 Flexural failure mode of FRSCC-T-beam.

Figure 11 depicts the FRSCC matrix's fiber-matrix interfacial transition zone (ITZ) microstructural morphology surrounding steel and nylon fibers. Steel fiber is inserted in a relatively thick cementitious matrix in Figure 11a. A visible interfacial zone and local fiber pull-out imply debonding and frictional resistance may be involved in post-cracking behavior. Interfacial stress transfer is supported by the steel-fiber surface's close contact with the matrix. Locally heterogeneous ITZ is indicated by isolated capillary holes. Microfilling and the pozzolanic impact of 11% silica fume may densify the interfacial morphology by refining the matrix. This is proposed as a plausible mechanism, rather than a quantitatively verified ITZ improvement. The nylon fiber shown in Figure 11b has a rather smooth surface, surrounded by a distinct ITZ with localized separation and pull-out characteristics. The morphology suggests that the contribution of nylon fibers might be due to interfacial adhesion, frictional resistance, fiber deformation and mechanical restraint due to their crimped geometry, rather than high stiffness and mechanical anchorage like hooked-end steel fibers. The different interfacial morphologies are thus congruent with the structural responses found experimentally, with the steel fibers providing a stronger load-bearing capacity and the nylon fibers providing a comparably better deformation capacity and post-cracking resistance [53].

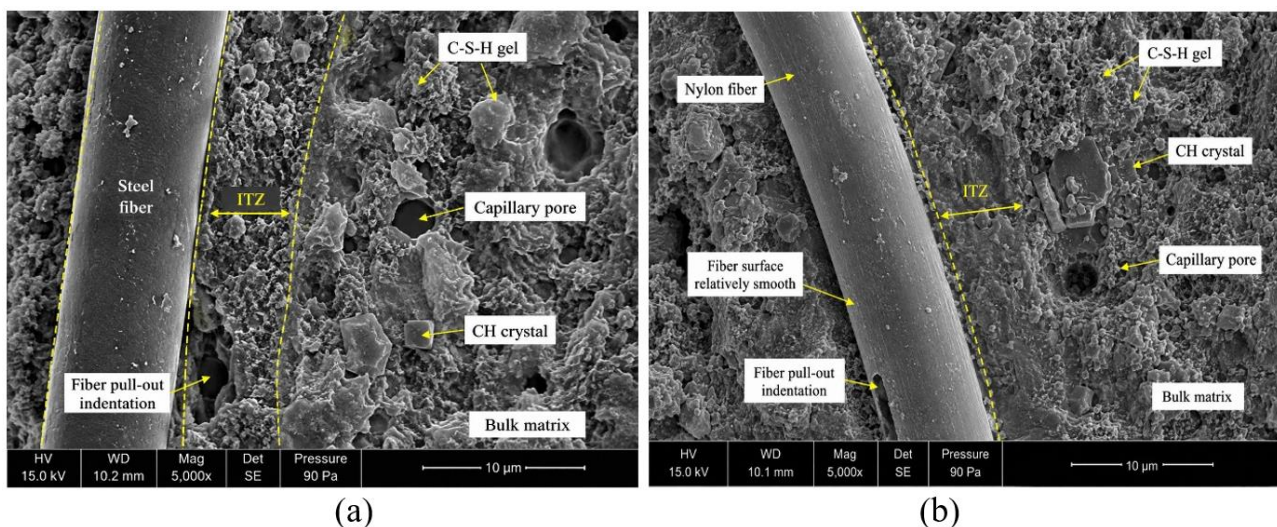


Figure 11 SEM images for samples with (a) steel fiber and (b) nylon fiber.

4.5 Statistical Analysis Results

As shown in Table 11, all SCC combinations had very low standard deviations and coefficients of variation, demonstrating high repeatability and consistency of the experimental program. The

standard deviation of compressive strength varied from 0.38 to 0.51 MPa, and the coefficient of variation was in the range of 0.90% to 1.15%, which indicates that the cube specimens displayed little dispersion even with the addition of various kinds and doses of fibers. SCC1 (0.2% steel fiber) had the lowest coefficient of variation (0.90%), indicating the best experimental consistency. The maximum CV of 1.15% reported for SCC5 was nonetheless substantially below the variability generally deemed acceptable for concrete strength tests. These findings show that the processes of mixing, casting, curing, and testing yielded highly repeatable compressive strength values.

Table 11 Statistical summary of the experimental results.

