Vol. 1, Iss. 4 (2024) 123-131, DOI: 10.61552/JMES.2024.04.001

Journal of Management and Engineering Sciences

www.jmes.aspur.rs

Mechanical Performance of Fiber-Reinforced Self-Compacting Concrete: Comparative Analysis and Structural Implications

Shrikant M. Harle[a*], Amol Bhagat[b], Nilesh Zanjad[c], Rajan Wankhade[d], Ruchita Ingole[c]

[a] *Department of Civil Engineering, Prof Ram Meghe College of Engineering and Management, Badnera, Maharashtra, India.*
[b] *Department of Information Technology, Prof Ram Meghe College of Engineering and Management, Badnera, Maharashtra, India.*
[c] *G. H. Raisoni University, Amravati, Maharashtra, India.*
[d] *Department, Civil Engineering, Government Polytechnic, Bramhapuri, Maharashtra, India.*

Keywords:

Steel fibers
Tensile strength
Concrete
SFRC
Structural

* Corresponding author:

Shrikant M. Harle
E-mail:
dr.shrikant.harle@gmail.com

Received: 18.04.2024.
Revised: 22.06.2024.
Accepted: 28.06.2024.

A B S T R A C T

The primary focus of this paper's analysis of the mechanical static behavior of concrete reinforced with steel fibers is its classification based on differences in mix design and fiber concentration. To find out the uniaxial compressive and tensile strengths, experimental experiments were run. Different mix patterns and fiber lengths were combined to create a variety of combinations with fiber percentages varying from 1% to 2% by volume. Uniaxial compression testing was used to mechanically characterize the SFRC in order to determine its ultimate compressive strength. Furthermore, ductility and first crack strength indices were evaluated using bending test with four-point consisted of the notched specimens. The evaluation of SFRC's tensile strength was conducted using both analytical modeling and experimental methods. The results of the experiments showed that the SFRC behaved differently depending on the length and fiber content. Direct tensile strength was calculated theoretically using an analytical model from the literature and compared to the experimental findings. The comparison showed a generally good agreement, confirming the results of the investigation.

1. INTRODUCTION

A key factor in how steel fiber reinforced concrete (SFRC) behaves is mix design, which calls for precise ratios between the various component parts [1]. The composition and dose of the constituents, such as the fibers and cementitious matrix, determine the composite's mechanical and physical qualities [2]. The accumulation of fibers (steel) to a concrete mixture significantly alters the behaviour of the composite, particularly during the cracking process [3]. The key factor influencing pre-cracking behavior is the matrix's features, which need to be strong (mechanically) and able to transfer stresses to the fibers even though the material is rigid-fragile [4]. However, the right mix component selection, dosage, and synergistic effects have a significant impact on the overall efficacy of SFRC [5].

The characteristics of the cementitious matrix and aggregate in concrete directly affect its mechanical behaviour [6]. The material displays uniform elasticity and abrupt failure when the coarse aggregate's elastic modulus roughly matches the cementitious matrix's [7]. On the other hand, microcracking happens when there is a difference in elastic moduli, which causes the stress-strain curve to soften [8]. While adding steel fibers to concrete mixtures can improve their strength and ductility, it can also make the mixture less workable [9]. Increasing the fine aggregate content or adding fluidizing chemicals can improve workability and counteract this [10,11]. In addition, the water-to-cement ratio and the mechanical strength of the cured concrete are determined by the minimum cement dose, which is based on the maximum coarse aggregate size [12,13]. Thus, in order to improve tangible performance, it is essential to comprehend and control these aspects [14].

This study examined various volume fractions and fiber lengths when examining steel-fiber-reinforced concrete [15]. Making a contribution to the ongoing study on composite materials was the goal. Concrete specimens with steel fibers at volume fractions of 1% and 2% underwent three experimental tests [16]. These tests comprised four-point bending tests on notched specimens to measure initial fracture strength and ductility, uniaxial compression tests to ascertain compressive strength, and direct tensile testing to assess ultimate tensile strain and strength [17]. The results demonstrated that while the insertion of fibers considerably changed post-cracking behavior, it had no influence on compressive strength [18]. Notably, specimens with longer fibers showed increased ductility as shown by an increase in the area under the curves of the four-point bending tests. In the presence of fibers, direct tensile testing indicated a greater ultimate strain but a lower maximum strength [19,20].

