

Experimental study on the influence of low-cost steel fibers on the rheological and mechanical properties of self-compacting concrete

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Abstract

This experimental study examines the contribution of steel fibers from cut tie wires, envisioned as an economical reinforcement for self-compacting concrete (SCC), by simultaneously analyzing their behavior in the fresh and hardened states. The study focuses on fiber length, comparing three lengths (2, 3, and 4 cm) at a constant dosage of 0.5% by volume. Methodologically, the evaluation focuses, on the one hand, on the rheological properties of SCC, and, on the other hand, on the mechanical performance after hardening. Scanning electron microscopy (SEM) analysis was also performed to characterize the microstructure and the interfacial transition zone between the steel fibers and the cementitious matrix. The results indicate that the introduction of fibers preserves the flowability of SCC while significantly improving its mechanical performance, particularly in flexure, with a shift in failure mode from brittle behavior to a more ductile, better-controlled post-cracking response. The best-performing mix, SCC reinforced with 4 cm-long fibers, illustrates this improvement, with toughness increasing from 125 N·mm (reference concrete) to 38,281 N·mm and the ultimate flexural load increasing by 57.1% at 28 days. Thus, this reinforcement enhances the SCC's robustness and adaptability, paving the way for sustainable, economically optimized construction applications, including in demanding structural contexts.

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1. Introduction

New to the building industry, self-compacting concrete (SCC) offers several advantages over traditional concrete. Initially developed in Japan in 1988, SCC was used there to make durable concrete with fewer workers required [1,2].

SCC is a highly flowable material that flows and consolidates under its own weight [3,4]. Its specific mix design provides high workability, enabling it to fill densely reinforced zones and complex architectural forms without the need for vibration, while ensuring good concrete homogeneity [5, 6]. The incorporation of fibers into the cementitious matrix has paved the way for a new generation of high-performance cement-based composites [7]. Steel fiber-reinforced self-compacting concrete

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combines the ease of placement of SCC with the enhanced mechanical properties of a fiber-reinforced composite. The addition of steel fibers results in a more efficient and durable material that compensates for some of its inherent limitations. These fibers improve crack control behavior, increase tensile strength, and reduce brittleness, without compromising the key advantages of SCC, namely flowability and homogeneity [8,9].

The efficacy of fiber-reinforced concrete is closely related to the geometric and mechanical properties of the fibers, notably their length, shape, cross-sectional geometry, and elastic modulus [10,11]. Longer fibers or those with a distorted surface offer superior fixing inside the cementitious matrix and facilitate better stress transfer. The topology of fibers (straight, hooked, crimped, etc.) immediately affects post-cracking performance and energy dissipation under load. In contrast, the fiber cross-section and volume fraction determine the distribution and efficacy of reinforcement [12,13].

Fiber failure mode is also a key factor. Depending on the fiber type and its bond with the cementitious matrix, failure may occur either through progressive pull-out or by sudden fiber rupture. The former promotes higher energy absorption capacity and a more ductile behavior, whereas the latter reflects a stiffer fiber–matrix bond with lower energy dissipation [14,15]. Owing to these properties, fiber-reinforced SCC is particularly well suited for complex structures and high-performance applications, such as industrial floors, structures in seismic zones, or slender elements requiring both strength and durability [16,17]. However, the use of standardized steel fibers remains costly, which limits their large-scale application. In this context, the use of low-cost alternative steel fibers, such as cut tie wires or other fibers derived from metallic waste, represents an economically and environmentally attractive solution for reinforcing self-compacting concrete [18,19]. These fibers provide a substantial decrease in total material costs while preserving, or potentially enhancing, specific mechanical qualities [20,21]. Furthermore, their use enhances the valorization of industrial waste and encourages a sustainable technique in self-compacting cement-based composites [22,23].

Among the available geometries, cut tie wire is a straight, smooth, and undeformed fiber. In terms of bond, cut tie wire is a disadvantage, since stress transfer relies on adhesion and friction alone, without the mechanical anchorage provided by hooked or crimped ends. In self-compacting concrete, however, it is also an advantage: deformed ends increase inter-particle interlocking. They are one of the main causes of the loss of passing ability reported for fiber-reinforced SCC. A smooth, straight fiber is therefore the geometry least detrimental to self-compactability. Moreover, the lower bond it develops is not necessarily a loss of performance, because a fiber that debonds and slides dissipates energy over a long pull-out stage instead of failing abruptly. The relevance of cut tie wire to self-compacting concrete rests on this trade-off between bond and self-compactability and not on its low cost alone. This experimental study examines the use of steel fibers sourced from cut tie wires as reinforcement for SCC. The aim is to present an economical substitute for traditional industrial fibers by utilizing inexpensive reinforcing elements. The analysis examines the impact of incorporating these fibers on the rheological properties of SCC, particularly its flowability, passing ability, and segregation resistance. In addition, the mechanical performance of the material is evaluated, including compressive strength, flexural tensile strength, and cracking behavior. Special attention is devoted to the influence of fiber length variation to achieve a better understanding and control of concrete behavior in both the fresh and hardened states. Furthermore, scanning electron microscopy (SEM) was performed to investigate the microstructural characteristics of the fiber–matrix interface and to understand better the bonding mechanisms between the steel fibers derived from cut tie wires and the cementitious matrix.

2. Materials and Methods

2.1 Materials Used

This investigation employed a CEM II/B-L 42.5N type cement, conforming to the Algerian Standard NA 442 [24]. Table 1 shows the chemical composition, Bogue analysis, and physical characteristics provided by the company that made it.

Table 1. Cement composition and characteristics

Chemical composition (% wt)										
CaO	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	MgO	Na ₂ O	SO ₃	K ₂ O	Cl	Loss on Ignition	Free CaO
65.27	4.63	19.51	2.98	1.91	0.05	2.16	0.59	0.002	2.05	< 1
Bogue composition (%)										
C ₃ S	C ₂ S	C ₃ A	C ₄ AF	Gypsum						
59.11	8.46	7.23	9.07	3						
Physico-mechanical properties										
Absolute density									3.10	
Bulk density (kg/m ³)									1105	
Specific surface (cm ² /g)									3700	
Initial set (min)									89	
Final set (hours)									4.15	
Normal consistency of cement paste (%)									27.5	
Cement strength class (MPa)									42.5	

The mineral additive consists of limestone filler (LSF), derived from the fine grinding of natural limestone rock containing approximately 98% calcium carbonate (CaCO₃). The substance was reduced to a particle size under 80 µm. The product originates from ENG in Constantine, Algeria. The chemical and physical properties are shown in Table 2.

Table 2. LSF composition and characteristics

Chemical composition (% wt)							
CaO	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	MgO	Na ₂ O	Loss on Ignition	pH
55.77	0.02	0.13	0.04	0.02	0.01	43	9
Physical properties							
Absolute density (g/cm ³)						2.7	
Bulk density (g/cm ³)						0.94	
Hardness (MOHS)						3	
Whiteness (%)						92	
Refraction index						1.71	
Moisture content (%)						0.1	

The admixture used is ViscoCrete 522 RMX, a new-generation polycarboxylate-based superplasticizer compliant with NF EN 934-2 [25], providing high water reduction and excellent workability. This admixture is manufactured by the Sika company; its properties are given in Table 3.

Table 3. Visco Crete 522 RMX characteristics

Density (g·cm ⁻³)	Dry-solids content	Chloride content	pH
1.085 ± 0.01	29.0 ± 1	< 0.1%	5 ± 1

Table 4. Physical properties of aggregates

Characteristics	Sand 0/3 mm	Gravel 3/8 mm	Gravel 8/16 mm
Apparent volumetric mass (g/cm ³)	1.42	1.48	1.52
Absolute volumetric mass (g/cm ³)	2.57	2.65	2.70
Sand equivalent (%)	78.18	-	-
Fineness modulus	2.30	-	-
Los Angeles testing (%)	-	24.3	24
Micro Deval testing (%)	-	9	9.4

Two fractions of coarse limestone aggregates with size ranges of 3/8 and 8/16 mm, as well as a limestone sand with a size range of 0/3 mm, were used. All of them are obtained by crushing and

are sourced from a local quarry in Guelma, Algeria, where they are commonly used for concrete production. They therefore present an angular, irregular particle shape with rough fracture faces, in contrast to the rounded morphology of alluvial aggregates; this shape increases inter-particle friction and is one of the reasons why the coarse aggregate volume must be limited in self-compacting mixtures. The physical characteristics of the aggregates are given in Table 4, and the particle size distributions are shown in Fig. 1.

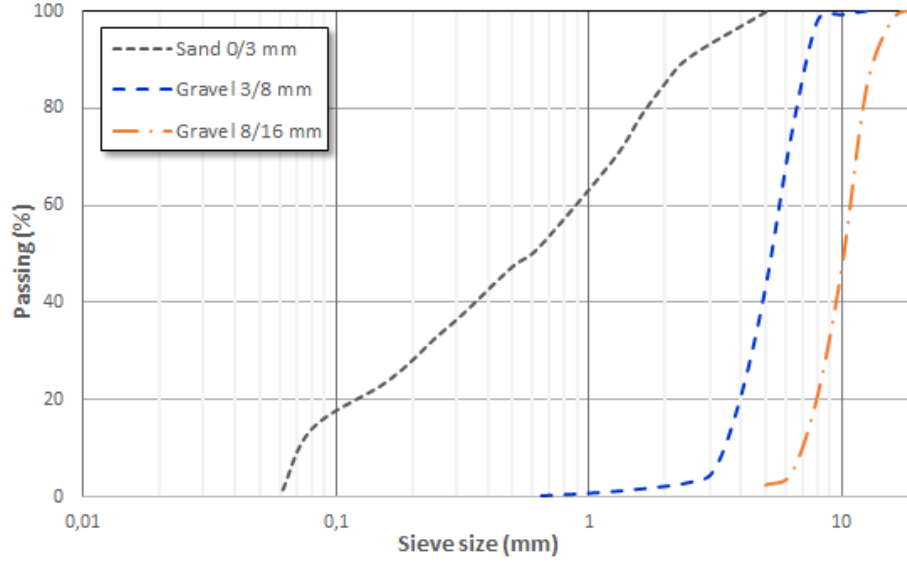


Fig. 1. Particle size distributions of aggregates

Figure 1 shows the particle-size distributions of the 0/3 mm sand and the 3/8 and 8/16 mm coarse aggregates, while their physical properties are reported in Table 4. The uniformity coefficient (C_u), curvature coefficient (C_c), and individual packing index (Φ_i) were calculated using Eqs. (1)–(3) respectively:

$$C_u = \frac{D_{60}}{D_{10}} \quad (1)$$

$$C_c = \frac{D_{30}^2}{D_{10}D_{60}} \quad (2)$$

$$\Phi_i = \frac{\rho_{bulk}}{\rho_{particle}} \quad (3)$$

The 0/3 mm sand exhibited $C_u = 12.7$, $C_c = 0.76$, and $\Phi_i = 0.553$, indicating a relatively broad particle-size distribution. The corresponding values were $C_u = 1.67$, $C_c = 1.03$, and $\Phi_i = 0.558$ for the 3/8 mm aggregate, and $C_u = 1.55$, $C_c = 1.01$, and $\Phi_i = 0.563$ for the 8/16 mm aggregate. The lower C_u values of the coarse aggregates reflect their narrower grading ranges, while their C_c values close to unity indicate regular grading within each size fraction. The similar packing indices (0.553–0.563) indicate comparable individual packing capacities; however, they do not represent the packing density of the combined aggregate skeleton.

