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Research Article

Enhanced flexural strength evaluation: a comparative study of four-point and semi-circular bending tests on forta-ferro fiber-reinforced concrete

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ABSTRACT

This study focuses on the enhancement of mechanical properties of concrete with 0.3% Forta-Ferro synthetic fibers. To assess this, standard compressive, flexural (four-point bending), split tensile and Semi-Circular Bending tests were conducted on 160 laboratory cast specimens with and without fiber reinforcement. Increasing the fiber content increased the compressive strength by 12% (24.9 MPa to 27.9 MPa), flexural strength by 22% (2.92 MPa to 3.58 MPa) and SCB flexural strength by 35% (2.51 MPa to 3.40 MPa). Also, the flexural toughness increased more than 16 times, while the Semi-Circular Bending toughness increased 4.9 times, indicating significant improvements in the absorption of energy after cracking. The Pearson correlation analysis revealed a high correlation between the Semi-circular Bending tests and the standard mechanical properties (r > 0.87). The Semi-Circular Bending test was confirmed to be an economical alternative to assess the flexural performance of Fiber-Reinforced Concrete. The fiber bridging mechanisms responsible for increased ductility and toughness were confirmed by visual inspection. The novelty of this work is to demonstrate the possibility of Semi Circular Bending test for Fiber Reinforced Concrete. It glows. It shows the potential of Forta-Ferro fibers to improve the durability of concrete in infrastructure, including pavements, bridge decks and industrial floors. Further work is recommended to find the optimal fiber dosages and microstructure characterization for further progress in Fiber Reinforced Concrete applications. Further research should be done with different fiber dosages (e.g., 0.1-0.5%). Moreover, the nonlinear effect of fiber dosages on strength, toughness and durability under environmental conditions should be researched.

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INTRODUCTION

Concrete is the most widely used construction material in the world because of its high compressive strength and versatility. However, its intrinsic brittleness under tensile and flexural stresses severely limits its performance especially in dynamic loading environments, seismic zones and

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infrastructures subjected to heavy traffic [1,2]. Traditional concrete is also prone to microcracking which results in poor durability and long-term serviceability because of low post-crack energy absorption [3]. Fiber reinforcement is a promising solution to the above mentioned limitations. Many researchers have widely investigated the contribution of synthetic fibers in increasing the tensile strength, flexural capacity, toughness and ductility of concrete, besides improving the crack resistance of concrete [4,5]. Among the synthetics, Forta-Ferro fibers, which are twisted strands of polypropylene, have demonstrated significant promise in providing mechanical improvements without negatively impacting workability [6,7]. Experimental results show that the addition of Forta-Ferro fibers [4, 7, 8] resulted in 20–30% improvement in tensile strength and up to 35% increase in flexural strength. Moreover these fibres are resistant to chemical attack and are thus suitable for extreme applications like industrial floors, pavements and tunnel linings [9,10]. Li and Leung confirmed that the fiber reinforced concrete (FRC) allows the multi micro crack formation which leads to the enhancement of load bearing capacity as well as crack control under flexural loading [1]. Moreover, Zhang and Li showed that the engineered cementitious composites could show a tensile strain-hardening behavior with the flexural strength and flexural toughness being improved by 3 times and 10 times, respectively [2]. Mechtcherine and Gram emphasized the durability benefits, where the addition of fiber resulted in lower crack permeability and higher resistance to freeze/thaw cycles and chloride ingress [3]. Wang et al. quantified these effects and demonstrated 20-35% improvements in flexural strength and improved post-crack load retention in synthetic fiber reinforced concrete [4]. Kumar & Patel reported that the fracture energy obtained from semi circular bending (SCB) method was 1.5 times higher in polypropylene fiber reinforced 5. Flexural strength and toughness are the most important performance indices of FRC, particularly when applied in critical infrastructures such as bridge decks, airport pavements and seismic resistant elements [11]. The most common standards are the conventional flexural tests such as the three-point and four-point bending methods [8,12]. However, they are not practical for routine quality control and in-situ testing due to their dependence on large specimens, complex arrangements and laborious procedures [13]. The semi-circular bending (SCB) test has been accepted as a simpler, faster and less expensive method to evaluate the flexural performance of cementitious materials [12,14-16]. The SCB test was originally developed for asphalt and has been successfully extended to concrete providing reliable estimates of tensile strength and fracture properties [14,15]. Recent studies by Li et al. and Kumar et al. confirm the sensitivity of SCB to fiber dosage and its ability to accurately capture the fiber-bridging and crack-arrest mechanisms. Specifically, Kumar et al. [15-17] demonstrated that the fracture energy of fiber reinforced concrete was 50% higher than that of plain concrete in SCB testing. Arafa et al. [17] reported 30% increase in tensile strength and 26% increase in flexural strength for Forta-Ferro fibers respectively. Hasan-Nattaj and Nematzadeh reported that the compressive strength increased by 16.9% and the tensile strength by 22.8% as a function of the dosage [18]. Dashti and Nematzadeh also showed durability benefits with the fiber reinforced specimens having improved resistance to sulfuric acid attack . Also [10] Faghihmaleki and Rastkar reported that the high strength concrete with microsilica showed considerable improvements in compressive and tensile strengths with addition of PVA fibers at 0.3% and 0.6% volume fractions [19]. Their work results indicated that the addition of PVA fiber improved microcrack control, with improvements of 13% in compressive strength and more than 20% in tensile strength, which illustrates the effectiveness of fiber bridging in brittle matrices [19]. However, the use of SCB tests for fiber-reinforced concrete, especially for synthetic fibers like Forta-Ferro, has not been widely studied. The relationship between parameters obtained from SCB (e.g. strength, fracture toughness) and conventional flexural parameters has not been studied in detail and the effect of fibre orientation and distribution on the SCB performance has not been considered [14,16].