In the latter section of this work, the tensile strength of steel fiber reinforced concrete (SFRC) is investigated using both theoretical and experimental methods. Based on the theoretical foundation provided in the research, an analytical model of SFRC is created [21]. Using homogenization methods and variational principles, upper and lower bounds for SFRC tensile stiffness and strength are determined [22,23]. When comparing the analytical and experimental data, assumptions about material constitutive relations and SFRC internal structure are taken into account in addition to the outcomes of direct tensile testing conducted using the suggested experimental approach [24]. The analysis shows that there is a usually positive consistency between the two data sets, suggesting that the theoretical model can be used to anticipate how SFRCs will behave.

2. MATERIALS AND MIX-DESIGN

Taking into consideration several factors that impact the mechanical properties of fiber-reinforced concrete, the mixes utilized in this study were developed to yield concrete with a cubic compressive strength exceeding 30 N/mm2. These variables include fiber type, cement-to-water ratio, aggregate quality and dosage, component dosage and mechanical properties, and adherence to current codes. Table 1 presents the creation of six distinct mixtures with variable percentages of cement, aggregate fractions, fiber length, and volume content. Square net sieves were used to carefully screen the sharp edge type of aggregates in order to obtain the necessary granulometric curve. The maximum size permitted for fine aggregate was 4 mm, and the maximum size allowed for coarse aggregate was 15 mm. In accordance with CNR DT 204/2006 Guidelines, the granulometric curve of the mixtures was constructed taking fiber length into consideration to provide consistent and efficient distribution of fibers. Therefore, the maximum aggregate size was restricted to not exceed 0.5 times the fiber length in order to facilitate optimal fiber distribution.

Table 1 details the mix designs for six concrete composites (Mix-A1, A2, B1, B2, C1, C2) with steel fibers. Each mix varies in cement (360 to 423 kg/m^3), coarse aggregates (different sizes), fine aggregates, water, and steel fibers of varying lengths (22 mm, 30 mm, 50 mm). Fiber content is either 0.009 or 0.018 by volume. Despite differences in components, all mixes maintain a constant water-to-cement ratio of 0.495. The designs aim to assess the impact of fiber length and content on concrete properties.

The experiment employed Portland cement Type CEM I, strength class 42.5R. The maximum aggregate size was used to determine the dose, in accordance with the guidelines provided in reference. FIBROCEV type II steel fibers with lengths of 22, 30, and 44 mm and an aspect ratio (lf/df) of 50 were employed. The fiber content was adjusted for volume and set at 1% and 2%, or 78 and 157 kg/m^3, respectively. A ratio of 0.55 of water to cement was utilized in order to ensure the highest level of mechanical strength and workability for the mixing processes.

Twenty-four 150 by 150 by 150 mm^3 cubic specimens are utilized for the compressive testing; four specimens are allocated to each mixture. There are a total of 24 prismatic examples, each with dimensions of 150 by 150 by 600 mm^3. For every mixture to be examined using four-point bending, four specimens are allocated. Not to mention, eight prismatic specimens measuring thirty by eighty by three hundred millimeters have been reserved specifically for types B and C combinations with one percent fiber content in volume. These specimens are intended to be utilized in direct tensile tests.

Table 1. Mix Design of concrete reinforced with steel fibers.

Composite characteristics	Mix-A1	Mix-A2	Mix-B1	Mix-B2	Mix-C1	Mix-C2
Cement	360	360	396	396	423	423
Coarse aggregate-15 mm	304.2	304.2	0	0	0	0
Coarse aggregate-12 mm	0	0	139.5	139.5	0	0
Coarse aggregate-10 mm	480.6	480.6	525.6	525.6	647.1	647.1
Fine aggregate	818.1	818.1	873	873	857.7	857.7
Steel fibers-22 mm	0	0	0	0	70.2	141.3
Steel fibers-30 mm	0	0	70.2	0	0	0
Steel fibers-50 mm	70.2	141.3	0	141.3	0	0
Water	198	198	217.8	217.8	232.2	232.2
Fiber content (volume)	0.009	0.018	0.009	0.018	0.009	0.018
Water to cement ratio	0.495	0.495	0.495	0.495	0.495	0.495

Table 2. Properties of Steel Fibers.