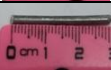
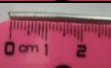
2.2.1 Steel Fibers

The fibers used in this study are straight galvanized steel tie wires, manufactured from galvanized steel complying with NF A35.051 [26], grade

MF10, which corresponds to a low-carbon mild steel ($\sim 0.10\%$ C). Three lengths (2 cm, 3 cm, and 4 cm) were tested, with a constant diameter of 1.3 mm. The wire is manufactured in Algeria and was supplied in coils, from which it was manually cut with cutting pliers to the three selected lengths (20, 30 and 40 mm); the cut ends were left as obtained, without any deformation or end anchorage. These lengths were not derived from a prior statistical optimization: they were set at regular 10

mm intervals, the 40 mm upper bound being fixed by the 16 mm maximum aggregate size and by the passing-ability requirement of self-compacting concrete, since longer fibers promote interlocking and balling. Unlike industrial hooked-end or crimped fibers, these wires present a smooth, undeformed galvanized surface, so that the fiber-matrix bond relies exclusively on adhesion and friction, without any mechanical anchorage; the consequences of this feature on the stress transfer are discussed in Section 3.2.3. The roughness itself was not quantified, since the analysis given there shows that the available embedment length remains well below the critical length, so that debonding and pull-out govern failure whatever the exact roughness value. The tensile strength of the tie wires was determined from three tested specimens and was found to be 1228.6 ± 2.7 MPa. Their geometric and mechanical characteristics are presented in Table 5.

Table 5. Characteristics of galvanized steel tie wires

Length (cm)	Diameter	Aspect ratio (l/d)	View	Density	Elastic modulus	Tensile strength
2 cm $\pm$ 2 mm	1.3 mm	15.4		7.8 g/cm ³	210 GPa	1228.6 $\pm$ 2.7 MPa
3 cm $\pm$ 2 mm		23.1				
4 cm $\pm$ 2 mm		30.8				

The tensile behavior of the galvanized steel tie wire (nominal diameter 1.3 mm, initial cross-section $S_0 = 1.327$ mm²) was characterized on three specimens. The corresponding engineering stress-elongation curves are plotted in Fig. 2, while Fig. 3 illustrates the test set-up and the appearance of the wire before and after testing. The three curves almost coincide, which indicates good repeatability of the test and a homogeneous material.

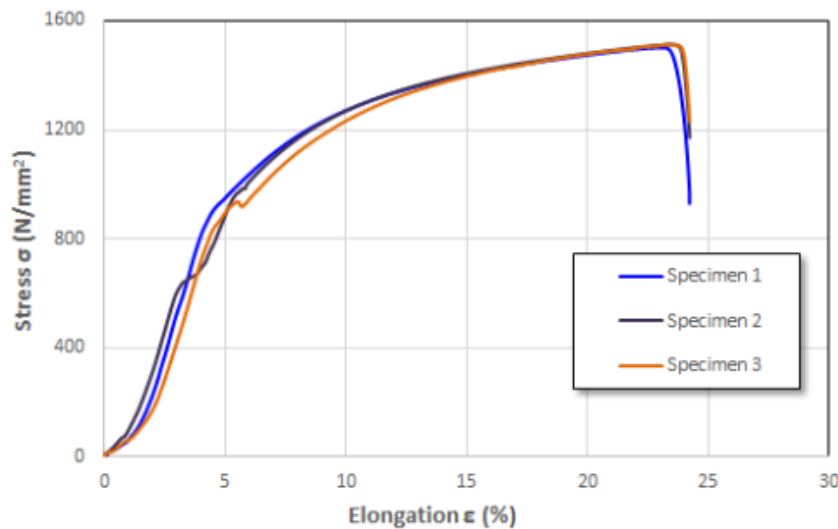


Fig. 2. Curves stress vs elongation

When loading begins, the curves show a steep, almost straight increase, which reflects the wire's elastic behavior. This elastic phase only covers very small stretches, usually just a few tenths of a percent, so it appears as a short straight line near the origin in Fig. 2. After this, the curves bend away from the straight line and move into a longer plastic phase, where stress keeps rising as the wire stretches. There is no clear yield plateau. Instead, the material gradually becomes stronger as it stretches, with the stress reaching about 1.2 GPa at its highest point. Following the attainment of maximum stress, the curves exhibit a significant decrease in stress corresponding to the initiation of local necking at the mid-span of the wire, which subsequently leads to final fracture. This concentration of deformation is evident in Fig. 3, where a substantial reduction in cross-section is observed prior to failure. The global elongation at fracture ranges from 18 to 25 mm, corresponding

to approximately 20–25% nominal strain, which confirms the highly ductile behavior of the tie wire before failure.



Fig. 3. Galvanized steel tie wire tensile test (necking and fracture)

2.2 Mix Design

In this study, SCC was designed using the Japanese mix design method [1], which proportions the mixture through three volumetric criteria: the coarse aggregate content is limited to 50 % of its loosely packed (bulk) volume, the fine aggregate is fixed at approximately 40 % of the mortar volume, and the water-to-powder ratio is adjusted experimentally until self-compactability is achieved. In the reference mixture, the coarse aggregates occupy 498.8 L/m^3 of bulk volume, i.e., 49.9% of the concrete volume. The paste volume amounts to 415.2 L/m^3 (cement 129.0 , limestone filler 69.6 , water 210.0 and superplasticizer 6.5 L/m^3), and the sand to 291.8 L/m^3 ; with 13.1 L/m^3 of entrapped air obtained by closure of the volumetric balance, the mortar volume reaches 720.1 L/m^3 , and the sand, therefore, represents 40.5% of it. The water-to-powder ratio by volume was set at 1.06 after adjustment of the superplasticizer dosage (1.20% of powder mass), the acceptance criteria being those recommended by EFNARC [4].

Table 6. Concrete mixture proportions

Mixture (Kg)	SCC R	SCC MF 2	SCC MF 3	SCCMF 4
Cement	400	400	400	400
Limestone filler	188	188	188	188
Sand (0/3)	750	750	750	750
Coarse aggregate (3/8)	300	294.6	294.6	294.6
Coarse aggregate (8/16)	450	441.8	441.8	441.8
Superplasticizer	7.06	7.06	7.06	7.06
Water	210	210	210	210
Steel fibers (Kg)	/	40	40	40

Steel fibers were then introduced by replacing an equal absolute volume of coarse aggregate, so that the paste volume, the sand-to-mortar ratio and the water-to-powder ratio remained strictly unchanged across the four mixtures. At 0.5 % by volume, the fibers occupy 5.13 L/m^3 and the coarse aggregate volume was reduced by 5.08 L/m^3 accordingly, lowering the bulk coarse aggregate content from 49.9 % to 49.0 %. This reduction is intended: a smaller coarse aggregate skeleton means fewer coarse particles with which the fibers can interlock, and therefore a smaller loss of passing ability. It does not, however, compensate for the increase in solid surface that the fibers introduce, since 0.5% by volume of 1.3 mm wire adds about 15 m^2 of surface per cubic meter of concrete against only a few square meters removed with the aggregate. At constant paste volume, the paste therefore has more surface to coat, which is the origin of the reduction in slump flow and the increase in T50 reported in Section 3.1. This substitution is consistent with the governing principle of the Japanese method, namely that self-compactability is obtained by limiting the coarse aggregate skeleton so as to reduce inter-particle collision and blocking, and with the experimental evidence that the maximum admissible fiber content in SCC increases as the coarse

aggregate content decreases [27]. Since the paste composition is identical in the four mixtures, no difference in the rheological or mechanical results can be attributed to it: the only quantities that vary are the presence of the fibers, their length, and the small reduction in coarse aggregate content that their introduction requires. The final optimized mix proportions of the four concretes investigated (one reference concrete and three fiber-reinforced concretes), expressed per cubic meter of material, are presented in Table 6.

2.3 Experimental Testing

The production of SCC requires special attention and a careful mixing procedure to guarantee the reproducibility of the tests in the fresh state. First, the different aggregate fractions are introduced into the mixer, then the cement and the filler, and the constituents are dry-mixed for 1 min. After this, 75% of the total mixing water is added and mixing continues for 2 min.