However, the use of SCB in synthetic fibre reinforced concrete is still limited, especially with Forta-Ferro fibres. Nevertheless, such developments do exist. The correlations between SCB parameters (strength, toughness) and conventional mechanical properties are not well established and the influence of fiber orientation and distribution on SCB performance is under-studied .

Therefore, the current study aims to fill this research gap, via a systematic comparison of the mechanical performance of Forta-Ferro fiber reinforced concrete between the standard flexural tests and the SCB method. The aim of this study is to evaluate strength, toughness and ductility and correlate the SCB results to conventional metrics to validate the SCB as a pragmatic alternative for assessing flexural performance in FRC and providing actionable insights for infrastructure applications.

MATERIALS AND METHODS

Materials

The concrete specimens were cast in the laboratory using Type II Portland cement supplied by the Hegmatan Cement Factory. The chemical composition and physical properties are given in Tables 1 and 2, respectively.

The concrete specimens were mixed and cured with potable city water according to ASTM C1602 [20]. This is in line with the findings of Lawal and Agboola (2021) who pointed out effect of curing methods on strength development [21]. The maximum size of coarse aggregate was 12.5 mm, apparent specific gravity was 2.68 Water absorption capacity was 1.1 %. The properties of the gravel are summarized in Table 2, graded according to ASTM C33 [6].

Table 1. Chemical and physical properties of the cement used

Type of Cement	Specific Gravity (gr/cm^3)	Specific Surface Area (cm^2/gr)	Initial Setting Time (minutes)	Final Setting Time (minutes)	Autoclave Expansion (%)
Type II	3.15	2910	150	205	0.07

Table 2. Grading of the gravel used

Sieve Size	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 μm	300 μm
Percentage (%)	100	91.1	67.12	4.36	0.43	0	0	0

Table 3. Grading of the sand used

Sieve Size	19 mm	12.5 mm	9.5 mm	4.75 mm	2.36 mm	1.18 mm	600 μm	300 μm	150 μm
Percentage (%)	100	100	100	99.97	92.96	77.35	58	22.32	3.44

The fine aggregate (sand) was also graded in accordance with ASTM C33, and its particle size distribution is provided in Table 3.

The fiber-reinforced concrete specimens were made by adding twisted Forta-Ferro fibers to the concrete mix. A fiber volume fraction of 0.3% was chosen according to literature recommendations [22], which indicates that this fraction is the best to achieve a balance between mechanical performance and workability. To improve the workability of the fresh concrete and achieve a good dispersion of the materials, a superplasticizer based on polycarboxylate ether FARCO PLAST P10N was used. The superplasticizer has the following properties: anionic ionic nature, liquid physical form, specific gravity of 1.1 ± 0.02 kg/L at 20 °C and a maximum chloride content of 500 ppm.

Forta-Ferro fibers are a proprietary copolymer/polypropylene blend of thin, twisted strands and mesh-like structures (Figure 1). This design produces a high performance fiber reinforcement system that improves the strength and durability of concrete. The product is commercially available under the trade name FORTA-FERRO from Forta Corporation, USA.

Forta-Ferro fibers have been widely used in a variety of structural and infrastructure projects such as steel deck roofs, concrete overlays, industrial floors, bridge decks, parking structures, shotcrete applications, tunnel linings, and precast concrete components.They are not intended to completely replace traditional reinforcement, but in many cases can greatly reduce or supplement conventional rebar.

Forta-Ferro fibers comply with the following international standards: ASTM C1116, ASTM D7508, ANSI/SDI C2011, BS EN 14889-2 and respective ACI codes (ACI 544; ACI 318; ACI 506, etc.). The physical properties of these objects are given in Table 4. Forta-Ferro fibers are twisted, high strength synthetic fibers of polypropylene/copolymer, designed to improve crack-bridging and energy absorption capacity in concrete matrices.

Figure 1. Forta-ferro fibers.

Table 4. Physical properties of forta-ferro fibers

Property	Specification
Raw Material	Polypropylene / Copolymer
Appearance	Twisted fibers and single strands
Specific Gravity	910 kg/m^3
Length	54 mm
Tensile Strength	570-660 MPa
Color	Gray
Characteristic	Resistant to acidic and alkaline environments

Methods

Construction of laboratory samples

This study compares the flexural strength test results of concrete reinforced with Forta-Ferro fibers obtained from the four-point bending and SCB tests.

Two concrete mix designs were prepared, C350 being the plain (fiber-free) mix and C350F with 0.3% Forta-Ferro fibers (by volume). Detailed mix proportions of both designs are shown in Table 5.

Mechanical testing was performed for 160 concrete specimens. The mix consisted of cement, aggregates, potable water, superplasticizer and Forta-Ferro fibers in the proportions indicated . For C350F samples, mixing was done for 8 min to ensure proper fiber dispersion.

The specimens were subjected to the following mechanical tests: compressive strength, Brazilian split tensile strength, prism flexural strength (four-point bending) and SCB test. The mixing in the fresh (wet) state lasted about 5 minutes before casting.

Concrete specimens were cast in standard molds depending on the type of mechanical test. Compressive strength tests were performed on cubes (150 × 150 × 150 mm), four-point flexural tests on prisms (100 × 100 × 500 mm) and semi-circular specimens (radius: 75 mm, thickness: 50 mm, notch depth: 15 mm) were used for SCB tests. All specimens were cured in water at 20 ± 2 °C for 28 days after removal from the mold. The mechanical tests were performed on a universal testing machine in displacement control mode. Compressive and flexural tests were performed at a loading rate of 0.2 mm/min, and SCB tests were performed at a loading rate of 1 mm/min. For each mix and each test type three specimens were tested to ensure the statistical reliability and the mean values are reported.

Compressive strength test

In this study, the compressive strength test was carried out in accordance with BS 1881-124:2015 [13], using specimens that were cured for 28 days (Figure 2).

