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Research Article

Investigation of shear strength of SCC beams with hybrid fiber as experimental and statistical

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ABSTRACT

In this study, the effects of different blending and combination of macro and micro steel fibers on the shear strength, ductility, failure mode and crack propagation of hybrid fiber reinforced self-compacting concrete beams were investigated experimentally and statistically. In the design of concrete, straight steel micro and hooked steel macro fibers were used. For this purpose, twelve 200x200x1000 mm reinforced concrete beam specimens, which had same reinforcing bar details, were produced and tested under four-point bending to investigate ultimate shear strength, displacement ductility, crack patterns, mode of failure, energy absorption capacity and yield stiffness properties. In conclusion, the beam specimens produced from self-compacting concrete (SCC) with hybrid steel fiber prevented the shear failure while all SCC beam specimens containing hybrid steel fiber reached the ultimate bearing capacity with the mode of flexural failure. Also, it can be clearly emphasized that the SCC beam specimens with hybrid steel fiber had higher shear strength, energy absorption capacity and yield stiffness than those of beam specimens containing only macro or micro steel fiber.

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INTRODUCTION

Due to earthquake risk, with increase in use of congested reinforcing bars in especially reinforced concrete elements, high workability of concrete has come into prominence in construction industry. Because, this type of concrete having sufficient consolidation, filling capability and passing ability between bars will inhibit structural flaws and inappropriate bond improvement to steel bars. Self-consolidating concrete called as innovative concrete was developed in Japan in 1989 to eliminate problems stated above and to ensure the desired fresh properties of a concrete. Because, SCC has high workability under its self-weight such that it can settle to formworks without vibration and the long distance concrete pumping can be possible [1]. Therefore, the use of SCC decreases workforce, develops the ultimate quality of the structural elements and increases the efficiency in construction. Thus,

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SCC was issued to many works in different fields that some researchers [2–4] investigated the bond strength between reinforcing bar and SCC. They found that SCC had in general highest bond strength compared with conventional concrete while SCC specimens carried out a stiffer behavior than NC at moderate load levels due to its greater filling capacity and less bleeding. However, though the innovative concretes have some advantages above mentioned compared to conventional concrete, they have low tensile strength to inhibit the formation and spreading of cracks. Therefore, the inclusion of fiber into concrete will be needed to improve the mechanical and durability properties of the concrete and significantly to change the behavior of the concrete elements [5–7]. The use of fiber reinforced concrete was also preferred in reinforced concrete beam elements because it made significant improvements in structural behavior.

The fibers in the tensile region reduce the deflection by limiting the crack widths and improve the ultimate capacity of the beam by significantly increasing the tensile strength of concrete [8–13]. Moreover, fibers increase the shear strength by limiting the principal tensile cracks in the concrete [14]. Also, the volumetric ratio, geometric properties and direction of the fibers used in the concrete can create differences in structural behavior. Fiber blends with different structural responses, sizes, slenderness and functions have been used to make the most effective use of the properties of the concrete and to improve the load carrying capacity performances of the concrete elements. For this purpose, fiber reinforced concrete obtained by adding more than discontinuous fiber type into concrete was called hybrid fiber reinforced concrete [15].

Hybrid fiber, which is used as a mixture of macro and micro fibers in concrete mixture, was firstly developed by Rossi et al. [16]. It was stated that micro fibers controlled and bridged the growth of micro cracks and caused high tensile strength in concrete while the macro fibers restrained the macro cracks by increasing both ductility and load carrying capacities of the structural elements [17]. The shear strength of reinforced concrete elements is also a study topic that is being constantly disputed by researchers. Shear behavior is affected fundamentally by shear span/effective depth (a/d) ratio, concrete compressive strength, the tension steel bar ratio and load conditions. Sahoo et al. [18], tested 7 reinforced concrete beams in 2015, so as to investigate shear behavior. This study relates to the effect of the type and content of fibers added into the concrete mixes on the shear strength of RC beams. They found that the beam specimens with hybrid fiber reinforced achieved the same shear strength as RC beam specimen without shear stirrups. Moreover, Alyousif et al. [19], conducted a series tests of high-performance FRC beams having three a/d ratios and two tension steel bar ratios. Six of the beams were manufactured from engineered cementitious composites and other concerned six beam specimens with ultra high-strength fiber reinforced cementitious composite (RMC). The experimental studies indicated that the RMC beams had higher shear strength values than the ECC beam specimens. The USA design code (ACI 318-14) allows steel fibers to be used in content ratios that surpass or equal 0.75% as a minimum shear steel bar in moderate strength concrete beams [20].