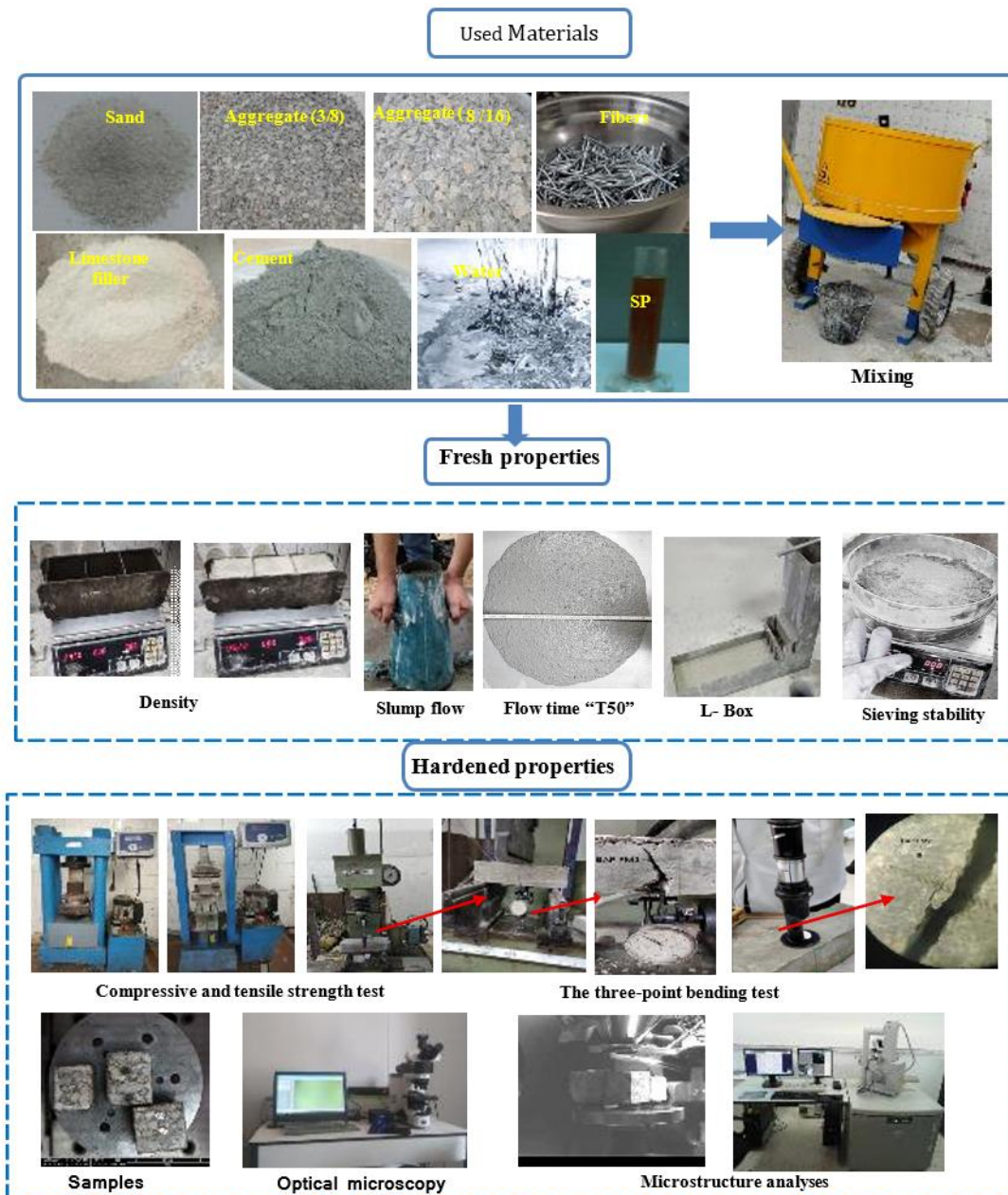


Fig. 4. Preparation process and experimental program

The admixture, diluted previously in the remaining 25% of the water, is then added and mixing continues for a further 2 min. For fiber-reinforced SCC mixtures, the fibers are added gradually, together with the cement and filler during the dry-mixing stage to facilitate their uniform distribution throughout the matrix. The fibers are added gradually and not all at once to keep the

local fiber concentration low during the dry-mixing phase so that aggregate particles separate the individual wires before any water is introduced. This is decisive because, once the paste has formed, its cohesion prevents the mixer from breaking up a cluster that has already been created: a fiber ball that survives the dry stage will survive the whole sequence and will remain in the hardened material as a defect. The gradual addition is thus a dispersion-control measure, not a convenience, and it is what enables the fresh-state results of the four mixtures to be compared with each other on equal terms. Accordingly, the total mixing time is fixed at 5 min for all mixtures to maintain consistent experimental conditions and prevent undesirable changes in the rheological properties of the fresh concrete. Before casting, the fresh concrete is inspected visually to confirm a homogeneous fiber distribution and the absence of visible fiber balls; no batch has to be rejected on this criterion. Fig. 4 summarizes the adopted experimental program, including the constituent materials, mixing procedure, and tests conducted in both the fresh and hardened states. The fresh-state properties are evaluated using the slump-flow test, T_{50} flow time, L-box test, sieve-segregation resistance test, and fresh-density measurement. The hardened-state mechanical properties are determined through compressive-strength tests on $100 \times 100 \times 100$ mm cubic specimens and three-point flexural tests on $70 \times 70 \times 280$ mm prismatic specimens. The uniaxial compression test is conducted using a hydraulic testing machine with a maximum capacity of 2,000 kN, whereas the three-point bending test is performed using a 100 kN testing machine. The mid-span deflection is measured using a mechanical dial gauge with a resolution of 0.01 mm.

The fiber-matrix interface is examined by scanning electron microscopy on fragments taken from the fracture surface of the three-point bending specimens, in the central tensile zone. Micrographs are acquired at an accelerating voltage of 20.0 kV, a working distance of 15.5 mm and a magnification of 1,200 $\times$, using a large-field detector (LFD), the horizontal field width being 249 μ m. Elemental analysis is performed by energy-dispersive X-ray spectroscopy under the same conditions, as a point spectrum on each phase and as a line scan crossing the matrix, the interfacial region and the fiber. No conductive coating is applied to the specimens.

3. Test Results and Discussion

3.1 Rheological Results

The four fresh-state tests used here do not measure the same property, and self-compactability requires all four to be satisfied simultaneously. The slump-flow diameter measures filling ability, that is, the extent to which the mixture deforms under its weight in an unconfined space. The T_{50} time measures the rate of that deformation rather than its extent and is an indicator of plastic viscosity: two mixtures may reach the same final spread while flowing at very different speeds. The L-box ratio H2/H1 measures passing ability, that is, the capacity of the mixture to move through congested reinforcement without the coarse phase being retained at the bars, a phenomenon known as blocking. The sieve segregation index measures dynamic stability, that is, the resistance of the mixture to the separation of the coarse phase from the mortar during placement. A fiber-reinforced mixture is particularly demanding on the last two, since the fibers introduce a further class of elongated solid inclusions liable to interlock at obstacles.

3.1.1 Flowability

The Abrams cone test is the reference method for assessing the flowability of SCC, in accordance with standard [NF EN 12350-8] [28]. Fig. 5 illustrates the variation in slump flow and slump flow time T_{50} . The results show that all tested mixtures exhibited satisfactory flowability in unconfined conditions, with slump-flow values ranging between 69 and 75 cm, corresponding to class SF2. This class allows spread values ranging from 66 to 75 cm [28]. A decrease in flowability was observed for the fiber-reinforced mixtures, accompanied by minor ovalization of the flow spread, while still remaining within the standard limits. Correspondingly, the T_{50} time increased with the addition of fibers, indicating elevated viscosity.

These observations are fully consistent with trends reported in the international literature [29]. Several studies have demonstrated that the incorporation of steel fibers into self-compacting concrete systematically leads to a reduction in slump-flow diameter and an increase in T_{50} time,

as a direct consequence of the enhanced internal resistance of the mixture [30]. A synthesis of 35 studies further confirms that fiber geometry and content strongly influence flowability while remaining within the standard limits for SCC. Finally, recent work [31] emphasizes that flow spread ovalization and increased T50 are typical effects in fiber-reinforced SCC, associated with the redistribution of internal stresses induced by the fibers.

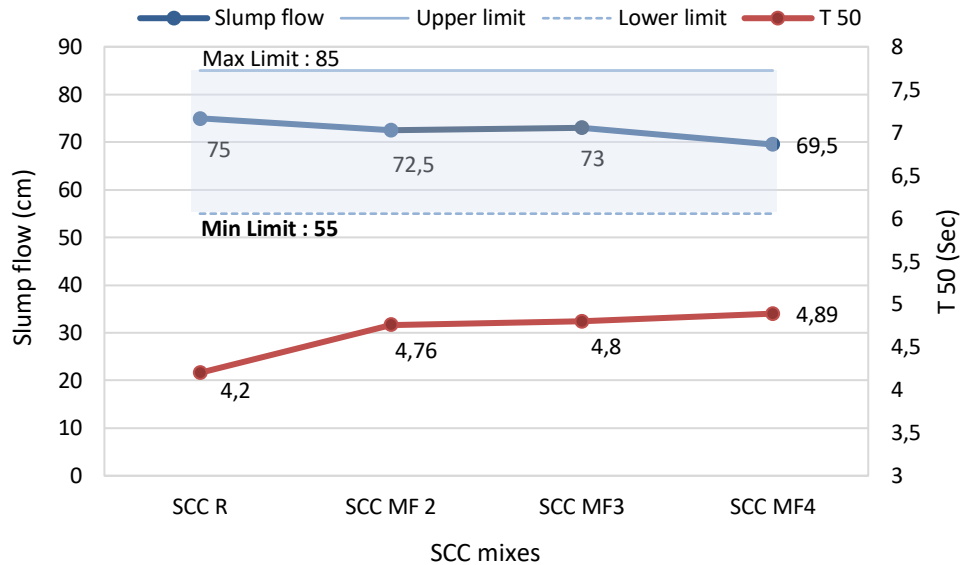


Fig. 5. Slump flow test results and corresponding T50 flow time

3.1.2 Passing Ability

The measured H_2/H_1 ratios were 0.96 for the reference mixture and 0.90, 0.94 and 0.87 for SCC MF2, SCC MF3 and SCC MF4, respectively, all above the 0.80 threshold required for passing ability. The behaviors observed in this study, namely, satisfactory passing ability for all mixtures, whether fiber-reinforced or not, and a slight reduction in flowability with increasing fiber length, without blocking, are largely consistent with recent findings in the international literature (Fig. 6). Indeed, a recent study on Steel Fiber Reinforced Self-Compacting Concrete (SFRSCC) demonstrated that longer fibers tend to reduce slump-flow diameter, indicating a decrease in flowability and passing ability [10]. Similarly, several studies report a reduction in filling and passing ability when steel fibers are added, while the concrete remains self-compacting and meets standard requirements, with H_1/H_2 ratios remaining within acceptable limits (≥ 0.8) [32,29].