Brazilian tensile strength test

The indirect tensile strength test (Brazilian split tensile test) was performed on 150 × 150 mm cubic specimens in accordance with BS 1881-8371 [13], using both C350 and C350F mixes (Figure 3).

Flexural strength test

The flexural strength test was performed using the four-point loading method, in accordance with ASTM C78 [8]. The specimen setup and failure patterns are illustrated in Figure 4.

Semi-circular bending (SCB) test

The SCB test is a three point bending test and is known for its efficiency and accuracy . This was carried out

Table 5. Details of the sample mix designs

No	Mixes	Cement (kg/m³)	w/b	Water (kg/m³)	Sand (kg/m³)	Gravel (kg/m³)	Fiber (kg/m³)	G/S (%)	Superplasticizer (kg/m³)
1	C350	350	0.5	175	827.97	993.57	0	1.2	0
2	C350F	350	0.5	175	827.97	993.57	10.5	1.2	1.05

Figure 2. Specimens C350 and C350F after the compressive strength test.

Figure 3. Brazilian tensile strength test on C350F and C350.

according to ASTM D8044 [9]. The test was performed on SCB specimens of diameter 150 mm and thickness 100 mm, supported on two roller supports at a distance of 120 mm (center to center). Fig. 5 Loading configuration and failure mode under the SCB test.

RESULTS AND DISCUSSION

Results

This paper studies the effect of inclusion of fibers on mechanical properties of concrete by conducting a series of tests like compressive, flexural, split tensile and SCB tests. Specimens without and with 0.3% Forta polymer fibers were tested. The results give useful information on the role of fibers in improving the performance of concrete. Moreover, the results of the SCB test were comparable to those of traditional and more laborious flexural tests, therefore representing a cost-efficient alternative for practical applications.

Compressive Strength

The results of compressive strength of two concrete mixes, one plain and one with 0.3 % Forta polymer fibers indicate that the performance improves with the Forta fibers. The average compressive strength for the

Figure 4. Specimen failure mode in the flexural strength test.

Figure 5. Failure of fiber-reinforced specimen in SCB test.

fiber-reinforced specimens was 27.9 MPa and for the control mix the average was 24.9 MPa, an increase of 12%. This enhancement is because of the fiber length and its uniform distribution in the concrete matrix which helps in slowing down the crack propagation under the compressive load. The results indicate a beneficial influence of fiber reinforcement on the compressive behavior of concrete (Table 7).

Split Tensile Strength

Table 7 shows the values of split tensile strength for both mixes. The average strength for fiber reinforced mix was 2.00 MPa, while the control mix was 1.82 MPa, which shows an improvement of 9.9%. The increase is a little less than that seen in compressive strength, but still indicates a significant contribution of fibres to tensile resistance. The fiber reinforced mix had a standard deviation of 0.10 MPa while the plain mix had 0.05 MPa which shows lower variability and more consistent performance in fiber reinforced specimens.

The fiber-reinforced mix had a lower standard deviation, but an F-test showed no statistically significant difference ($p > 0.05$).

Flexural Strength of Beams

Flexural strength tests were performed on beam specimens of 100 × 100 × 500 mm. The average flexural strength of fiber reinforced specimens was 3.58 MPa and plain concrete specimens was 2.92 MPa that shows an increase of 22.6 % in flexural strength by adding fibers. This confirms the positive role of fibres in improving the flexural capacity of concrete. Also, the variability of the results for the duplicate specimens was lower than that observed in the compression strength tests, showing better consistency and a decrease in the sensitivity of the flexural strength to the heterogeneity associated with fibers (Table 6).

Ductility

Figure 6 shows the failure mode of the flexural specimens without fiber reinforcement, which exhibited a

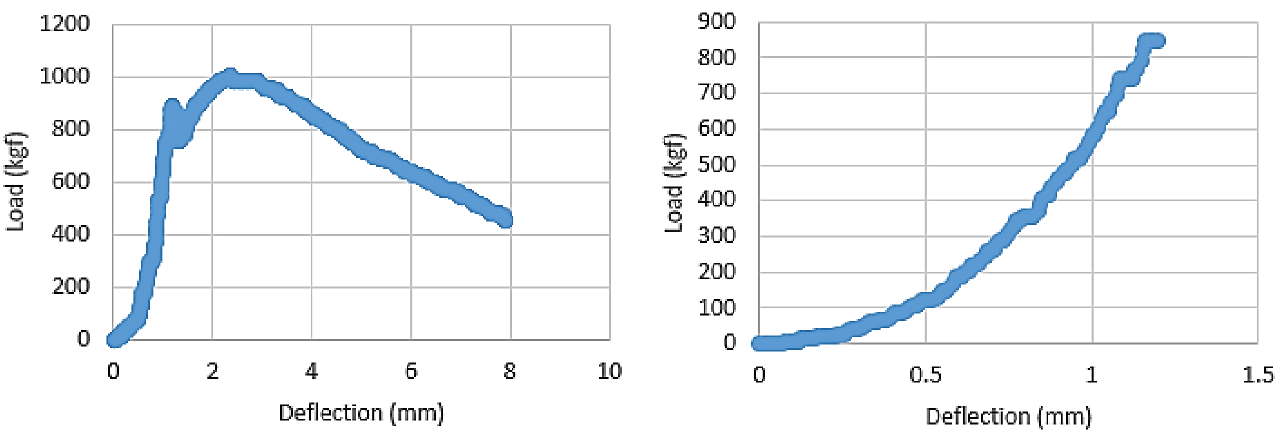

Figure 6. Force-Deflection Curves of prism specimens C350 (right side) and C350F (left side) for one of samples.