In this work, SCC beams was exposed to four-point bending to investigate the effect of different blends and contents of macro and micro steel fiber on the shear strength of the beams with hybrid fiber. Then, the ultimate shear strength, displacement ductility, crack patterns, mode of failure, energy absorption capacity and yield stiffness properties of reinforced concrete beam elements were analyzed by using the results obtained from experimental programme. Besides, to estimate the ultimate shear strength of hybrid steel fiber reinforced SCC, the regression analysis was performed by using experimental results. Contour plot was drawn by using the equation obtained from statistical analysis.

RESEARCH SIGNIFICANT

There are a lot of works about the study of shear strength of conventional concrete beams with fiber-reinforced in literature. But, in this study, half-scale beams produced from micro and/or macro steel fiber reinforced SCC were tested under four-point bending to investigate the effect of hybrid steel fiber reinforced on the normalized shear stress, ultimate shear strength, displacement ductility, energy absorption capacity and initial stiffness. The type and combination of fibers were the main parameters for this work. Moreover, to predict the ultimate shear strength of hybrid steel fiber reinforced SCC, the regression analysis was made by using test results. Contour plots were drawn as two-dimensional non-linear curve by using the equations obtained from regression analysis.

EXPERIMENTAL PROCEDURE

Materials

In this study, in all mixtures, standard CEM II 42.5 R Portland cement (PC) and fly ash (FA) were used as cementitious materials. The chemical composition and physical characteristics of PC and FA were given in Table 1. Three various batch of aggregates were used. The comparative density values for 0-2, 2-4, and 4-8 were 2.43, 2.64 and 2.68 and water absorption values were 1.57%, 0.6% and 0.2%, respectively. From the sieve analysis of the aggregate as given in Figure 1 it can be seen that the maximum aggregate size was 8 mm. High-range water reducing (HRWRA) admixture having specific gravity of 1.06 was employed to accomplish targeted workability for all concrete mixtures with hybrid fibers.

Table 1. Chemical composition and physical properties of PC and FA (%)

Composition	PC	FA
SiO_2	19.41	63.04
Al_2O_3	5.58	21.63
Fe_2O_3	3.67	6.77
CaO	58.85	1.07
MgO	2.12	-
SO_3	3.16	0.10
K_2O	0.69	-
Na_2O	0.61	-
LOI	6.07	2.6
Specific gravity (g/cm^3)	3.06	2.3
Surface area (cm^2/g)	4891	-
Fineness (<45μm) (%)	1.1	21

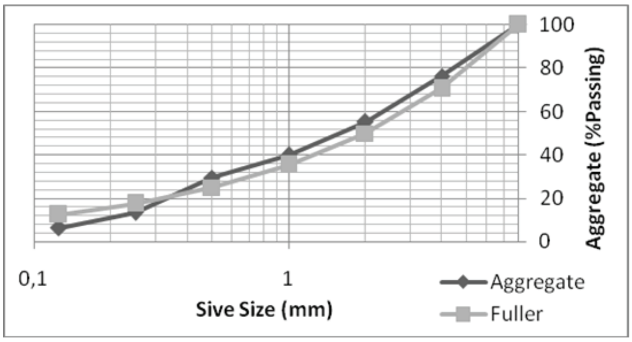


Figure 1. Grading of the total aggregate.