3.1.3 Segregation Resistance

All studied mixtures, whether fiber-reinforced or not, exhibited satisfactory resistance to segregation, with stability values within the accepted thresholds and meeting standard requirements (Fig. 6) [33]. The sieve segregation indices were 18.6 % for the reference mixture and 12.4 %, 16.6 % and 14.4 % for SCC MF2, SCC MF3 and SCC MF4, all below the 20 % upper limit. The reinforced mixtures were in fact more stable than the reference concrete, the fibers acting as a physical obstacle to the settlement of the coarse aggregate during placing. Likewise, the incorporation of fibers did not compromise mixture homogeneity, with constituent distribution remaining uniform. These observations are consistent with several recent studies on SFRSCC, which indicate that a reasonable fiber dosage allows the cohesion and stability of SCC to be maintained without significantly increasing the risk of segregation [34].

At constant fiber content and constant diameter, the three reinforced mixtures do not contain the same number of fibers: approximately 188,000, 126,000, and 94,000 fibers per cubic meter for the 20, 30, and 40mm lengths, respectively. The total fiber-matrix interfacial area, however, is the same in all three cases and equal to $4V_f/d = 15.4 \text{ m}^2$ per cubic meter of concrete, since it depends only on the volume fraction and the diameter. Fiber length, therefore, does not change how much interface is available; it changes how that interface is distributed, and in particular the embedment length available to each fiber. That constant interfacial area accounts for the fact that all three reinforced

mixtures are less workable than the reference concrete, since the paste has the same additional surface to coat in each of them (Section 2.2); it cannot, however, account for the differences between them.

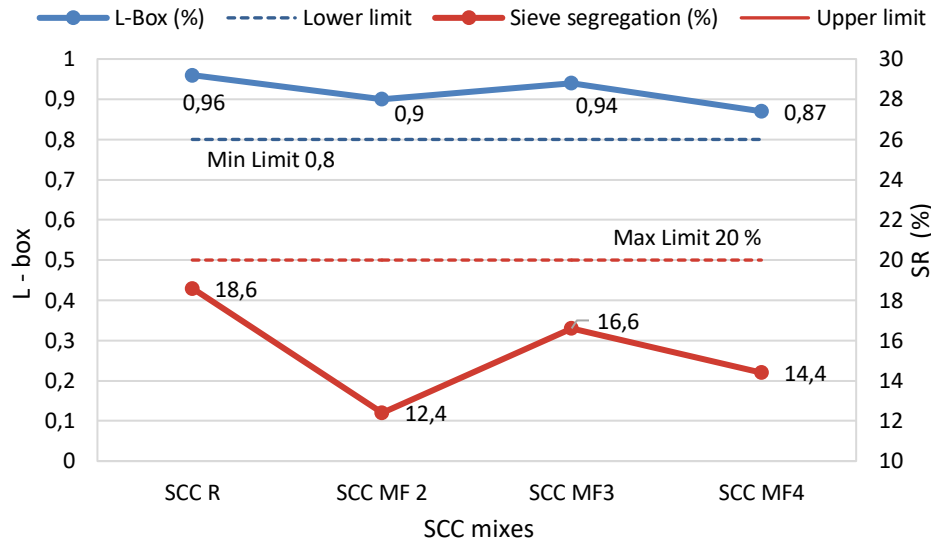


Fig. 6. L-Box test results and sieve stability

In the fresh state, the governing parameter is the fiber factor $V_f l/d$, which rises from 0.077 to 0.115 and 0.154 as the length increases from 20 to 40 mm. A longer fiber sweeps a larger excluded volume as it rotates, so the number of fiber–fiber and fiber–aggregate contacts per unit volume increases and the internal resistance of the fresh suspension rises. This is consistent with the monotonic increase of T50, from 4.20 s for the reference mixture to 4.76, 4.80, and 4.89 s, and with the reduction of the slump flow from 75 cm to 69.5 cm for the longest fibers. The slump-flow and L-box values of SCC MF2 and SCC MF3 differ by less than the repeatability of these tests and should not be read as a reversal of that trend. The same geometrical parameter governs the hardened state, where it acts in the opposite direction; the phenomenon is examined in Section 3.2.4.

3.2 Mechanical Properties

The results of the mechanical properties for all mixes are presented in the following section. These values represent the average of three specimens [35]. The two mechanical tests were chosen for complementary reasons. Compression refers to the matrix itself. The fibers are not loaded in compression, so any gain in compression that is measured is a modification of the matrix by limiting microcrack coalescence rather than a bridging action. Three-point bending, by contrast, produces a bending moment that is maximum in a single section and forces the crack to form at mid-span, in a known location. The resulting load–deflection curve can therefore be read as the response of one bridged crack, and the area beneath it integrated as a fracture energy. A four-point configuration would provide a constant moment over the central third and allow the crack to initiate at the weakest section in it, which is better for a statistical description of the modulus of rupture but less suitable for the controlled single-crack post-peak measurement that is desired here.

3.2.1 Compressive Strength

The compressive strength results and relative gain (%) at 7 and 28 days, along with the corresponding standard deviation values for the different concrete mixtures, are presented in Fig. 7. The results of the compressive strength tests show that incorporating metal fibers derived from tie wires improved the compressive strength of SFRSCC compared to SCCR. The increase of approximately 35% observed in this study is a notable result. This improvement can be attributed to better fiber–matrix interaction, the limitation of microcrack initiation and propagation, and improved stress transfer within the cementitious matrix. The fibers may also contribute to local confinement and a more compact matrix, which can delay the development of damage under compression [36]. Results published in a recent study [36] also show that the addition of steel fibers

can improve the strength, ductility, and durability of concrete. In particular, an increase in compressive strength ranging from 10% to 35% has been reported. In another study, the use of 0.75% steel fibers, combined with recycled aggregates, led to a 35.14% increase in 28-day compressive strength compared to the control mix [36]. An increase of 34.22% was also reported for a fiber content of 1% [30,37]. It should be noted, however, that in the study using 0.75% fibers, this improvement resulted from the combined effect of recycled aggregates and steel fibers. Furthermore, a study conducted with 0.5% steel fibers reported increases in compressive strength ranging from 11% to 26% at 28 days [38], while another study observed an increase of approximately 20% for a comparable fiber content [39]. These results show that the improvement in compressive strength depends not only on the fiber content but also on the fibers' geometry, dispersion, interaction with the cementitious matrix, and the concrete's composition. However, several previous studies have shown that at higher fiber contents, compressive strength may decrease, highlighting the importance of a controlled, optimized fiber dosage to maximize the mechanical performance of SFRSCC [30].

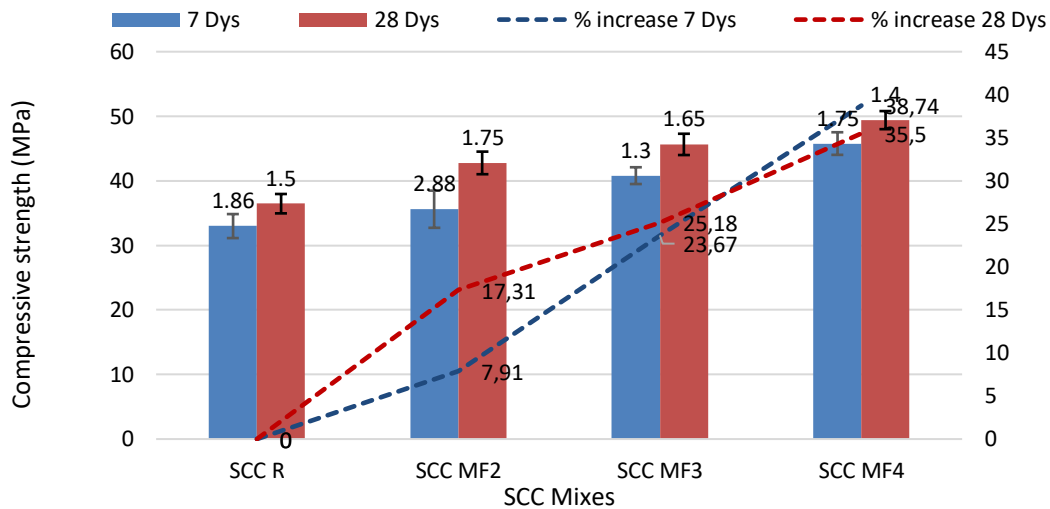


Fig. 7. Compressive strength and relative Gain (%)

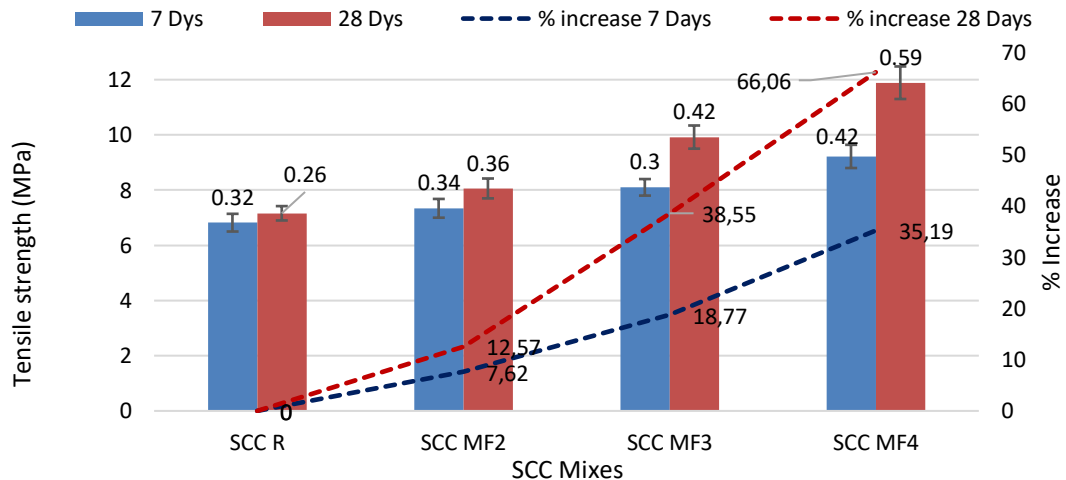


Fig. 8. Tensile strength and relative Gain (%)

3.2.2 Tensile Strength

The results of the flexural tensile strength tests and the relative gain (%) at 7 and 28 days, along with the corresponding standard deviation values for the different concrete mixtures, are presented in Fig. 8. According to the literature, the incorporation of steel fibers into SCC significantly improves flexural tensile strength. Increases of 36.3% and 56.8% have been reported for fiber contents of 0.5% and 1.0%, respectively, while a fiber dosage of 1.5% allows a maximum gain of 77.2% compared to the reference concrete. Beyond this level, a slight reduction in

performance is generally observed, mainly due to a loss of material workability [40]. These improvements are primarily attributed to the effective crack-bridging mechanism provided by steel fibers, as widely confirmed in previous studies [29,41]. In the present study, similar trends were observed. The incorporation of steel fibers derived from tie wires resulted in a significant increase in flexural tensile strength, with a maximum gain of 66.06% at 28 days, even at a relatively low fiber content of 0.5% by volume. This finding confirms the effectiveness of the proposed fiber reinforcement and highlights that the recycled fibers used exhibited mechanical behavior comparable to that of conventional steel fibers.