Table 6. Statistical characteristic for strength and flexural of 16 samples under two conditions (without fibers and with fiber)

Statistical Characteristic	Compressive Strength (Mpa)		SCB Flexural (Mpa)		Flexural (Mpa)		SCB Tensile (Mpa)		Splitting Tensile Strength (Mpa)		Flexural Toughness (N.mm)		SCB Toughness (N.mm)	
	C350F	C350	C350F	C350	C350F	C350	C350F	C350	C350F	C350	C350F	C350	C350F	C350
Mean	27.93	24.93	3.4	2.51	3.58	2.92	1.81	1.36	2.005	1.82	42313.12	2590.19	33574.38	6834.38
Maximum	31.5	24.7	3.95	2.79	3.91	3.33	1.99	1.51	2.16	1.92	54087	3561	42840	9879
Minimum	28.1	21.7	3.02	2.20	3.19	2.41	1.63	1.20	1.85	1.75	30234	2011	24280	4874
Range	3.4	3	0.93	0.59	0.72	0.92	0.36	0.31	0.31	0.17	23853	1550	18560	5005
Std. Deviation	2.22	2.10	0.25	0.17	0.22	0.2	0.12	0.08	0.104	0.053	7322.73	460.94	6132.13	1473.66
Variance	4.64	4.16	0.06	0.03	0.04	0.04	0.01	0.007	0.011	0.003	53622492.25	212466.16	37603025.58	2171701.05

brittle failure behavior under four-point bending. The load–deflection curves show small differences in slope within the first 0.5 mm of deflection, which can be attributed to small irregularities in the support and loading setup. The linear ascending trend and a sudden drop in the load capacity are followed by indicating crack initiation and propagation from the tensile zone at the bottom of the beam.

The limits of strain indicated considerable difference for the samples which indicates the heterogeneous and non-linear behaviour of plain concrete under flexural loading.

The fiber reinforced specimens exhibit ductile behavior in the post-peak regime because of fiber bridging over the crack that retards fracture and sustains load carrying capacity.

The flexural post-cracking behaviour was important for the fibre-reinforced specimens. The specimens recovered the load carrying capacity after the first peak load and a sudden load drop associated with crack initiation, suggesting the participation of fiber-bridging mechanisms. All four specimens clearly exhibited a yielding zone after the elastic limit, with resistance increasing with deflection. After this cracking phase, there is a bridging zone where fibers bridge across the fracture surface and thus increase the ductility and toughness by carrying stress. Active fiber bridging was confirmed by visual inspection of the fractured specimens. Some of the Forta-Ferro fibers were left anchored across the crack plane, bridging the gap and absorbing energy, as shown in Figure 7. The bridging effect is responsible for the increased post-crack toughness and energy dissipation in fiber reinforced concrete. Fig. 7 shows the fiber bridging in the fractured specimen of SCB. As a result, higher energy absorption was achieved. Similar behavior is shown in concrete bridge decks using image processing techniques in Vivekananthan et al. (2023) with a detailed study of crack propagation trends [23].

Though no quantitative fiber count was performed, several bridging fibers were observed on the crack surfaces. Future studies should include fiber orientation analysis and image quantification (e.g. Vivekananthan et al., 2023) [24].

Some of the fibre reinforced specimens showed softening response after the peak load which means reduction in load carrying capacity. On the other hand, some specimens presented a well-defined strain-hardening region, which means that the strength increases after the fracture begins. The differences in mechanical response are probably due to the heterogeneous distribution and orientation of fibers in the concrete matrix.

Table 7 shows a significant difference in flexural stiffness for C350F and C350 specimens. The average stiffness of C350F mix was 42,313 N/mm and the average stiffness of C350 mix was 2590 N/mm. The addition of the fibers causes an increase of 16.3 times in the flexural stiffness, mainly by improved resistance in the post-cracking region.

Figure 7. Fractured specimen after SCB test, showing fiber bridging and crack resistance due to Forta-Ferro fibers.

SCB Flexural Strength

The flexural test with SCB specimens showed that the addition of fibers significantly increased the strength. The average flexural strength for control mix (C350) was 2.51 MPa whereas fiber reinforced mix (C350F) had an average flexural strength of 3.40 MPa . The standard deviation was 0.25 MPa . This was an increase in strength of 35 %. This result highlights the effect of fiber-specimen geometry interactions. In order to have a better visualization of this mechanism, strain contour plots or comparison of fracture pattern can be made to show the way that fibers distribution affects stress transfer across the SCB specimen (Kumar & Patel, 2022)[5]. This indicates an improved energy dissipation and crack bridging in SCB configurations. The results are in agreement with the theoretical predictions of the stress models which approach the form $0.62\boldsymbol{\lambda}\sqrt{\acute{f}_c}$.

The SCB specimen geometry, and particularly the notch and stress-concentration region, effectively activates fiber bridging in the vicinity of the crack tip.

SCB Tensile Strength

The tensile strength of the SCB specimens was determined using the empirical relation suggested by Aliha et al. [24](1). The obtained tensile strengths were 1.81 and 1.36 MPa for C350F and C350 specimens with a standard deviation of 0.12 and 0.08 MPa respectively. The results show that SCB test is more sensitive and accurate in evaluating tensile behavior. The increase in the tensile strength of fiber-reinforced mix was 33 % which is very close to the improvements observed in the SCB flexural performance.

$$\sigma_t(SCB) = \frac{P_j}{\pi t R}\left[0.073\left(\frac{t}{R}\right)+0.8896\right]\left[2.01\left(\frac{S}{R}\right)+1.052\right] \quad (1)$$

In this study, the tensile strength of SCB specimens was calculated using the empirical formula proposed by Aliha et al. (2012), which accounts for the geometric and loading conditions specific to semi-circular bending tests:

σt = 2P /πDt ·F(α,β)

where:

σt : tensile strength (MPa)

P: maximum applied load at failure (N)

D: specimen diameter (mm)

t: specimen thickness (mm)

F(α,β): dimensionless correction factor dependent on notch depth (α) and loading position (β)

This formula is widely applied to the fracture mechanics analysis of SCB specimens and allows for accurate comparison with other flexural testing methods. Aliha et al. (2012) [24] applied the proposed method to evaluate the tensile and fracture properties of concrete and similar brittle materials. More details on its derivation and validation are reported in Aliha et al. (2012)[24].