The geometry of macro (Dramix 65/60) and micro (OL 13/.16) steel fibers used were indicated in Figure 2. Moreover, the properties of their geometry and mechanical properties were also shown in Table 2.

Mixture Proportions

In all mixtures, macro and micro fibers were used as total of 1%. The micro (OL 13/.16) fiber ingredient was replaced by macro steel fiber as 0%, 0.25%, 0.50%, 0.75% and 1% by volume fraction. In Table 3, mix code was used to define the mixtures. As an example of the mix code, MIC0.50 indicates that the mixtures were produced using hybrid fibers with 0.5% micro and 0.5% macro. In all mixtures, water-cementitious materials (w/cm) ratio was fixed as 0.28. The aggregates were classified as 0-2 mm, 2-4 mm and 4-8 mm and as seen in Figure1, the distribution of the particle size of aggregates was conformed to fuller curve to obtain highest compactness. In Table 3, to obtain the workability limits, HRWRA was used as changeable ingredient of SCC mixtures. The fresh concrete properties of all concrete mixes were presented in Table 4. The results displayed that the slump-flow values of all SCC mixtures conformed to EFNARC while the T_{500} and J-ring values got out of the limits of EFNARC with increase the content of micro steel fiber. Furthermore, as seen in Figure 3, the mixtures of Control, MIC0.00 and MIC0.25 had good flow, filling and passing ability while all mixtures in general provided self-compactibility.

Test Specimens

A total of twelve reinforced SCC beams (1000 x 200 x 200 mm) were produced and tested. To assess the shear resistance of reinforced SCC beams subjected to four-point

(a) (b)

Figure 2. Shape of macro and micro fibers used in the mixtures.

Table 2. Properties of the macro and micro fibers

Fiber	Diameter (mm)	Length (mm)	Aspect Ratio	Tensile Strength (MPa)	Elastic Modulus (GPa)	Density (kg/m^3)
Macro (Dramix 65/60)	0.92	60	65	2300	210	7850
Micro (OL 13/.16)	0.15	13	87	3000	200	7200

Table 3. Concrete mixes (kg/m^3)

Mixture Name	Cement	FA	Water	Steel Fiber		Aggregate			HRWRA
				Macro	Micro	0-2 mm	2-4 mm	4-8 mm	
CONTROL	350	250	167	0	0	631	473	473	5
MIC0.00	350	250	167	78.5	0	605.1	453.8	453.8	7
MIC0.25	350	250	167	58.9	19.6	602.2	451.6	451.6	10
MIC0.50	350	250	167	39.25	39.25	598.8	449.1	449.1	13.5
MIC0.75	350	250	167	19.6	58.9	597.4	448	448	15
MIC1.00	350	250	167	0	78.5	593.5	445.1	445.1	19

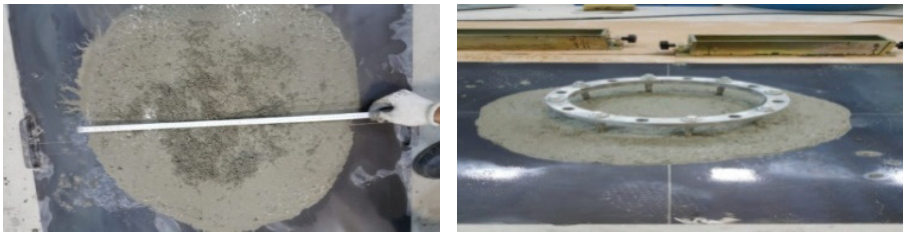
Table 4. Properties of fresh concretes

Mixture	T_{500} (sec)	Slump-flow diameter (mm)	J-ring (H_2-H_1) (mm)
CONTROL	3	820	5
MIC0.00	4	800	9
MIC0.25	4	800	10
MIC0.50	6	770	15
MIC0.75	10	670	19
MIC1.00	13	670	21
Limits*	2-5	650-800	0-10