Type	Length (mm)	Equivalent Diameter-df (mm)	Aspect Ratio (length/equivalent diameter)	Tensile Strength (Mpa)	Young's modulus (Gpa)
F-DUE 22/50	27.5	0.55	50	410	210
F-DUE 30/50	37.5	0.75	50	410	210
F-DUE 44/50	55	1.1	50	410	210

Table 2 presents the properties of three steel fiber types: F-DUE 22/50, F-DUE 30/50, and F-DUE 44/50. All fibers share a tensile strength of 410 MPa and a Young's modulus of 210 GPa. Their lengths are 27.5 mm, 37.5 mm, and 55 mm, respectively, with equivalent diameters of 0.55 mm, 0.75 mm, and 1.1 mm. Each fiber has an aspect ratio of 50, indicating consistent performance characteristics despite varying lengths and diameters.

In order to ensure compliance during the phases of mixing and mold-filling as well as compaction, which was achieved with a vibrating board, current codes were followed in the preparation and mixing of mixes and specimens. The consistency of the freshly reinforced concrete was determined and a consistency class was assigned by measuring the slump using the Abrams cone method, often known as the Slump Test. After preparing the mixtures for twenty-four hours, the specimens were removed from the molds and allowed to cure under normal conditions. In a restricted area maintained at 20 degrees Celsius and 90% relative humidity, this involved covering them with damp sand. The specimens were held in this curing atmosphere up to 48 hours prior.

3. EXPERIMENTAL EQUIPMENT AND TEST PROCEDURES

3.1 Compression test

Uniaxial compression tests were conducted on 150 x 150 x 150 mm^3 cubic specimens in order to assess the compressive strength of fiber-reinforced concrete. These tests were performed after the curing process using the procedures outlined in reference. The experimental trials were conducted with a hydraulic press that had a 0.5% accuracy class, a 3000 kN capacity, and a closed-loop regulating system. During the testing process, load-displacement diagrams could be collected thanks to a data collection device that was fixed to the press. Up to specimen failure, loads were applied at a constant load velocity of 0.5 N/mm^3 per second.

3.2 Direct tensile test

After a 28-day curing period, prismatic specimens of 30 x 80 x 350 mm^3 were subjected to direct tensile tests, as per the protocol outlined in reference. The experimental setup concentrated on fiber lengths of 22 mm and 30 mm in order to investigate the bridging effect of fibers during tensile tests, thereby narrowing the range of values for defining the tensile behavior of steel fiber-reinforced concrete (SFRC). Type A specimens are expected to have longer fibers (40 mm) with higher tensile strength, which is why this approach was chosen to highlight the bridging effect. For the combined tensile-torsion tests, an electromechanical testing apparatus with a maximum tensile capability of 250 kN was utilized. Data collection and recording of failure tensile load and load-displacement diagrams were facilitated by connecting to a personal computer. 0.3 mm/min was used as the displacement-controlled testing velocity. The primary objective of these tests was to determine the tensile strength of the fiber concrete in order to compare it with an analytical value that was derived indirectly from a theoretical model that was published in the literature.

3.3 Four-point-bending test

Four-point bending tests were used to assess how fibers affected the strength of the concrete. Prismmatic specimens 150 x 150 x 600 mm^3 in size were used for the testing. The studies were conducted using a universal electromechanical testing apparatus with a capacity of 100 kN. This gadget was connected to a data collection device and a personal computer. The load velocity of 0.3 mm/min was chosen to replicate conditions that were nearly static. The testing device used a static technique, applying no shear stress, allowing the specimens to flex solely between loading sites.

Notched specimens were put through four-point bending tests in order to examine the properties of crack opening. On the tip side, the crack tip opening displacement (CTOD) and on the bottom side, the crack mouth opening displacement (CMOD) were measured. The objective was to find the material's initial fracture strength and ductility index, denoted as D0 and D1, respectively, within established parameters for crack mean opening displacement (0–0.6 mm for D0 and 0.6–3 mm for D1). These indices were generated from the experimental load-CTOD graphs. The specimens included tools to facilitate measuring. CTOD was computed as the average value between CTOD1 and CTOD2, using two linear inductive displacement transducers (W10) positioned on both lateral sides of the specimens between two Plexiglas bases cemented together as a measurement platform for stresses. The CMOD was measured using a linear inductive displacement transducer (W10) that was fixed to the bottom side of the specimen. To detect displacement at the loading locations, four linear inductive displacement transducers (WA20) were mounted to a steel bar that was fixed to both sides of the specimen along the loading direction. To record the stresses experienced during the test method, data from each instrument was collected using a data collection device.