The FRSCC mixtures exhibit a significant improvement in mechanical properties compared to the SCC-R, with a more pronounced enhancement in tensile performance. Of the examined mixes, SCC MF4 exhibited the best overall performance, with strength increases of over 35% in compression (Fig. 7) and 66% in flexural tensile strength at 28 days (Fig. 8). These results highlight the significant influence of fiber characteristics on the mechanical performance of SFRSCC.

3.2.3 Crack Resistance

This section presents the results related to the crack resistance of the various concrete mixtures developed in this study. The analysis focuses on the influence of steel fiber incorporation on the cracking behavior of SCC, particularly on crack initiation and propagation. The corresponding results obtained at 7 and 28 days are presented in Figs. 9 and 10.

The load–deflection curves of Figs. 9 and 10 must be read in two successive regimes governed by different mechanisms. Crack initiation corresponds to the point at which the tensile capacity of the matrix at mid-span is exhausted and the first crack forms. Up to that point, the fibers are only marginally mobilized, since the bond of a smooth galvanized wire is purely frictional, and friction requires a relative slip between the fiber and the matrix that a crack of near-zero opening has not yet produced; their contribution to initiation is therefore indirect and consists in limiting the coalescence of the microcracks that precede the formation of the main crack. The post-cracking behavior is all of the regimes beyond that point. After the crack has opened, the tensile force across the fracture plane is carried by the fibers alone, through progressive debonding and frictional pull-out. In this regime, the fiber geometry is decisive. The two regimes are quantified separately in what follows: the absorbed energy and the residual load, which describe the post-cracking response, in Section 3.2.4, and the opening measured at the first crack in Section 3.2.5.

The results at 7 and 28 days clearly show that incorporating steel fibers improved the cracking behavior of self-compacting concrete. This improvement is reflected not only in the increase in failure load, but also in a shift from a brittle to a more progressive, pseudo-ductile response. In other words, the presence of fibers helped the concrete behave in a less sudden and less catastrophic manner under loading. These observations are in line with recent international studies. Reference [29] reported that steel fibers significantly enhance tensile strength and reduce the inherent brittleness of self-compacting concrete, thereby improving its energy absorption capacity. Likewise, the study in [42] showed that both recycled and industrial steel fibers increase toughness, improve post-peak behavior, and effectively limit crack propagation. More recently, the work in [43] confirmed that optimizing fiber geometry and anchorage can markedly enhance the flexural toughness of SFRSCC compared with unreinforced mixtures.

A closer look at the results also reveals that the fiber-reinforced concretes developed fewer and less severe cracks than the reference concrete. This can be explained by the steel fibers' ability to control the propagation of microcracks before they evolve into larger, visible cracks. Among the different fibers tested, the 4 cm fibers gave the most convincing results, providing the highest resistance to cracking. This suggests that their length was particularly suitable to guarantee a more homogeneous distribution within the matrix and a stronger bond with the cementitious paste. This is also attributed to the higher fiber aspect ratio ($l/d = 30.8$) of SCC MF4 compared to 23.1 and 15.4 for SCC MF3 and SCC MF2, respectively. A higher aspect ratio provides a longer embedded length for stress transfer, and a higher energy requirement for fiber pull-out. Therefore, longer fibers are more efficient in bridging developing cracks, delaying crack propagation and improving the post-cracking response of SCC.

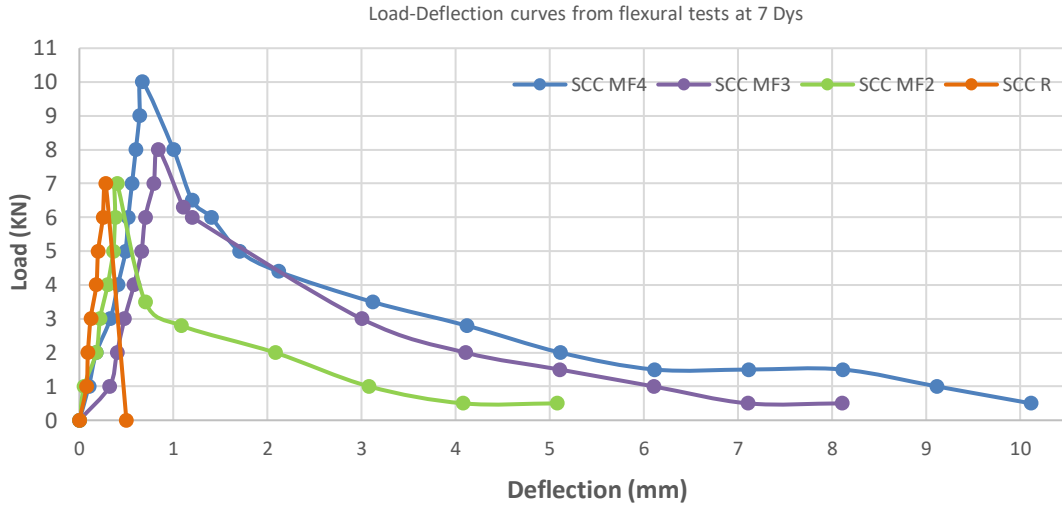


Fig. 9. Load-deflection curves from flexural tests of SCC mixes at 7 Days

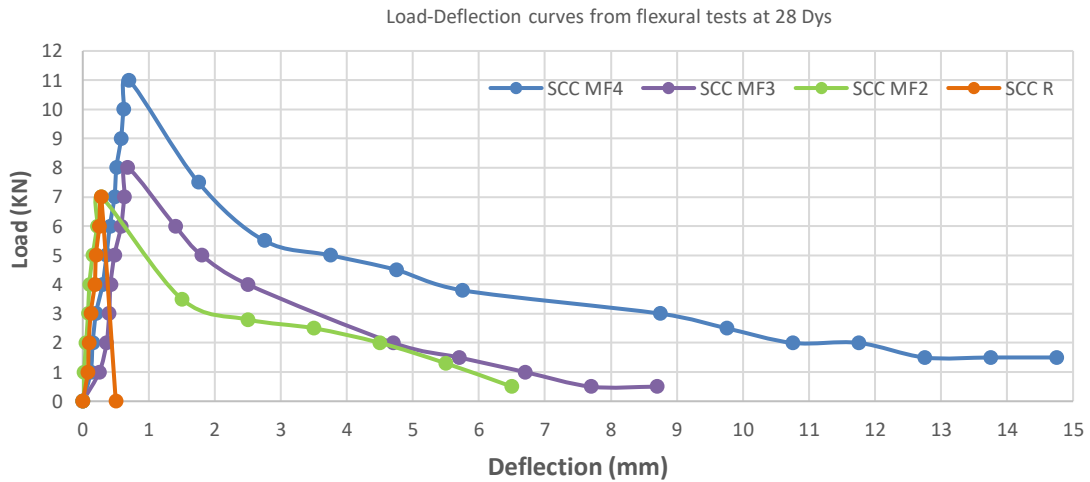


Fig. 10. Load-deflection curves from flexural tests of SCC mixes at 28 Days

The aspect ratio does not act on the two regimes with equal weight. Its influence on crack initiation is limited, because as long as the crack has opened, no slip has occurred, and the embedded length available on either side of the crack has not yet been called upon; the load at which the matrix cracks therefore remains governed by the matrix. After cracking, the aspect ratio becomes the controlling parameter, since that embedded length is half the fiber length and increases from 10 mm for SCC MF2 to 15 mm for SCC MF3 and 20 mm for SCC MF4. The frictional work required to extract a fiber increases accordingly, so that a wider crack opening must be reached before the bridging force decays. The data is what the curves show as delayed crack propagation and sustained residual load-carrying capacity, quantified in Section 3.2.4, and it is consistent with the reduction of the first-crack opening reported in Section 3.2.5.

At 7 days, the SCC R reached its maximum load rapidly and then lost load-carrying capacity almost immediately, indicating unstable crack propagation and a typical brittle failure mode. By contrast, the fiber-reinforced concretes showed a more gradual post-peak response, highlighting the important role of the steel fibers in bridging cracks and delaying complete failure. Among these mixtures, SCC MF4 performed best, with a peak load close to 10 kN and the longest post-cracking stage. SCC MF3 also showed a clear improvement, while SCC MF2, although less efficient than SCC MF3 and SCC MF4, still remained more stable than SCC R.

At 28 days, the same general tendency was observed, but the improvement in the fiber-reinforced concretes became even more pronounced. The reference SCC R mixture still behaved in a brittle manner, whereas SCC MF4 reached approximately 11 kN and maintained a significant residual load

over a wider deflection range. SCC MF3 showed an intermediate response, while SCC MF2 exhibited a gradual descending branch. This evolution suggests that the bond between the fibers and the matrix strengthened with curing age, thereby improving fiber anchorage and crack-bridging efficiency. The post-cracking branches of the fiber-reinforced mixes showed a gradual decline, which means that the stress transfer was still maintained after matrix cracking. The fibers resisted crack opening gradually instead of a catastrophic failure, and continued to transfer stresses across the fracture plane. This post-cracking response resulted in an improved residual load bearing capacity and enhanced energy dissipation during fracture, which leads to a much higher toughness than the reference SCC.

Overall, the incorporation of tie-wire steel fibers clearly enhanced crack control, increased energy absorption, and changed the failure mode of self-compacting concrete from a brittle response to a more progressive and pseudo-ductile behavior. Beyond the numerical improvement, these results show that the fibers helped the material retain its integrity for longer after crack initiation, which is particularly important for improving the durability and mechanical reliability of the concrete.