*Workability ratios recommended by EFNARC

bending, the ratio of shear span (a) to effective depth (d) was preferred as 2.5. Diversity in failure mode of RC beams with alteration in a/d ratio were shown in Figure 4 [21]. This figure indicates that as the chance of shear failure occurs especially when a/d is between 1.0 and 3.0. The details of beam specimen and reinforcing bar were shown in Table 5 and Figure 5, respectively. Two part notation system was employed to display the variation of each beam. The first part of the notation displays the beam specimens. The second part displays that the mixtures with hybrid fibers contained micro fiber in different proportions.

Self-compacting concrete was poured into formwork at once without any vibration for all beams. After casting,



(a) (b)

Figure 3. The slump-flow and J-ring tests for MIC0.25 mixture.

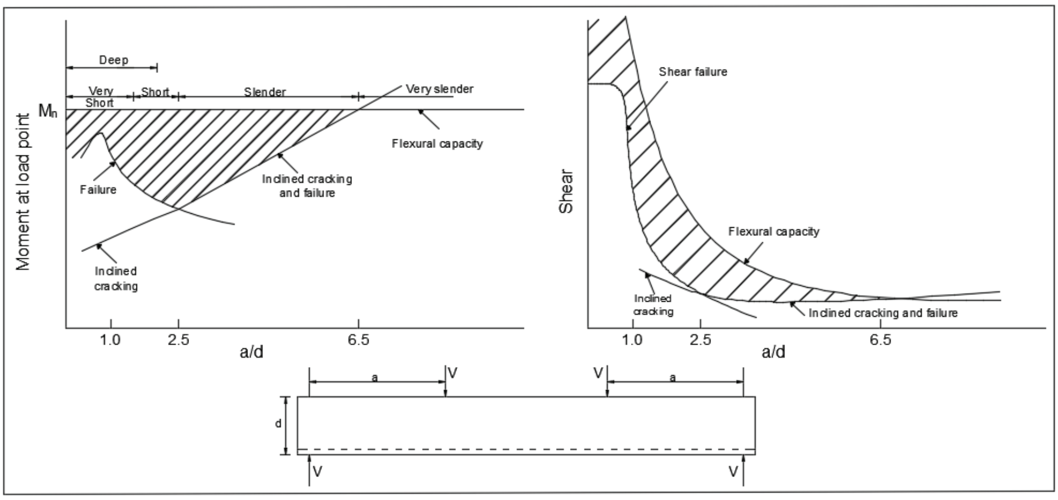


Figure 4. Diversity in failure modes, shear and moment capacities of RC beams to a/d ratio [21].

Table 5. Values of main parameters of test specimens

Spec. No.	Name	Length (mm)	Effective Height (mm)	b (mm)	h (mm)	a/d Ratio	ρ (%)
1	B.CONTROL	1000	175	200	200	2.5	0.44
2	B.SCC.MIC-0.00	1000	175	200	200	2.5	0.44
3	B.SCC.MIC-0.25	1000	175	200	200	2.5	0.44
4	B.SCC.MIC-0.50	1000	175	200	200	2.5	0.44
5	B.SCC.MIC-0.75	1000	175	200	200	2.5	0.44
6	B.SCC.MIC-1.00	1000	175	200	200	2.5	0.44

Figure 5. Casting position and reinforced bar details.

Figure 7. Test Setup.

all beams and 150 mm concrete cubes were wrapped with watery burlap and covered with nylon overlay, which continued for 56 days. Then, the beams were demolded after 24 h. All beams were exposed to four-point bending at 56 days.

Test Setup

The four-point flexural test was performed to assess the shear strength of reinforced SCC beams. Loading was gradually implemented to the beams before failure, and measurements of mid-span deflections were recorded. The test setup and the loading regulation used were given in Figure 6. Load was applied to all the beam specimens at a mean constant deflection rate of 1.20 mm/min. Beam specimens were simply supported over a span of 950 mm. The load from testing actuator was transmitted via a rigid steel plate onto the beam specimens in the shape of two equally loads (Figure 7). At every load stage, deflection readings were recorded at the center of the beam specimens by using an LVDT and cracks were marked after testing.