4. EXPERIMENTAL RESULTS

4.1 Compression test

The experimental findings indicate that the fiber content of Steel Fiber Reinforced Concrete (SFRC) has no effect on its compressive strength. But there was a big change in the failure mode—from fragile to ductile. This change is caused by the fibers' bridging action. As a result, the cubic specimens were structurally intact throughout the trial and did not fracture during testing.

Table 3 shows the compressive strength data for concrete specimens in six sets (A1, B1, C1, A2, B2, C2), each containing four specimens. The mean compressive strengths are as follows: A1 (49.28 MPa), B1 (52.58 MPa), C1 (47.443 MPa), A2 (49.115 MPa), B2 (47.333 MPa), and C2 (49.06 MPa). Minimum strengths recorded are A1 (46.42 MPa), B1 (49.72 MPa), C1 (45.1 MPa), A2 (48.95 MPa), B2 (44.66 MPa), and C2 (46.64 MPa). Overall, Set B1 has the highest mean compressive strength, indicating superior performance compared to other sets. Variations in compressive strength suggest differences in material properties or testing conditions.

Table 3. Compressive strength of the specimens.

Specimen	Weight (kg/cum)	Compressive Strength (Mpa)	Compressive Strength mean value (Mpa)	R-min (Mpa)
A1-1	2721.4	51.26	49.28	46.42
A1-2	2770.9	52.36		
A1-3	2737.9	46.42		
A1-4	2704.9	47.08		
B1-1	2673	49.72	52.58	49.72
B1-2	2704.9	54.56		
B1-3	2688.4	53.35		
B1-4	2721.4	52.69		
C1-1	2673	46.31	47.443	45.1
C1-2	2695	45.43		
C1-3	2718.1	46.53		
C1-4	2656.5	51.48		
A2-1	2786.3	49.28	49.115	48.95
A2-2	2770.9	49.28		
A2-3	2737.9	48.95		
A2-4	2721.4	48.95		
B2-1	2673	47.19	47.333	44.66
B2-2	2721.4	48.29		
B2-3	2688.4	44.66		
B2-4	2704.9	49.17		
C2-1	2704.9	51.26	49.06	46.64
C2-2	2688.4	50.38		
C2-3	2737.9	47.96		
C2-4	2721.4	46.64		

Table 4 shows the load versus displacement data for six specimens (A1, B1, C1, A2, B2, C2) during a compression test. The displacement increases with the load, peaking at 1100 kN, indicating material deformation. As the load decreases back to 300 kN, displacement continues to rise, suggesting permanent deformation. Variations in displacement among specimens highlight differences in their material properties or structural integrity. This data is crucial for analyzing the compressive behavior and strength of the materials tested.

Table 4. Load vs Displacement for comp test.

Load (kN)	Displacement (mm)					
	A1	B1	C1	A2	B2	C2
0	0	0	0	0	0	0
200	1.89	2.079	2.130975	2.23752	2.05852	1.96589
400	2.31	2.541	2.604525	2.73475	2.51597	2.40275
600	2.625	2.8875	2.9596875	3.10767	2.85906	2.7304
800	2.94	3.234	3.31485	3.48059	3.20215	3.05805
1000	3.465	3.8115	3.9067875	4.10213	3.77396	3.60413
1100	3.885	4.2735	4.3803375	4.59935	4.23141	4.04099
1000	4.41	4.851	4.972275	5.22089	4.80322	4.58707
800	5.775	6.3525	6.5113125	6.83688	6.28993	6.00688
600	7.14	7.854	8.05035	8.45287	7.77664	7.42669
400	8.505	9.3555	9.5893875	10.0689	9.26335	8.8465
300	8.925	9.8175	10.0629375	10.5661	9.7208	9.28336

4.2 Direct tensile test

Through direct tensile tests, the tensile strength of SFRC was examined. For the two types of specimens that were tested. To improve comprehension of SF tensile behavior, results from a single specimen are presented for each mixture under examination. This approach was adopted as the trends of the experimental curves were similar for each specimen. By doing this, the potential for misunderstanding caused by displaying multiple overlapping curves is eliminated. The analytical outcomes of a theoretical model that was published in the literature were then compared with the experimental data.