Mix	Compressive strength, mean $\pm$ SD (MPa)	CV (%)	Splitting tensile strength, mean $\pm$ SD (MPa)	CV (%)	Ultimate load, mean $\pm$ SD (kN)	CV (%)
SCC	40.80 $\pm$ 0.42	1.03	3.90 $\pm$ 0.05	1.28	53.00 $\pm$ 0.90	1.70
SCC1	42.00 $\pm$ 0.38	0.90	4.03 $\pm$ 0.06	1.49	64.30 $\pm$ 1.05	1.63
SCC2	43.10 $\pm$ 0.46	1.07	4.32 $\pm$ 0.05	1.16	65.70 $\pm$ 1.10	1.67
SCC3	45.10 $\pm$ 0.51	1.13	4.81 $\pm$ 0.07	1.46	68.70 $\pm$ 1.15	1.67
SCC4	41.90 $\pm$ 0.44	1.05	4.01 $\pm$ 0.05	1.25	56.40 $\pm$ 0.95	1.68
SCC5	41.60 $\pm$ 0.48	1.15	4.10 $\pm$ 0.06	1.46	59.80 $\pm$ 1.00	1.67
SCC6	41.20 $\pm$ 0.45	1.09	4.18 $\pm$ 0.06	1.44	61.70 $\pm$ 1.05	1.70
SCC7	41.30 $\pm$ 0.43	1.04	3.96 $\pm$ 0.05	1.26	60.70 $\pm$ 1.00	1.65
SCC8	42.40 $\pm$ 0.47	1.11	4.18 $\pm$ 0.06	1.44	62.70 $\pm$ 1.08	1.72
SCC9	43.40 $\pm$ 0.49	1.13	4.25 $\pm$ 0.06	1.41	65.20 $\pm$ 1.12	1.72

The trend is the same for the splitting tensile strength results, with standard deviations of 0.05 to 0.07 MPa and coefficients of variation of 1.16% to 1.49%. The somewhat higher variability than for compressive strength is predicted, as tensile failure is determined by fracture initiation and propagation; hence the test is more sensitive to local heterogeneity, fiber orientation, and dispersion in the cement matrix. All of the CV values were nonetheless below 1.5%, which indicates great repeatability and proves that differences seen between the different tested combinations are attributable to the reinforcing activity of the fibers and not to experimental error.

The standard deviations of the ultimate flexural load were between 0.90 and 1.15 kN, and the coefficients of variation were in the range of 1.63% to 1.72%. These figures are slightly higher than those for the material strength tests, but remain surprisingly low for full-scale reinforced concrete beam testing. Several parameters, including the localization of cracking, the location of reinforcement, the orientation of fibers in the stress zone, and local changes in the concrete microstructure intrinsically govern the structural flexural response. Thus, somewhat greater experimental dispersion is to be expected for beam testing than for small-scale laboratory specimens. The coefficients of variation were consistently low, indicating that the experimental approach yielded highly reliable and reproducible assessments of structural performance. The statistical parameters generally show that the measured values deviated very little; the reported improvements from steel, nylon, and hybrid fiber reinforcement may be accepted with a high degree of confidence.

4.5.1 One-Way ANOVA Results

Table 12 presents the one-way analysis of variance to assess the statistical significance of the effects of fiber type and fiber volume percentage on the observed mechanical and structural parameters of SCC. The ANOVA showed F-values of 24.046, 61.362, and 59.258 for compressive strength, splitting tensile strength, and ultimate flexural load, respectively, and p-values of 7.76×10^{-9} , 1.33×10^{-12} , and 1.85×10^{-12} . Because all p-values are far below the significance threshold (0.05) for all responses studied, we reject the null hypothesis that all SCC combinations have the same mean.

Table 12 One-way ANOVA results.

Response variable	F-value	p-value	Statistical interpretation
Compressive strength	24.046	7.76×10^{-9}	Significant
Splitting tensile strength	61.362	1.33×10^{-12}	Significant
Ultimate flexural load	59.258	1.85×10^{-12}	Significant

The relatively high F-value for compressive strength indicates that variability among the fiber-reinforced mixtures was significantly greater than the random variability within each experimental group, confirming that the addition of fibers significantly influenced the compressive resistance of SCC. The F-values, and hence the statistical significance, were much higher for the splitting tensile strength and the ultimate flexural load. Results showed that the fiber reinforcement influenced the tensile and flexural behavior more than the compressive strength, which is consistent with the well-established crack-bridging mechanism of discrete fibers. Steel fibers successfully transmitted tensile loads across the developing fractures, whereas nylon fibers improved crack distribution and delayed crack propagation. The hybrid system's combined action yielded more uniform stress redistribution and enhanced post-cracking behavior, leading to statistically significant gains in structural performance.