RESULTS AND DISCUSSION

To evaluate the mechanical properties of conventional and fiber reinforced concrete, testing of small-scale specimens like standard cubes, cylinders and prismatic beams were executed. The essential parameters examined were the compressive strength, splitting tensile strength and flexural tensile strength of concrete. Moreover, half-scale beam specimens of B.CONTROL without fiber and B.SCC

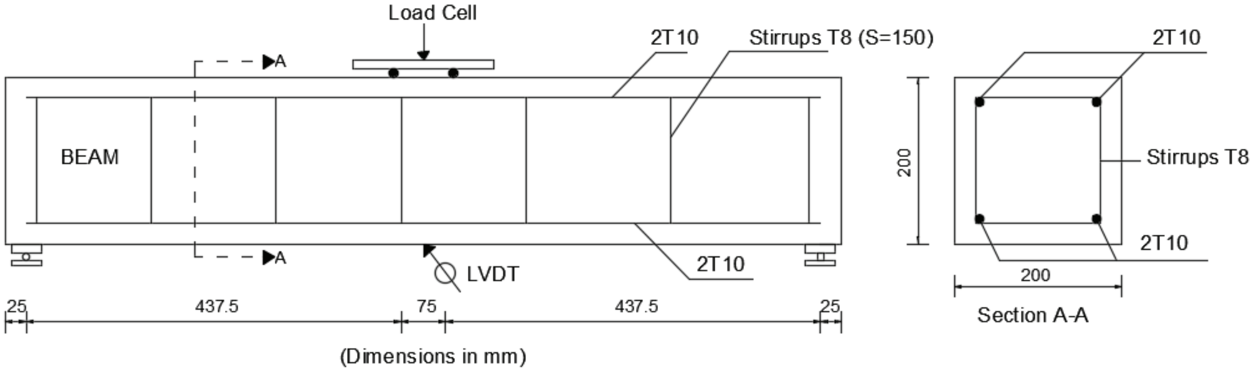


Figure 6. Reinforcement and cross-section details of the beam specimens.

Table 6. Mechanical properties of concrete mixes

Concrete mixes	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Flexural Tensile Strength (MPa)
B.CONTROL	64.75	4.45	5.73
B.SCC.MIC-0.00	60.65	10.85	12.74
B.SCC.MIC-0.25	68.70	10.35	12.57
B.SCC.MIC-0.50	72.60	8.25	12.42
B.SCC.MIC-0.75	73.70	8.40	11.93
B.SCC.MIC-1.00	75.95	7.00	8.87

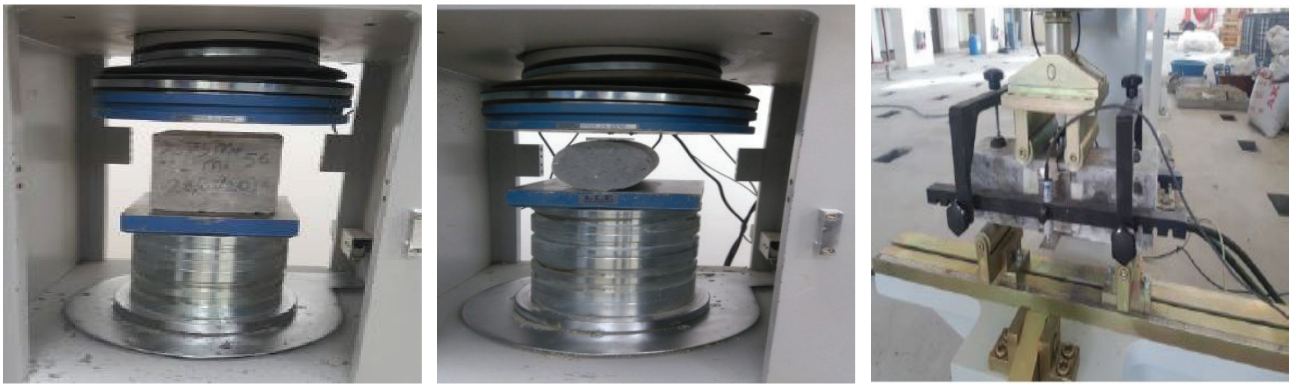
with steel fiber were tested monotonically with increasing loading. The essential parameters examined were load-deflection response, ultimate shear strength, ductility, crack pattern and failure mode. All these parameters are discussed in detail in the following parts for each beam specimen.