Table 5 displays the load-displacement relationship from a direct tensile test on specimen C1. Load initially increases from 0 N to 5500 N, resulting in displacement ranging from 0 mm to 3.6 mm. Notable points include peak displacement of 2.6 mm at 5500 N and subsequent post-peak behavior. This data illustrates the material's tensile response, capturing elastic deformation, peak load, and post-peak behavior succinctly.

Table 6 displays the mean values of direct tensile strength for concrete specimens. Specimen B1, with 1% steel fiber volume fraction, showed a mean strength of 1.87 MPa, while specimen C1, with a higher volume fraction, had a mean strength of 2.31 MPa. These results highlight the influence of steel fiber volume fraction on the direct tensile strength of concrete.

Table 5. Load vs Displacement for direct tensile test.

Load (N)	Displacement (mm)
	C1
0	0
1000	1
2000	1.5
3000	2.1
4000	2.15
5000	2.4
5500	2.6
4000	2.7
3000	3.1
2000	3.3
1000	3.6

Table 6. Direct tensile strength mean values.

Specimen (%)	Direct tensile strength mean values (Mpa)
B1	1.87
C1	2.31

4.3 Four-point-bending test

Using notch specimens put through four-point bending testing, tested steel fiber reinforced concrete (SFRC) was categorized and described. Such experiments are sometimes conducted to assess the fibers' functionality and determine whether or not they could be applied to the building of structural components. The tests are intended to ascertain the material's ductility and tenacity, according to the sources.

Table 7 presents data on Load (kN) and CTODm (mm) for mixtures containing 1% fiber content by volume. Three mixtures labeled A1, B1, and C1 were tested. Load refers to the applied force in kilonewtons, while CTODm represents the critical crack tip opening displacement in millimeters. The table illustrates the relationship between load and CTODm at various stages of testing, ranging from 0 to 4.5 mm CTODm. Overall, the data shows how load values vary across different mixtures as the CTODm increases, providing insights into the fracture behavior and toughness of the materials under investigation.

Table 7. Load–CTODm: Mixtures with 1% fiber content in volume.

CTODm (mm)	Load (kN)		
	A1	B1	C1
0	25	32	24
0.5	27.5	22	18.5
1	23.5	10.1	12.5
1.5	20.5	6.5	8.5
2	17.5	5.5	7.1
2.5	15.5	3.5	5.5
3	13.5	3.1	3.1
3.5	12.1	2.7	2.65
4	11.5	2.2	2.25
4.5	9.5	1.8	1.85

Table 8 presents the relationship between load (kN) and CTODm (mm) for mixtures containing 2% fiber content in volume, denoted as A2, B2, and C2. The table showcases the CTODm values at various load levels, ranging from 0 kN to 5 kN. As the load increases, the CTODm values generally decrease, indicating a decrease in crack tip opening displacement with increasing applied load. This trend suggests that higher loads result in reduced crack growth resistance in the concrete specimens. Additionally, the table allows for a comparison of CTODm values between different mixtures (A2, B2, and C2) at each load level, providing insights into how fiber content may influence crack behavior under applied loads.

Table 8. Load–CTODm : Mixtures with 2% fiber content in volume.

CTODm (mm)	Load (kN)		
	A2	B2	C2
0	37.5	42	27
0.5	35.5	32.5	24.5
1	25.5	21.5	17.5
1.5	20.6	15.5	14.5
2	17.5	12.5	12.4
2.5	16.5	9.5	9.55
3	15.1	8.5	8.55
3.5	12.5	7.5	7.55
4	11.5	6.5	6.55
4.5	9.5	6.15	6.1
5	8.5	5	5.1

The provided data as per Fig. 1 represents the results of four-point bending tests conducted on various specimens labeled A1, A2, B1, B2, C1, and C2. For each specimen, the following parameters are recorded: P1f (kN) - the load applied at the first fracture point, f1f (MPa) - the corresponding stress at the first fracture point, U1 (10^{-3} J) - the energy absorbed until the first fracture point, and U2 (10^{-3} J) - the total energy absorbed until the test completion. These results are indicative of the mechanical behavior and strength properties of the tested specimens under bending conditions. Analysis of these data points can provide insights into factors such as material toughness, fracture resistance, and overall structural integrity, which are essential considerations in engineering design and material selection processes.