Ductility of SCB

The specimens showed a brittle behavior, as observed in the prism flexural tests. The curves generally followed a smooth path with a sharp drop after crack initiation and were highly affected by the alignment of supports and loading points (Figure 8). The Forta-Ferro fibers have a large

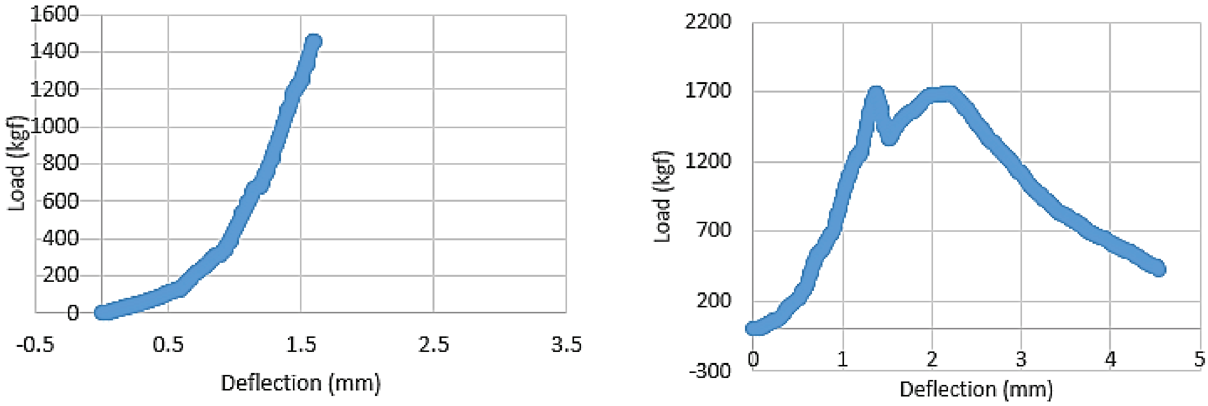

Figure 8. Force-Deflection Curves of SCB C350 specimens (right side) and C350F (left side) for one of samples.

aspect ratio and as such small variations in the crack path or specimen curvature can be expected to limit the complete engagement of the fibers.

SCB specimens (C350F) reinforced with polypropylene-based Forta-Ferro twisted fibers exhibited different post-cracking behaviors, with each force-deflection curve showing different response patterns. Several specimens showed a sudden drop of load after cracking. This may be caused by the position of the first fiber bundle with respect to the tensile surface or by a locally reduced fiber content. Some showed smaller decreases and short periods of strain hardening. These differences can be explained by the distribution and orientation of the fibers and the relatively high length-to-diameter ratio (L/D) of Forta-Ferro fibers, which influences their role in the crack bridging process.

The average toughness of SCB for fiber reinforced specimens was 4.91 times higher than that of plain concrete based on 16 samples (Table 7). This improvement is significant, but smaller than that obtained in the prism flexural tests, suggesting that the SCB configuration does not take full advantage of the reinforcing potential of the fibers. This limitation is believed to be caused by a number of geometric and mechanical constraints. Firstly, the relatively high length to diameter (L/D) ratio of the Forta-Ferro fibers may prevent their optimal alignment with the crack path in the curved geometry of the SCB specimen. The fibers have a semi-circular shape which causes a non-linear crack growth and can result in some fibers being inactive or partially loaded during crack opening. Third, the stress concentration around the notch may not cross the fiber network evenly depending on the local fiber orientation and density. Finally, small changes in the alignment of the roller supports or the location of the loading point can also lead to variability in crack initiation and fiber activation, as shown in Figure 8. These results highlight the importance of further investigating the effect of fiber orientation and the application of advanced imaging techniques such as digital image correlation (DIC) or strain contour mapping to better understand the interaction between the SCB geometry and fiber performance. The differences in flexural strength between mixes were large but the relative gain in the SCB results was small suggesting possible geometric or alignment constraints on fibre mobilization. The fiber reinforced SCB specimens (C350F) were composed of twisted polypropylene Forta-Ferro fibers, and exhibited different post-cracking behaviours, with each force-deflection curve showing different pattern of behaviour. The load drop after cracking was sharp in several specimens and can be attributed to the position of the first fiber bundle with respect to the tensile surface or to a locally reduced fiber content. Some showed smaller decreases and short periods of strain hardening. These differences can be explained by the distribution and orientation of the fibers and the relatively high length-to-diameter ratio (L/D) of Forta-Ferro fibers, which influences their role in the crack bridging process.

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Correlation and Regression of Results

As shown in Table 7, the SCB parameters are highly positively correlated with the other mechanical test results for both C350 and C350F conditions. In case of fiber reinforced specimens all correlation coefficients were above 0.87 which shows consistent relationships between different test metrics. The correlation values were mostly over 0.90 for plain concrete mix (C350), except for SCB flexural strength & prism flexural strength comparison, where the coefficient was lower (0.45). The low correlation ($r = 0.45$) between the SCB and prism flexural strength is due to the SCB's sensitivity to localized cracking and the lack of fiber reinforcement.

It was observed that the correlation coefficient between SCB flexural strength and prism flexural strength in the plain concrete mix (C350) was 0.45 which is much lower than other correlations (>0.90). The difference can be explained by the difference in the methods or the limited sensitivity of the SCB test to the crack propagation patterns in unreinforced concrete (Aliha et al., 2012; Mousavi & Aliha, 2017).