4.5.2 Two-Way ANOVA Results

The results of the two-way ANOVA to examine the individual and interaction impacts of the fiber type and the fiber dose on the compressive strength, splitting tensile strength, and ultimate flexural load of FRSCC are shown in Table 13. The fiber type had a statistically significant impact on the compressive strength (F-value = 36.235, p-value < 0.001, partial eta squared = 0.801). The fiber dose was similarly significant (F-value = 24.321, p-value < 0.001, partial eta squared = 0.730). Also, the interaction between fiber type and dose was significant (F = 14.265; p < 0.001; partial eta squared = 0.760), demonstrating that the effect of increasing fiber content on the compressive strength was dependent on the fiber system. This result aligns with the experimental trends, which showed an increase in compressive strength for steel-fiber combinations from 42.0 to 45.1 MPa and for hybrid mixtures from 41.3 to 43.4 MPa, while the nylon-fiber mixtures showed a minor decrease from 41.9 to 41.2 MPa. For example, previous research has shown that the mechanical performance of fiber-reinforced concrete is substantially influenced by the kind and amount of fibers used, as changes in fiber stiffness, shape, and compatibility with the matrix impact the effectiveness of reinforcement [54]. Fiber type, dose and their interaction were all highly significant factors for splitting tensile

strength, with F-values of 67.095, 113.842 and 25.485, respectively, and p-values less than 0.001, and partial eta-squared values of 0.882, 0.927 and 0.850. The strong significance of the fiber dosage effect suggests that the split tensile behavior was very sensitive to fiber content variations. The significant interaction reveals that this impact was different for the steel, nylon, and hybrid systems. Such behavior is consistent with the known ability of discrete fibers to bridge developing cracks and sustain tensile stresses after matrix cracking, with steel fibers in general providing particularly effective crack bridging resistance due to their high stiffness and mechanical anchorage [44]. For ultimate flexural load, fiber type had an F-value of 96.783, p-value < 0.001 and partial eta squared of 0.915. Fiber dosage had an F-value of 45.122, p-value < 0.001 and partial eta squared of 0.834, indicating significant impacts of both variables on structural load-carrying capacity. The ultimate load rose experimentally from 64.3 to 68.7 kN for steel fibers, from 56.4 to 61.7 kN for nylon fibers and from 60.7 to 65.2 kN for hybrid reinforcement by increasing the fiber content from 0.2% to 0.4%.

Table 13 Two-ways ANOVA results.

Compressive strength						
Source	df	SS	MS	F	p-value	Partial η^2
Fiber type	2	15.207	7.603	36.235	<0.001	0.801
Fiber dosage	2	10.207	5.103	24.321	<0.001	0.730
Fiber type $\times$ dosage	4	11.973	2.993	14.265	<0.001	0.760
Error	18	3.777	0.210	-	-	-
Total	26	41.164	-	-	-	-
Splitting tensile strength						
Source	df	SS	MS	F	p-value	Partial η^2
Fiber type	2	0.4533	0.2266	67.095	<0.001	0.882
Fiber dosage	2	0.7691	0.3845	113.842	<0.001	0.927
Fiber type $\times$ dosage	4	0.3443	0.0861	25.485	<0.001	0.850
Error	18	0.0608	0.00338	-	-	-
Total	26	1.6275	-	-	-	-
Ultimate flexural load						
Source	df	SS	MS	F	p-value	Partial η^2
Fiber type	2	216.380	108.190	96.783	<0.001	0.915
Fiber dosage	2	100.880	50.440	45.122	<0.001	0.834
Fiber type $\times$ dosage	4	3.200	0.800	0.716	0.592	0.137
Error	18	20.122	1.118	-	-	-
Total	26	340.582	-	-	-	-

However, the interaction between fiber type and dosage was not statistically significant for ultimate flexural load ($F = 0.716$, $p = 0.592$), suggesting that the effect of increasing dosage on peak load was not sufficiently different among the three fiber systems to establish a significant interactive influence. Thus, although the hybrid system exhibited promising deformation and post-cracking characteristics, these results do not statistically support synergistic enhancement in ultimate flexural capacity, and its response is better described as complementary rather than synergistic. The load-deflection data are consistent with this interpretation and imply that hybrid reinforcement

resulted in a balanced structural response without surpassing the ultimate strength of the steel fibers. The results are consistent with Song and Hwang [44], who found that steel-fiber reinforcement significantly enhances the flexural toughness and post-cracking behavior, and Spadea et al. [52], who showed that nylon fibers may improve the toughness and deformation capacity of cementitious composites.