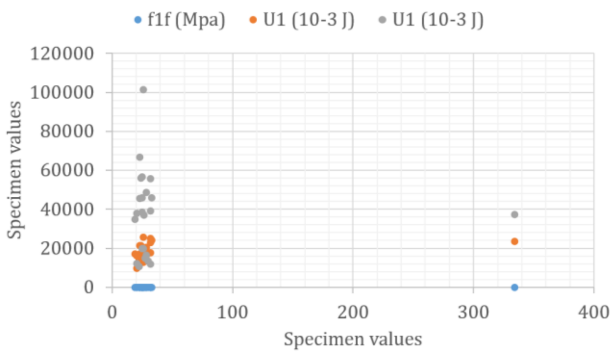

Fig. 1. Four-point-bending test results.

SFRC mixes as per Fig. 2 are classified based on compressive strength, consistency, and first crack strength. For instance, mix A1 has a compressive strength class of C30/37, consistency class S1, and a first crack strength of 4.62 MPa. These classifications help engineers select the right mix for various applications, considering factors like strength and workability.

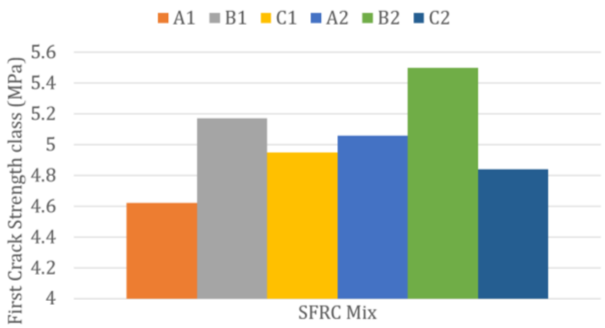

Fig. 2. Steel fiber reinforced concrete classification.

5. CONCLUSIONS

The study set out to find out how variations in fiber volume composition and mix design impacted the mechanical properties of steel fiber reinforced concrete. The material's compressive strength was hardly affected by the fibers, according to the findings of uniaxial compressive testing. Conversely, reinforced specimens exhibited a significant change in the mode of compressive failure from brittle to ductile. The bridging action of the fibers prevented the cubic specimens from crushing and maintained their integrity until the end of the test, which is why this shift occurred.

Steel Fiber Reinforced Concrete (SFRC) was categorized and characterized using four-point bending tests in accordance with current requirements, to aid in the derivation of first crack and ductility indexes. The testing findings showed a considerable increase in ductility and tenacity for SFRC with longer fiber lengths and a higher fiber volume content. This phenomenon can be explained by the fact that because of its improved deformability and energy absorption, SFRC displays higher bending stiffness and a distinct cracking pattern throughout the cracking phase compared to normal concrete. Moreover, specimens with shorter fibers exhibit a softening behavior, whereas specimens with longer fibers exhibit a plastic or hardening reaction linked to a notable rise in maximum load. This means that fiber length has an impact on the post-cracking behavior of SFRC. Consequently, an increase in fiber volume content improves ductility, initial crack strength, and flexural strength without appreciably changing compressive strength.

REFERENCES

[1] M. Musmar, "Tensile strength of steel fiber reinforced concrete," Contemp. Eng. Sci., vol. 6, no. 5, pp. 225–237, 2013.

[2] R. S. Olivito and F. A. Zuccarello, "An experimental study on the tensile strength of steel fiber reinforced concrete," Compos. B Eng., vol. 41, no. 3, pp. 246–255, 2010.

[3] P. S. Song and S. Hwang, "Mechanical properties of high-strength steel fiber-reinforced concrete," Constr. Build. Mater., vol. 18, no. 9, pp. 669–673, 2004.

[4] A. M. Shende, A. M. Pande, and M. G. Pathan, "Experimental study on steel fiber reinforced concrete for M-40 grade," Int. Refereed J. Eng. Sci., vol. 1, no. 1, pp. 43–48, 2012.

[5] H. P. Behbahani, B. Nematollahi, and M. Farasatpour, "Steel fiber reinforced concrete: a review," in Proceedings of the International Conference on Structural Engineering Construction and Management (ICSECM2011), Kandy, Sri Lanka, 2011.

[6] J. Thomas and A. Ramaswamy, "Mechanical Properties of Steel Fiber-Reinforced Concrete," J. Mater. Civ. Eng., vol. 19, no. 5, pp. 385–392, 2007, doi: 10.1061/(ASCE)0899-1561(2007)19:5(385).