The rupture images provide clear visual support for the two distinct rupture mechanisms observed (Fig. 11). The SCC R has a single wide crack in the central tensile area, with a large opening and almost complete separation of the specimen. This rectilinear and localized crack is characteristic of a brittle fracture, in which a dominant crack spreads rapidly as soon as the tensile capacity of the unreinforced matrix is exceeded. The absence of any bridging effect explains the sudden drop in load observed on the load–displacement curves.

On the other hand, fiber-reinforced blends have a less severe and better-controlled fracture facies. In the case of SCC MF2, the crack remained centered but followed a more irregular path, while the specimen still retained partial continuity after cracking. This suggests that the fibers contributed to delaying the crack opening and maintaining some stress transfer, even though the bridging effect remained moderate. SCC MF3 showed a more relevant pseudo-ductile behavior, with a tortuous crack path and fiber bridging observed. These mechanisms delayed crack propagation, maintained part of the load-bearing capacity after matrix cracking, and helped preserve specimen integrity. The fracture surfaces further suggest that failure occurred progressively through fiber–matrix debonding and pull-out rather than through instantaneous crack propagation, thereby sustaining the post-peak response.

Among all the mixtures, SCC MF4 showed the best control of cracking. The crack remained narrow and almost vertical, with a limited opening and without complete separation of the specimen. This confirms that the 4 cm tie wire fibers provided the most effective bridging, limiting crack widening and preventing abrupt breakage. The specimen remained largely intact even at large deflections, consistent with the higher residual load and wider post-cracking response observed in the curves. The macroscopic observation presented in Fig. 12 provides additional evidence of this mechanism. Most fibers remained intact after testing and were still bridging the crack surfaces, while cementitious material adhered to their surfaces after extraction. No significant fiber rupture was observed. Instead, the predominant failure mode corresponded to progressive fiber pull-out, indicating that the fiber–matrix interface developed sufficient bond strength to ensure efficient stress transfer before debonding occurred. This observation is fully consistent with the extended post-peak response and higher residual load recorded for SCC MF4 in the load–deflection curves.

This pull-out-dominated behavior can be explained by the interaction between the smooth surface of the galvanized wire and its relatively low aspect ratio. The critical length L_c , defined as the embedment length required to develop the ultimate tensile strength of the steel, is given by:

$$L_c = \sigma_u \cdot d / (2\tau) \quad (4)$$

where $\sigma_u = 1228.62$ MPa is the tensile strength of the wire, $d = 1.3$ mm is its diameter, and τ is the interfacial bond strength. For straight, smooth fibers, τ typically ranges from 1 to 5 MPa [44], a range taken from the literature and not measured for the galvanized wire and the matrix used in this study, which yields L_c values between approximately 160 and 800 mm. The maximum embedment length available in the present study, corresponding to half the longest fiber ($L/2 = 20$ mm for the 4 cm fibers), four to twenty times smaller than $L_c/2$, depending on the value assumed

for τ . Consequently, the interfacial friction is systematically overcome before the tensile stress in the fiber reaches σ_u , and the fibers inevitably debond and pull out rather than rupture. This conclusion does not depend on the value assumed for τ . Inverting Eq. (4) shows that the interfacial bond strength would have to exceed about 20 MPa for the 4 cm fibers to reach σ_u before pulling out, and about 40 MPa for the 2 cm fibers, that is four to eight times the upper bound reported for smooth fibers in a cementitious matrix. Only the inequality $L \ll L_c$ is used here: the absolute values of L_c are uncertain within the same factor of five as τ and should not be read as a quantitative estimate of the anchorage length. The failure mode itself was observed directly on the fracture surfaces (Fig. 12), where the fibers were recovered intact and still bridging the crack faces, with no fiber rupture; Eq. (4) therefore explains this observation rather than establishing it. This condition ($L \ll L_c$) accounts for the failure mode observed in Fig. 12 and explains why the increase in aspect ratio from 15.4 to 30.8 improves crack bridging through a longer frictional pull-out stage rather than through a change in failure mechanism.

Overall, these fracture observations confirm that the incorporation of recycled tie-wire fibers fundamentally modifies the fracture mechanism of SCC. Instead of a single unstable crack leading to sudden brittle failure, the reinforced concretes exhibited progressive crack propagation governed by fiber bridging and gradual pull-out. The combined evidence from the load–deflection curves, the fracture patterns (Fig. 11) and the macroscopic pull-out observations (Fig. 12) demonstrates that increasing the fiber aspect ratio significantly enhances crack resistance, post-cracking load-carrying capacity and energy dissipation, thereby producing the pseudo-ductile behavior observed experimentally.

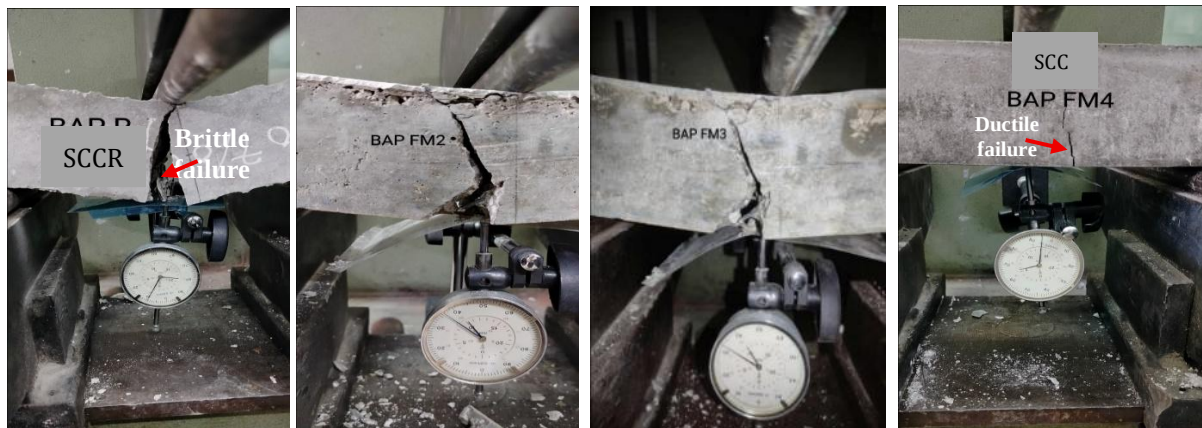


Fig. 11. Failure mode and crack pattern of mixes under three-point bending

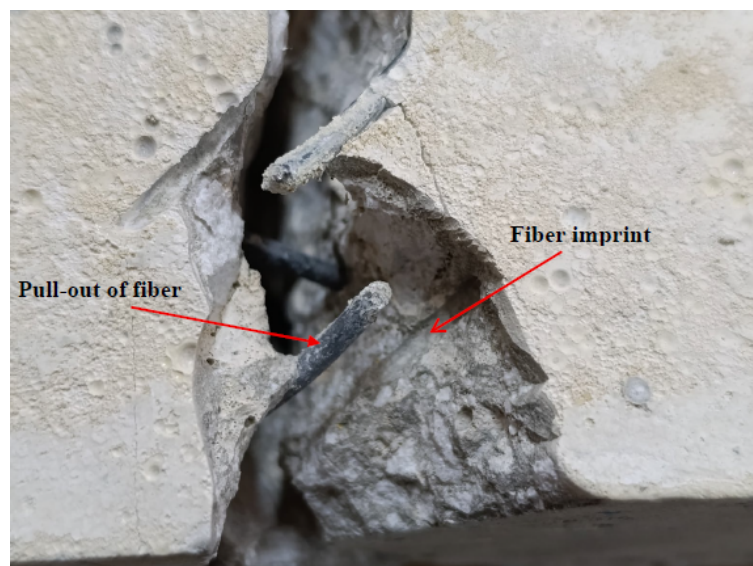


Fig. 12. Fracture surface showing fiber pull-out and crack-bridging mechanisms in fiber-reinforced SCC

3.2.4 Flexural Toughness

The use of metallic fibers in self-compacting concrete significantly enhances its energy absorption and its capacity to undergo a large amount of deformation prior to failure. This property, referred to as flexural toughness, was evaluated by integrating the area under the load-deflection curves up to a maximum deflection of 6.5 mm, based on the curves in Fig. 10. This area, which also represents the energy dissipated in 10^{-3} J, constitutes a relevant comparative indicator of the mechanical work absorbed during cracking. The corresponding results are presented in Fig. 13. The latter highlights the particularly favorable effect of metallic fibers on the post-cracking response. The SCC R only exhibited an absorbed energy of 125 N·mm, indicating a primarily brittle failure and a rapid loss of load-bearing capacity after the appearance of the main crack. In contrast, the fiber-reinforced formulations showed a progressive increase in toughness, reaching up to 38,281 N·mm for SCC MF4, which is more than 300 times the energy absorption capacity of SCC R. This formulation combined the highest maximum load and the longest post-peak branch, which confirms its capacity to maintain residual loads despite the increasing deflection.

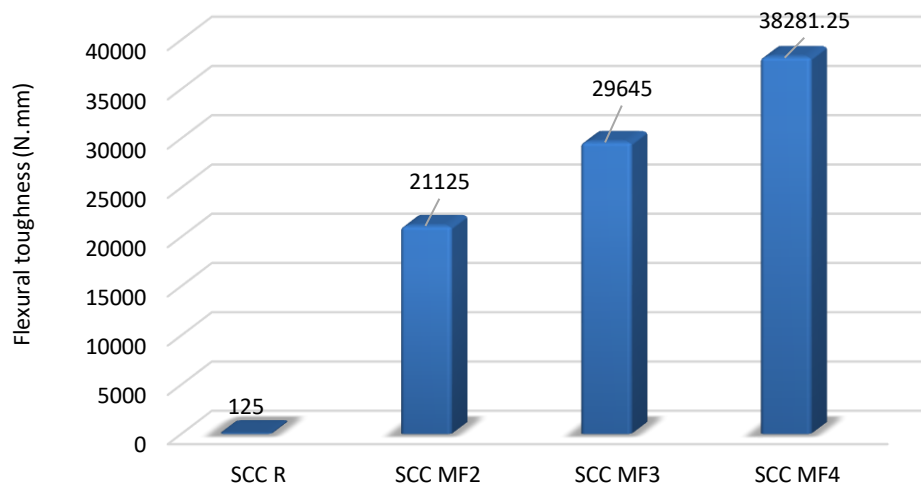


Fig. 13. Flexural toughness of SCC mixes

The additional analysis based on the energy principle of ASTM C1018 [45] confirms this trend overall. The indices I_5 , I_{10} , and I_{20} reach 4.37, 7.07, and 10.97 respectively for SCC MF4, compared to 1.85 for SCC R. SCC MF3 nevertheless presented the highest normalized indices, with respective values of 5.24, 8.40, and 11.29, while SCC MF2 showed intermediate values of 3.89, 6.45, and 9.96. The relative superiority of SCC MF3 does not contradict the higher absolute toughness of SCC-MF4. Indeed, the ASTM indices express the post-cracking energy relative to that absorbed up to the first crack, while the total area under the curve measures the overall energy capacity of the specimen.