Compressive Strength

The compressive strength tests were performed by using the standard cube specimens with the size of 150x150x150 mm according to ASTM C39 [22]. As shown in Figure 8(a), the specimens were applied monotonically increasing uniaxial compressive load until failure. A minimum of three concrete cubes were tested at 56 days for each concrete mix. The average values of compressive strengths of SCC with/out fiber were presented in Table 6. As can be seen from the table, at 56 days, the mixture of B.SCC.MIC-1.00 had the highest compressive strength with 75.95 MPa. The values of compressive strength for all mixtures increased when the volume of micro steel fiber in mixture was increased. This result may be attributed to higher aspect ratio of micro steel fiber with 87 than that of macro steel fiber with 65 as well as the length of micro fibers as related to maximum aggregate size. Because, Song and Hwang [23] also have found similar results. Moreover, as found by Haddadou [24] , micro steel fiber delayed the formation of micro crack and inhibited the propagation of the crack due to its short length.

Splitting Tensile Strength

In order to determine the splitting tensile strength, cylinder specimens with the dimensions of Ø100x200 mm were used based on ASTM C496 [25]. The test setup used was shown at Figure 8 (b). The splitting tensile strength was calculated by using the formula of 2P/πLD, where, P is the failure load, L and D are the height and diameter of the cylinder specimens, respectively. Three cylinder specimens for each mixture were tested after 56 days curing period. Table 6 shows the average values of splitting tensile strength of SCC with/out fiber. In contrast to compressive strength, decrease in the splitting tensile strength was observed as the increasing micro steel fiber ratio in the mixture. At 56 days, the highest splitting tensile strength was obtained for the mixture with only macro steel fiber as 10.85 MPa. Because, the macro-crack spreading can be delayed with transmitted the tensile stress to macro steel fibers. Similar result also was found by N. Haddadou [24] that inadequate macro steel fiber in the mixture caused to decreasing in the splitting tensile strength.



(a) (b) (c)

Figure 8. Test Setup for (a) Compressive Strength, (b) Splitting Tensile Strength, (c) Flexural Strength.