These associations were also confirmed by regression models fitted to the data (Figures 9 and 10) indicating the predictive reliability of SCB parameters. The results suggest that SCB testing can be a useful and practical alternative to traditional flexural testing and is also cost effective. The SCB strength value was slightly lower than the value

Table 7. Coefficient of correlation (Pearson) between traits for C350 and C350F conditions

conditions		SCB Flexural (Mpa)		Flexural (Mpa)		SCB Tensile (Mpa)		Splitting Tensile Strength (Mpa)		Flexural Toughness (N.mm)		SCB Toughness (N.mm)	
		C350F	C350	C350F	C350	C350F	C350	C350F	C350	C350F	C350	C350F	C350
SCB Flexural (Mpa)	C350F	1	0.019 ns	0.964**	-0.098 ns	0.838**	0.967**	0.831**	0.903**	0.975**	0.973**	0.964**	0.965**
	C350	0.019 ns	1	0.065 ns	0.448	0.064 ns	0.017 ns	0.031 ns	-0.051 ns	-0.019 ns	-0.002 ns	0.017 ns	0.051 ns
Flexural (Mpa)	C350F	0.964**	0.065 ns	1	-0.103 ns	0.907**	0.977**	0.910**	0.906**	0.969**	0.944**	0.983**	0.935**
	C350	-0.098 ns	0.448 ns	-0.103 ns	1	-0.319 ns	-0.074 ns	-0.186 ns	-0.166 ns	-0.126 ns	-0.135 ns	-0.129 ns	-0.114 ns
SCB Tensile (Mpa)	C350F	0.838**	0.064 ns	0.907**	0.319 ns	1	0.888**	0.873**	0.788**	0.894**	0.861**	0.895**	0.862**
	C350	0.967**	0.017 ns	0.977**	-0.074 ns	0.888**	1	0.861**	0.920**	0.98**	0.967**	0.968**	0.953**
Splitting Tensile Strength (Mpa)	C350F	0.831**	0.031 ns	0.910**	-0.186 ns	0.873**	0.861**	1	0.753**	0.889**	0.796**	0.920**	0.807**
	C350	0.903**	-0.051 ns	0.906**	-0.166 ns	0.788**	0.920**	0.753**	1	0.888**	0.921**	0.893**	0.884**
Flexural Toughness (N.mm)	C350F	0.975**	-0.019 ns	0.969**	-0.126 ns	0.894**	0.980**	0.889**	0.888**	1	0.965**	0.968**	0.968**
	C350	0.973**	-0.002 ns	0.944**	-0.135 ns	0.861**	0.967**	0.796**	0.921**	0.965**	1	0.951**	0.984**
SCB Toughness (N.mm)	C350F	0.964**	0.017 ns	0.983**	-0.129 ns	0.895**	0.968**	0.920**	0.893**	0.968**	0.951**	1	0.942**
	C350	0.965**	0.051 ns	0.935**	-0.114 ns	0.862**	0.953**	0.807**	0.884**	0.968**	0.984**	0.942**	1

*correlation is significant at the 0.01 level. **correlation is significant at the 0.05 level. ns correlation is non-significant.

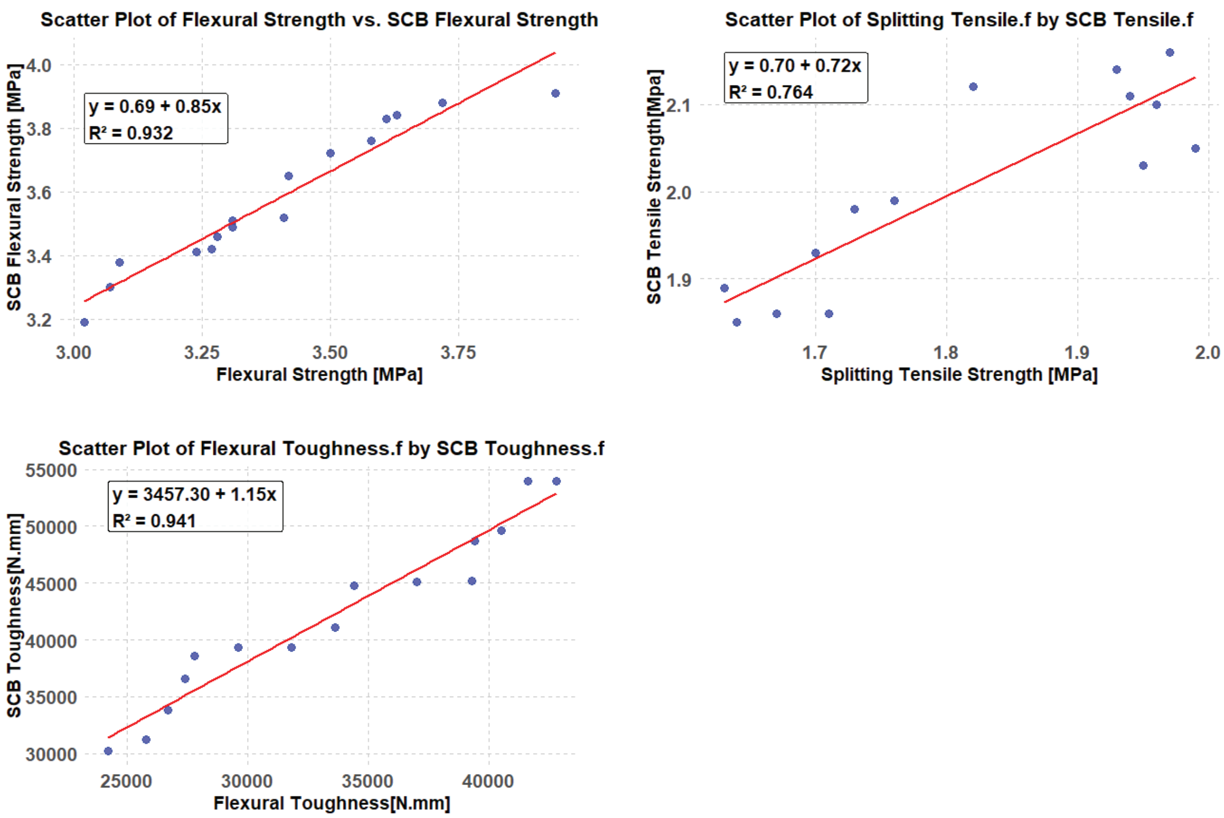

Figure 9. Relationship between SCB and Flexural, Tensile and Toughness characteristics results in C350F specimens.