This interpretation is also corroborated by the residual strength factors $R_{5,10}$ (calculated according to the energy-based approach adapted from ASTM C1018), which are 51.24%, 63.15%, and 53.84% for SCC MF2, SCC MF3, and SCC MF4, respectively, compared to a zero value for SCC R. Post-peak degradation was assessed through the residual load-bearing capacity rather than through a single post-peak stiffness value, since the descending branches are markedly non-linear. At a deflection of 6.5 mm, SCC MF2, SCC MF3 and SCC MF4 still carried approximately 0.5, 1.1 and 3.6 kN respectively, whereas SCC R had completely lost its load-bearing capacity. After the matrix has cracked, the fibers ensure crack bridging and allow for the progressive transfer of stresses. As illustrated in Figure 10, the additional energy is primarily absorbed by the debonding at the fiber-matrix interface, friction, and the progressive pullout of the fibers. These mechanisms delay the opening and propagation of cracks, preserve the integrity of the specimens, and transform the brittle failure of unreinforced concrete into a pseudo-ductile behavior, in accordance with the results reported in the literature [41,44].

The influence of fiber length on the hardened state is the counterpart of its influence on the fresh state discussed in Section 3.1. For randomly oriented fibers at constant volume fraction and

constant diameter, the number of fibers crossing a given crack plane does not depend on their length. This is confirmed by Soroushian and Lee [47], who derived and experimentally verified the theoretical expressions giving the number of fibers per unit cross-sectional area of a steel fiber reinforced concrete; for a three-dimensional random orientation, this number reduces to $2V_f/(\pi d^2)$, that is, about 1,900 fibers per square meter of crack surface in the present mixtures, whatever the fiber length used. The three reinforced concretes, therefore, bridge a crack with the same number of fibers; what differs is the embedment length available to each of them.

Since that embedment remains far below the critical length (Eq. 4, Section 3.2.3), every fiber fails by frictional pull-out, and the slip over which friction is mobilized increases with the fiber length. Naaman and Najm [48] established this dependence experimentally for smooth steel fibers by testing five diameters and three embedment lengths in cement-based matrices. They derived the bond shear stress-slip relationship at the interface from the pull-out load-slip curves, which indicates that for a smooth fiber, the bond testing was conducted on five diameters and three embedment lengths in cement-based matrices and derived from the pull-out load-slip curves the bond shear stress-slip relationship at the interface, which for a smooth fiber is entirely frictional once debonding is complete. The same behavior has been characterized in self-compacting concrete by Cunha, Barros, and Sena-Cruz [15]. This mechanism explains the measured toughness, which increased from 21,125 N·mm for the 20 mm fibers to 29,645 N·mm for the 30 mm fibers and 38,281 N·mm for the 40 mm fibers, as well as the residual load that was maintained up to a deflection of 6.5 mm. The two states of the material respond to the same geometrical change in opposite ways: what increases the viscosity of the fresh mixture is what enhances the toughness of the hardened composite, and the fiber length selected for a given application represents a compromise between placement requirements and post-cracking performance.

Considered together, the compressive and flexural results show how the fiber contribution develops. At 28 days the fibers raised the compressive strength by 35.5 %, the flexural strength by 66.1 %, and the absorbed energy by a factor of 306: the same reinforcement acted weakly on the matrix, moderately on the peak load, and overwhelmingly after cracking. The evolution with curing age separates the two mechanisms. In compression the fiber effect was essentially independent of age, 38.7 % at 7 days against 35.5 % at 28 days, as expected for a contribution that does not rely on interfacial bond; in flexure it nearly doubled over the same period, from 35.2 % to 66.1 %, which is the signature of a bond-controlled mechanism and is consistent with the longer post-peak branches recorded at 28 days in Fig. 10.

3.2.5 Peak Load and First-Crack Opening of SCC Mixes

Table 7 presents the evolution of peak loads and first-crack parameters of FRSCC compared to the unreinforced reference concrete (SCC R) at 7 and 28 days.

Table 7. Peak load and first-crack parameters of SCC mixes

SCC mixes	Peak load (kN)		% increase relative to SCC R		First crack opening (mm)	
Age	7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
SCC R	6	7	0	0	-	-
SCC MF2	7	8	16.7	14.3	0.6	1.3
SCC MF3	8	9	33.3	28.6	0.5	1.0
SCC MF4	9	11	50	57.1	0.2	0.3

The results clearly show that incorporating steel fibers derived from tie wires significantly increases the failure load of SCC compared to the unreinforced reference concrete.

- At 7 days, the increases reached +16.7 % for SCC MF2, +33.3 % for SCC MF3, and up to +50 % for SCC MF4.
- At 28 days, the improvements were even more pronounced, with +14.3 % for SCC MF2, +28.6 % for SCC MF3, and +57.1 % for SCC MF4.

Thus, the SCC MF4 mixture stood out as the most effective, confirming the efficiency of waste-derived steel fibers in enhancing mechanical strength, particularly over the long term.

Table 7 shows that incorporating steel fibers significantly reduced the first-crack opening.

- For the reference self-compacting concrete, no cracking was observed, indicating brittle failure behavior.
- At 7 days, the SCC MF4 mixture reduces the crack opening by 66.7 % compared to MF2 and by 60 % compared to SCC MF3, indicating an improved ability to limit the initial widening of cracks.
- At 28 days, the differences were even more pronounced: SCC MF4 reduced the crack opening by 76.9 % relative to SCC MF2 and by 70 % relative to SCC MF3.

This behavior highlights the essential role of steel fibers, which act as stitching elements contributing to crack stabilization. Moreover, a longer fiber offers a longer embedment length on either side of the crack, which increases the frictional work required to extract it, even though the total fiber–matrix interfacial area is the same in the three mixtures. This greater pull-out resistance is what limits the widening of the crack during loading.

These results indicate that the effect of steel fibers was particularly significant at early ages, effectively limiting crack opening during initial loading stages. The SCC MF4 mixture stood out, achieving a very high reduction, indicating improved toughness and effective long-term crack control.

In summary, these results demonstrate that the addition of waste-derived steel fibers not only enhances the failure load but also improves the long-term mechanical performance of self-compacting concrete.

Figure 14 illustrates the correlation between the maximum load and the first crack opening for self-compacting concretes reinforced with waste-derived steel fibers at 7 and 28 days. A decreasing linear trend was observed, indicating that larger crack openings are associated with lower maximum load capacities. The high coefficients of determination, with R^2 values of 0.9231 at 7 days and 0.9986 at 28 days, highlighted a very strong relationship between these two parameters, particularly at later ages. This evolution confirms that the increase in maximum load over time is closely related to improvements in the concrete's mechanical strength and the enhanced fiber–matrix bond during hardening.

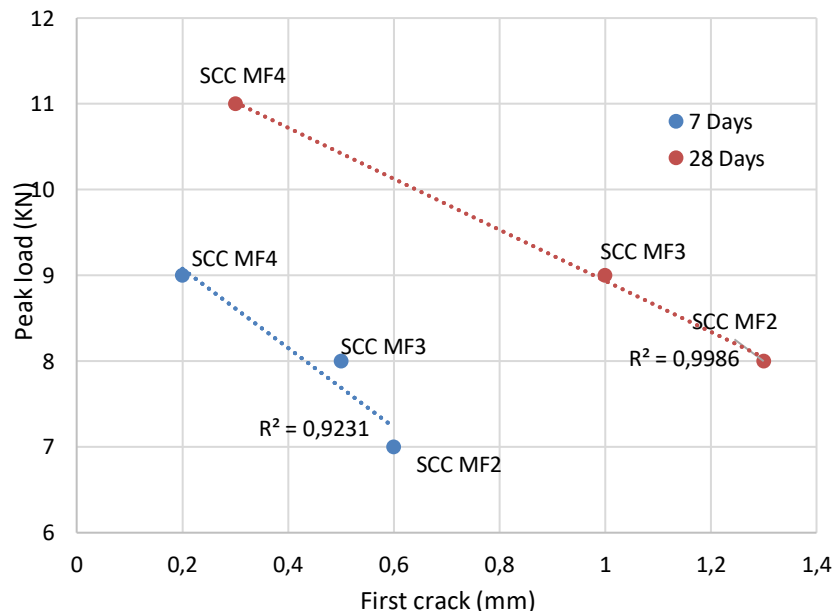


Fig. 14. Correlation between peak and first crack in SCC mixes

3.2.6 Microstructure of Fiber–Matrix Interface

The microstructural features of the fiber–matrix interface were examined using optical microscopy and scanning electron microscopy (SEM). Figure 15a demonstrates that the steel fibers are

properly embedded in the cementitious matrix, indicating a satisfactory distribution within the SCC.

The SEM image in Figure 15b distinctly differentiates the steel fiber from the surrounding matrix. The fiber is observed as a dense, relatively uniform phase with a smooth surface, while the cementitious matrix displays a more irregular, granular texture characteristic of hydration products. The transition zone at the interface appears compact, with no visible cracks or large voids. These microstructural characteristics suggest good physical contact between the steel fiber and the cementitious matrix and may contribute to stress transfer across the interface. However, SEM observations alone do not provide a direct measure of interfacial bond strength or stress transfer.