[7] B. W. Xu and H. S. Shi, "Correlations among mechanical properties of steel fiber reinforced concrete," Constr. Build. Mater., vol. 23, no. 12, pp. 3468–3474, 2009.

[8] W. Abbass, M. I. Khan, and S. Mourad, "Evaluation of mechanical properties of steel fiber reinforced concrete with different strengths of concrete," Constr. Build. Mater., vol. 168, pp. 556–569, 2018.

[9] C. D. Atiş and O. Karahan, "Properties of steel fiber reinforced fly ash concrete," Constr. Build. Mater., vol. 23, no. 1, pp. 392–399, 2009.

[10] A. Behnood, K. P. Verian, and M. M. Gharehveran, "Evaluation of the splitting tensile strength in plain and steel fiber-reinforced concrete based on the compressive strength," Constr. Build. Mater., vol. 98, pp. 519–529, 2015.

[11] M. V. Mohod, "Performance of steel fiber reinforced concrete," Int. J. Eng. Sci., vol. 1, no. 12, pp. 1–4, 2012.

[12] M. Abdi Moghadam and R. A. Izadifard, "Prediction of the Tensile Strength of Normal and

Steel Fiber Reinforced Concrete Exposed to High Temperatures," Int. J. Concr. Struct. Mater., vol. 15, no. 1, p. 47, 2021, doi: 10.1186/s40069-021-00485-6.

[13] T. S. Lok and J. R. Xiao, "Flexural Strength Assessment of Steel Fiber Reinforced Concrete," J. Mater. Civ. Eng., vol. 11, no. 3, pp. 188–196, 1999, doi: 10.1061/(ASCE)0899-1561(1999)11:3(188).

[14] A. R. Khaloo and N. Kim, "Mechanical properties of normal to high-strength steel fiber-reinforced concrete," Cement Concrete Aggr., vol. 18, no. 2, pp. 92–97, 1996.

[15] A. M. Shende and A. M. Pande, "Experimental study and prediction of tensile strength for steel fiber reinforced concrete," Int. J. Civ. Struct. Eng., vol. 1, no. 4, pp. 910–917, 2011.

[16] R. N. Swamy and P. S. Mangat, "A theory for the flexural strength of steel fiber reinforced concrete," Cem. Concr. Res., vol. 4, no. 2, pp. 313–325, 1974.

[17] G. Meng, B. Wu, S. Xu, and J. Huang, "Modelling and experimental validation of flexural tensile properties of steel fiber reinforced concrete," Constr. Build. Mater., vol. 273, p. 121974, 2021.

[18] Y. Şahin and F. Köksal, "The influences of matrix and steel fibre tensile strengths on the fracture energy of high-strength concrete," Constr. Build. Mater., vol. 25, no. 4, pp. 1801–1806, 2011.

[19] T.-S. Lok and J.-S. Pei, "Flexural Behavior of Steel Fiber Reinforced Concrete," J. Mater. Civ. Eng., vol. 10, no. 2, pp. 86–97, 1998, doi: 10.1061/(ASCE)0899-1561(1998)10:2(86).

[20] W.-C. Choi, K.-Y. Jung, S.-J. Jang, and H.-D. Yun, "The influence of steel fiber tensile strengths and aspect ratios on the fracture properties of high-strength concrete," Materials, vol. 12, no. 13, p. 2105, 2019.

[21] V. S. Vairagade, K. S. Kene, and N. V. Deshpande, "Investigation of steel fiber reinforced concrete on compressive and tensile strength," Int. J. Eng. Res. Technol., vol. 1, no. 3, pp. 1–7, 2012.

[22] V. S. Vairagade, K. S. Kene, and T. R. Patil, "Comparative study of steel fiber reinforced over control concrete," Int. J. Sci. Res. Publ., vol. 2, no. 5, pp. 1–3, 2012.

[23] M. Moradi, A. R. Bagherieh, and M. R. Esfahani, "Tensile modeling of steel fiber reinforced concrete," Asian J. Civ. Eng., vol. 20, no. 2, pp. 269–280, 2019, doi: 10.1007/s42107-018-00104-y.

[24] W. A. Tanoli, A. Naseer, and F. Wahab, "Effect of steel fibers on compressive and tensile strength of concrete," Int. J. Adv. Struct. Geotech. Eng., vol. 3, no. 4, pp. 393–397, 2014.