5. Conclusion

This research examines the effect of steel, nylon, and hybrid steel-nylon fibers on the fresh, mechanical, and structural behavior of SCC with 11% silica fume. Based on the collected findings, the following conclusions may be made:

- The slump flow gradually decreased, while the T_{50} flow time, V-funnel flow time, and flow resistance increased as the fiber volume fraction increased from 0.2% to 0.4%, due to increased internal friction and fiber-matrix interactions. However, all combinations under consideration met the EFNARC acceptance criteria, demonstrating that the good self-compacting features were retained throughout the experimental program.
- The mixture containing 0.4% steel fibers exhibited the highest compressive strength (45.1 MPa), an increase of approximately 10.5% over the reference SCC (40.8 MPa). The improvement is mainly attributed to the crack-bridging capacity of hooked-end steel fibers, which slowed the development of microcracks and enhanced stress redistribution in the cementitious matrix.
- The reference mixture exhibited a splitting tensile strength of 3.90 MPa, whereas the mixture containing 0.4% steel fibers reached 4.81 MPa, representing a 23.3% higher value. Nylon-fiber mixtures exhibited comparatively lower tensile strength but showed effective crack control and improved post-cracking behavior.
- The beam containing 0.4% steel fibers exhibited the highest ultimate load (68.7 kN), approximately 29.6% higher than the control beam (53.0 kN). The improved structural performance was attributed to greater fracture bridging, slower crack propagation, increased stiffness, and more effective stress transmission across the cracked portion. However, the observed difference relative to the control should not be interpreted as a pure fiber.
- The steel-fiber mixture had the highest compressive strength, splitting tensile strength, and ultimate beam load, while the hybrid steel-nylon system showed a balanced response with good mechanical performance, workability retention, crack distribution, and post-cracking behavior. Thus, the hybrid system may be a good choice for balancing strength and serviceability rather than a universal answer.
- Low coefficients of variation (<2%) and significant ANOVA findings ($p < 0.05$) indicate that observed changes in the tested mixtures are due to fiber type and dosage, not random experimental variation.
- FRSCC mechanical performance was significantly impacted by fiber type and dosage in the two-way factorial ANOVA. Compressive strength and splitting tensile strength were significantly impacted by fiber dosage depending on the fiber system, with p-values below 0.001 and partial eta-squared values of 0.760 and 0.850, respectively.
- This study directly connected fresh concrete rheology, mechanical properties, and structural behavior at full size using a combined experimental technique. Results recommend optimizing

the fiber system for optimum workability and structural performance in silica fume-modified SCC.

6. Recommendations for Future Research

- Investigate the long-term durability of hybrid fiber-reinforced SCC under aggressive environmental conditions, including chloride exposure, sulfate attack, freeze-thaw cycles, and elevated temperatures.
- Evaluate the flexural and shear behavior of full-scale reinforced SCC structural members with various steel-nylon hybrid fiber proportions under static and cyclic loading.
- Assess the environmental and economic performance of hybrid fiber-reinforced SCC through life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) to support its practical implementation in sustainable construction.

Author Contributions

The authors declare that all authors have contributed equally to the work. Arjan Fakhruddin Abdullah and Inas Mahmood Ahmed have conducted the experimental work, while Nabaz Yassen Ezuldin and Zainab Al-Khafaji have written the manuscript and analyzed the results.

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Competing Interests

All authors declare that “there is no conflict of interest”.

AI-Assisted Technologies Statement

Grammarly was used solely for basic grammar correction and language refinement during the preparation of this manuscript. Specifically, Grammarly was employed to improve the grammatical accuracy, readability, and linguistic clarity of the English text. All scientific content, research methodology, data analysis, interpretation of results, and conclusions were developed independently by the author(s). The author(s) have thoroughly reviewed and edited the text to ensure its accuracy and appropriateness and accept full responsibility for the content of the manuscript.

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