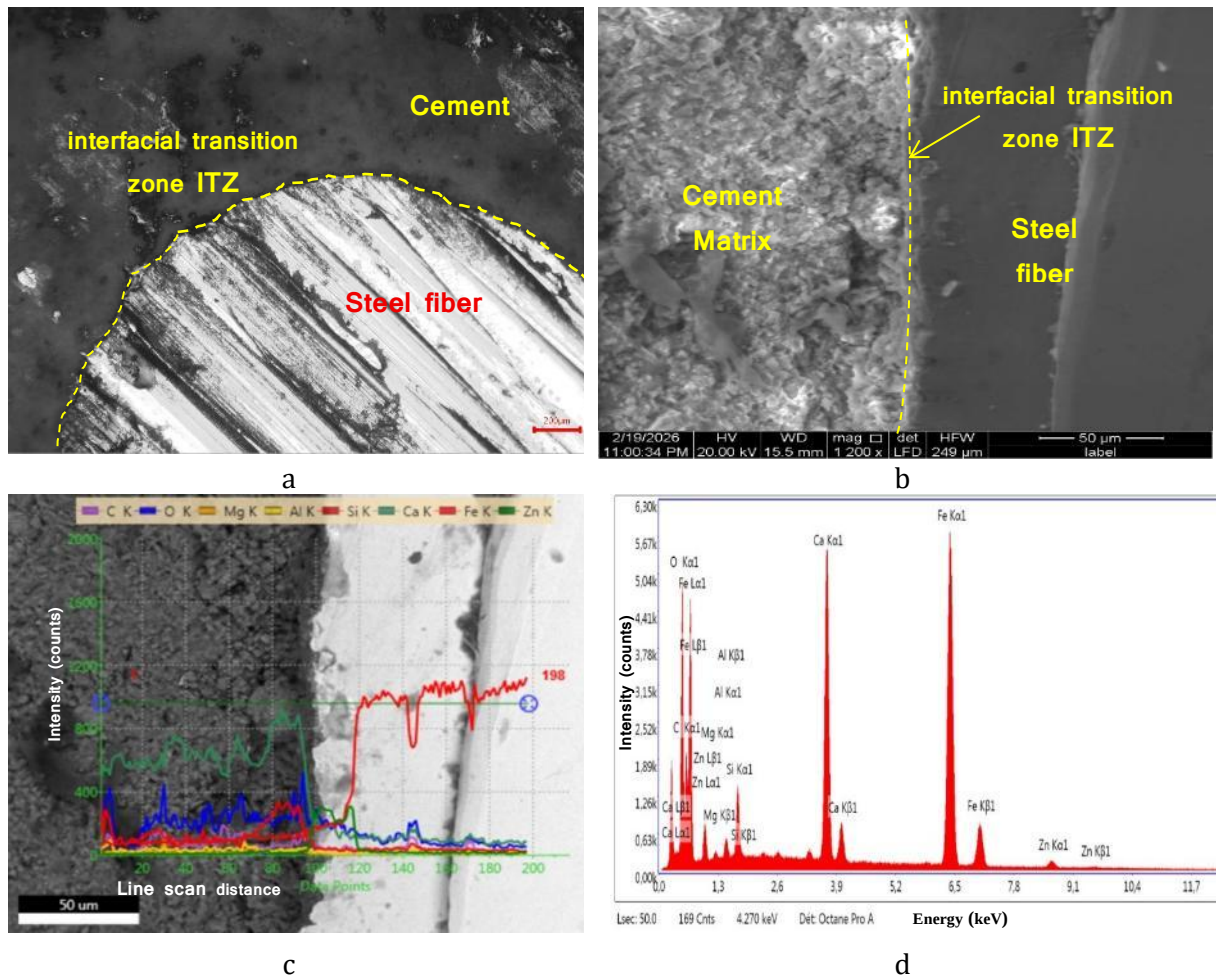


Fig. 15. Microstructural characterization of fiber-matrix interface: a) Optical microscopy observations. b) SEM of fiber- Matrix interface. c) EDS spectrum of interface. d) EDS line scan across interface

The energy-dispersive X-ray (EDX) spectrum shown in Figure 15c corroborates these observations by identifying the chemical composition of the distinct phases. The pronounced Fe signal is associated with the steel fiber, whereas the presence of Ca, Si, O, Al, and Mg corresponds to the cementitious matrix and its hydration products, primarily calcium silicate hydrate (C-S-H) and calcium hydroxide. The Zn signal originates from the galvanized coating of the tie wire; no conductive coating was applied during specimen preparation, so this element cannot be an artefact of the observation procedure. A more detailed analysis is provided by the EDX line scan across the interface (Figure 15d), which reveals three distinct compositional zones. In the matrix region, Ca and Si are the predominant elements, confirming the abundance of hydration products. As the scan approaches the interface, the concentrations of Ca and Si decrease gradually, while the Fe content increases. Within the fiber zone, Fe becomes the dominant element. This gradual transition in

composition, rather than an abrupt separation, is consistent with a gradual transition between the cementitious matrix and the steel fiber and suggests a relatively continuous interfacial zone.

It should be emphasized, however, that these observations are corroborative rather than a measurement of bond strength: no interfacial-transition-zone width, porosity gradient or nanoindentation profile was determined, and such a quantitative appraisal would require a dedicated protocol on purpose-prepared samples. SEM and EDX observations provide direct information on the morphology and elemental composition of the fiber–matrix interface, but do not allow for direct quantification of stress transfer or interfacial bond strength. The interface's contribution to stress transfer is therefore interpreted in relation to the mechanical response of the composites. The evidence that stress transfer across the interface is effective comes from the mechanical response, debonding and pull-out rather than fiber rupture; fibers recovered intact and still bridging the crack faces, gradual post-peak branches, and a toughness rising from 125 to 38,281 N·mm, for which the micrographs provide a microstructural explanation.

3.3 Economic and Environmental Considerations

The advantage of cut tie wire is that it is not produced as a reinforcing product in the first place. Tie wire is manufactured locally in Algeria for the binding of reinforcing bars, is stocked by every builder's merchant, and generates off-cuts that are usually discarded on site. Reusing this material as fiber reinforcement therefore removes two costs at once: the purchase of purpose-made fibers and the disposal of the off-cuts.

At the dosage adopted here, 40 kg of wire are required per cubic meter of concrete (Table 6). At 2026 local prices in Algeria, 150 DZD/kg for MF10 tie wire supplied in coils, against 350 DZD/kg for imported hooked-end steel fibers of the RC-80/50 type supplied in 1 kg bags [49], the cost of the reinforcement falls from 14,000 to 6,000 DZD per cubic meter, a saving of 8,000 DZD/m³, while the flexural strength at 28 days is increased by 66 % and the flexural toughness by a factor of 306 for the 40 mm fibers. The comparison is made on the cost of an equal mass of reinforcement and not at equal structural performance: the RC-80/50 fiber is 50 mm long with an equivalent diameter of 0.62 mm and hooked ends, so that its aspect ratio of 81 and its mechanical anchorage would give a different response at the same dosage. The two steels are nevertheless of comparable grade, the tensile strength of the tie wire being 1228.62 MPa against 1270 MPa for the commercial fiber, so that the difference in behavior is attributable to geometry and end anchorage rather than to the quality of the steel.

These figures cover the material only. Unlike the commercial fibers, which are ready for use, the tie wire is supplied in coils and must be cut to length: at 0.5% by volume, one cubic meter of concrete requires about 3.8 km of wire, which corresponds to roughly 188,000 cuts for the 20 mm fibers and 94,000 for the 40 mm fibers. In the present study, this operation was performed manually, using hand shears, at laboratory scale, and it would have to be mechanized for any practical application; its cost is not included in the comparison given above. By contrast, the unit price used for the wire is that of new material and is therefore a conservative upper bound, since off-cuts recovered on site carry no material costs.

These figures are indicative and should not be read as a life-cycle assessment. No inventory of the energy or carbon associated with the drawing and galvanizing of the wire has been established in this work. The environmental benefit claimed here is limited to what can be stated with confidence: an existing material stream is diverted from disposal, the manufacture of an equivalent mass of purpose-made fibers is avoided, and an imported product is replaced by a material manufactured locally.

4. Conclusions

This experimental study investigated the fresh and hardened properties of self-compacting concretes (SCC), highlighting the influence of the length of low-cost steel fibers on the rheological and mechanical performance of the material.

In the fresh state, all investigated mixtures exhibited satisfactory rheological properties in compliance with current standards. The incorporation of steel fibers did not adversely affect

flowability or stability, confirming their suitability for SCC formulations. In the hardened state, the SFRSCC mixtures surpassed the reference concrete in compressive strength, flexural tensile strength, and ultimate load capacity. Crack resistance testing showed that steel fibers improve post-cracking behavior. The fiber-reinforced concretes-controlled fracture propagation and stress redistribution better than the reference SCC, which failed in a brittle manner at 7 and 28 days. These findings confirm that incorporating steel fibers, particularly longer fibers, favorably alters the mechanical behavior of SCC by providing enhanced ductility, greater flexural toughness, and improved energy dissipation capacity, thereby leading to superior short- and long-term structural performance.

The energy-based analysis adapted from ASTM C1018 confirmed the substantial improvement in post-cracking performance provided by the fibers. SCC MF3 exhibited the highest normalized toughness indices (I_5 , I_{10} , and I_{20}) and residual-strength factor $R_{5,10}$, indicating the most efficient post-cracking energy absorption relative to the energy absorbed up to first cracking.

SEM–EDX analysis revealed a compact interfacial region and a gradual chemical transition between the metallic fiber (Fe-rich zone) and the cementitious matrix (Ca–Si–O-rich zone). This profile is consistent with the effective stress transfer inferred from the mechanical response.

This study was deliberately restricted to a single fiber content of 0.5 % by volume so that fiber length, and therefore aspect ratio, remained the only variable. The length-dependent effects reported here cannot be separated from dosage-related mechanisms on the basis of this program alone, and the advantage found for the 40 mm fibers holds at this content only. A program crossing several lengths with several dosages, aimed in particular at identifying the maximum content compatible with the filling and passing requirements of self-compacting concrete, is a natural continuation of this work.

In conclusion, the incorporation of alternative metallic fibers, such as tie wires, represents an innovative and cost-effective approach to reinforcing SCC. By prioritizing low-cost constituents, this solution enables effective control of material costs while ensuring mechanical performance and durability that meet the technical requirements of SCC.

Acknowledgments

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