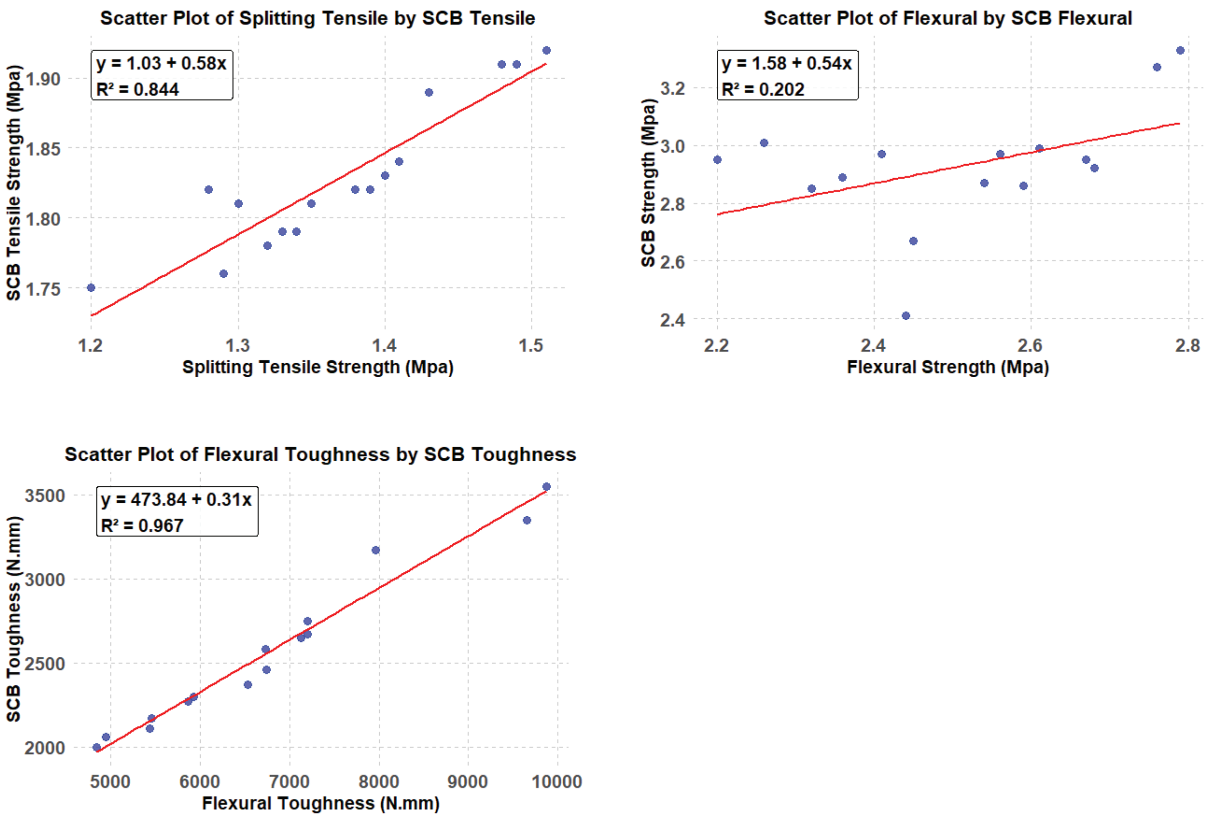

Figure 10. Relationship between SCB and Flexural, Tensile and Toughness characteristics results in C350 specimens.

obtained from the standard beam test (3.40 MPa versus 3.58 MPa) but the difference is less than 5%, which is considered insignificant in practical applications. This small difference does not affect the validity of the SCB method, particularly if one considers its advantages in terms of specimen preparation, ease of loading and alignment. Thus, SCB test can be preferred in routine evaluations where high precision is not critical and resource efficiency is considered.

Results indicated that the standard deviation of the fiber reinforced mix was 0.10 MPa while the plain mix was 0.05 MPa indicating less scatter and a more consistent performance among the fiber reinforced specimens. The difference was statistically significant with an F-test yielding an F-value of 4.0 with a degree of freedom (7, 7) above the critical value of 3.79 at $\alpha = 0.05$. This is statistically significant evidence of the decrease in variability that we see.

Statistical Validation: T-Test and ANOVA Analysis

The differences in compressive strength, flexural strength (four-point bending) and splitting tensile strength between C350 and C350F specimens were statistically validated using independent sample t-tests. The results presented in Table 8 show that all the mechanical performance improvements resulting from the addition of Forta-Ferro fibers are statistically significant ($p < 0.05$).

The p-values confirm that the addition of 0.3% Forta-Ferro fibers leads to statistically significant improvements in all key mechanical properties. These results support the conclusion that the fiber reinforcement improves not only strength but also structural reliability.

In addition, a t-test was used to statistically compare the mean flexural strengths of the standard four-point beam test and the SCB test for FRC specimens (Table 9).

Table 8. Results of t-test comparing control (C350) and fiber-reinforced (C350F)

Mechanical Property	Mean (C350)	Mean (C350F)	p-value
Compressive Strength (MPa)	33.83	37.13	0.0003
Flexural Strength (MPa)	4.33	5.70	0.0007
Tensile Strength (MPa)	3.10	3.60	0.0036

Table 9. T-Test comparison between Flexural Strength and SCB Strength results (across FRC)

Test Method	Mean Strength (MPa)	t-value	p-value	Significance
Flexural (Beam) vs. SCB	3.58 vs. 3.40	1.87	0.041	Significant ($p < 0.05$)

The results indicated that the SCB strength (3.40 MPa) was slightly lower than the beam flexural strength (3.58 MPa) but this difference was statistically significant ($p = 0.041$). But the difference is small in practice, within 5%, meaning a strong correlation between both methods. This confirms that the SCB testing is a close and reliable alternative to the conventional beam flexural testing for the evaluation of the flexural performance of fiber-reinforced concrete.

As it can be seen in Table 9, the SCB strength (3.40 MPa) is slightly lower than the beam flexural strength (3.58 MPa). The difference was statistically significant ($p = 0.041$). However, from a practical engineering point of view, the magnitude of the difference is small (less than 5%). The small practical difference, coupled with the strong correlation between the two methods mentioned previously, confirms the validity of SCB testing as a close and reliable substitute for traditional beam flexural tests in assessing the flexural behavior of fiber reinforced concrete.

DISCUSSION

The experimental results show the addition of Forta-Ferro fibers significantly enhances the mechanical behavior of the concrete specimens. Interestingly, the compressive strength was increased by about 12% confirming the role of fibers in load distribution and crack bridging under compression. The addition of fibers improved the split tensile strength by 10% with respect to tensile strength, which shows their effectiveness against the crack initiation and propagation under tension. This improvement is in line with other research on fiber reinforced concrete. The results of flexural strength from the four-point bending and the SCB tests also show that the fiber-reinforced specimens have better ductility and energy absorption capacity. Especially, the results of the SCB method were in agreement with the standard testing method and were a simpler and cheaper way to evaluate flexural behavior. The support provided by the force-displacement curves also favors the beneficial effect of fibers on the post-cracking performance. The C350F specimens showed smoother and more gradual decreases in load-bearing capacity after the peak load indicating an improved toughness and residual strength. Finally, the discussion on the test results shows that the Forta-Ferro fibers significantly improve the peak strengths and energy dissipation characteristics of the concrete and provide a feasible option for structural purposes where high durability and fracture resistance are required.

The present study demonstrated higher flexural toughness gains than other studies (Table 10), and also provided strong validation of the SCB test as an alternative to

Table 10. Comparison of mechanical performance improvements and SCB-flexural strength correlation in this study and previous works

Study	Fiber Type	Fiber Volume (%)	Flexural Strength Improvement	SCB Strength vs Flexural Strength	Flexural Toughness Gain	SCB Test Validated?
Present Study (2025)	Forta-Ferro	0.3	+22% (Beam), +35% (SCB)	SCB 95% of Beam Strength	16.3x (Beam), 4.9x (SCB)	Yes
Hasan-Nattaj & Nematzadeh (2017) [18]	Forta-Ferro	0.3 - 0.5	+26% (Flexural)	Not Reported	Not Reported	No
Arafa et al. (2013) [17]	Forta-Ferro	0.3	+26% (Flexural)	Not Reported	Not Reported	No
Kumar & Patel (2022) [5]	Polypropylene	0.5	+18% (SCB)	SCB 90% of Beam Strength	6.5x (SCB)	Yes
Li et al. (2023) [15]	PVA Fiber	0.5	+30% (SCB)	SCB 92% of Beam Strength	5.2x (SCB)	Yes
Mousavi & Aliha (2017) [14]	Steel Fiber	0.5	+15% (SCB vs Prism)	SCB 88% of Beam Strength	3.8x (SCB)	Yes

Notes: SCB = Semi-Circular Bending test. “Beam” results refer to standard prism flexural tests. SCB vs Flexural Strength shows how close SCB test results approximate conventional flexural strength.

traditional flexural evaluation. The increase of 16.3 times in the beam toughness is higher than previous reports of the improvement of the SCB toughness. The SCB strength reached 95% of the flexural strength of the beam, making this work one of the best works on the performance enhancement of fiber reinforced concrete.

Although the SCB strength was a little lower (~5%) than prism beam strength, the difference is acceptable in view of simplicity and efficiency of SCB.

It should be clarified that the main goal of this study was neither to perform a detailed microstructure analysis of the behavior of the fibers nor to perform a thorough comparison of the mechanical responses of fiber reinforced concrete using different flexural testing methods.

Discrepancies in reported toughness values may result from variations in specimen dimensions, curing protocols, or testing rates across different studies.

CONCLUSION

The research clearly showed that the mechanical properties of concrete were significantly improved by the addition of 0.3% forta-ferro fibers in concrete. The resistance to crack initiation was increased by 12% in case of compressive strength and 10% in case of tensile strength. Most importantly, the flexural strength was increased by 22% and the flexural toughness was improved 16.3 times. This indicates better energy absorption capacity after cracking, which is a significant advantage for applications in seismic zones and heavy load-bearing structures. The SCB test results indicated the increase in flexural strength by 35% and tensile strength by 33%. This ensures SCB as a reliable low-cost alternative of conventional flexural tests.

The bridging of fibers across the cracks observed confirms the role of fibers in post-crack load transfer that underlies the improved ductility observed in force-deflection responses . The good correlation between SCB and standard tests also supports the applicability of the SCB method for the assessment of fiber reinforced concrete. The results of this research show the feasibility of Forta-Ferro fibers to improve the durability and service life of concrete, especially for infrastructure applications such as pavements, bridge decks and industrial floors. More studies on different fiber dosage, fiber distribution uniformity and microstructure analysis are needed to optimize the design and application of fiber reinforced concrete.

The present study confirms that the SCB test slightly underestimates the flexural strength but it is a reliable and cost effective method to evaluate the performance of FRC. The novelty is the quantification of the validation of the results of SCB through the conventional flexural parameters of Forta-Ferro reinforced concrete.

NOMENCLATURE

C350	Concrete mix without fibers
C350F	Fiber-reinforced concrete mix with 0.3% Forta-Ferro fibers
SCB	Semi-Circular Bending test
MPa	Megapascal, unit of mechanical strength
R^2	Coefficient of determination in regression models
SEM	Scanning Electron Microscopy
FRC	Fiber-Reinforced Concrete

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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