Flexural Strength

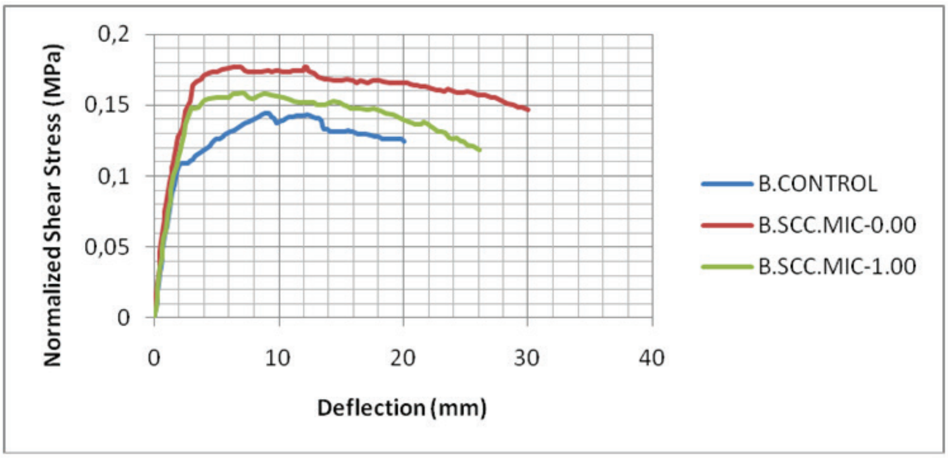
The flexural tensile strength of SCC mixes with/out fiber were evaluated by applying four-point bending test on prismatic specimens with the dimension of 100x100x400 mm as per ASTM C78 [26]. Figure 8(c) shows the test setup used for flexural strength tests. The flexural tensile strength was calculated by using the formula of PL/Bd^2, where P is the failure load, L is the effective length of beam, B and d are the width and depth of the beam, respectively. The average values of flexural strengths of SCC with/out fiber are shown in Table 6. It can be seen from this table that the decrease in macro steel fiber ratio induced decrease in the flexural tensile strength values of all mixtures. The highest flexural tensile strength with 12.74 MPa was obtained from the concrete mixtures including 1% macro steel fiber while the concrete mixtures with 1% micro steel fiber had lowest flexural tensile strength with 8.87 MPa except for the mixture without steel fiber. When the ratio of micro steel fiber increased, the flexural strength of the mixtures reduced due to reducing of macro steel fiber ratio. Because, the macro steel fibers can bridge the macro cracks, and thus, the flexural tensile strength increase. Haddadou et al. [24] also found that an adequate macro steel fiber content has vital importance to obtain high tensile strength. Reduce in the flexural tensile strength of mixtures also can be attributed to a balling effect of micro steel fiber with the higher aspect ratio during mixing process [27].

Half-scale Beam Tests

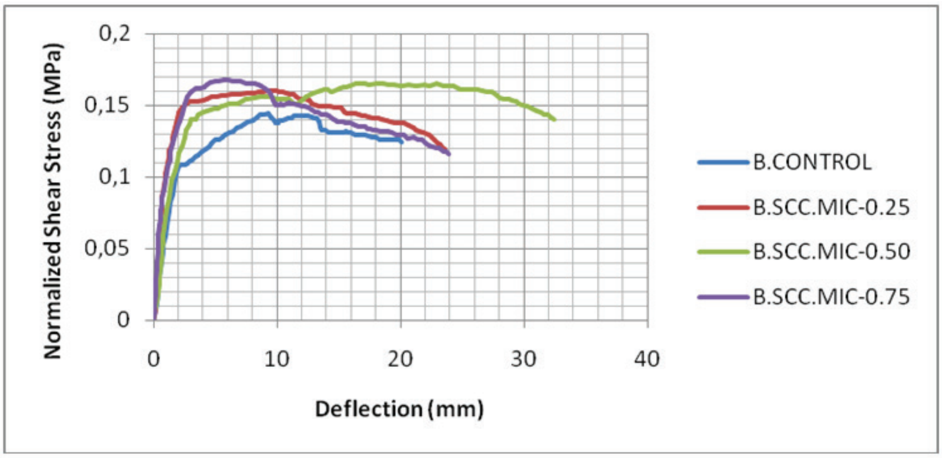
Normalized Shear Stress-Deflection Curves

The normalized shear stress-deflection curves of reinforced beam specimens were given in Figure 9. The normalized shear stress (τ) of reinforced beam specimen was calculated using the following Equation (1):

$$\tau = V/(bd\sqrt{f'c}) \tag{1}$$



(a)



(b)

Figure 9. Normalized shear stress-deflection curves, (a) Single micro or macro fiber reinforced beam specimens, (b) Hybrid fiber reinforced beam specimens.

where, V=Shear strength, b=width of beam specimen, d=depth of beam specimen, f’c=cylinder compressive strength of concrete. The normalization process was applied to eliminate the divergent in the compressive strengths. B.SCC.MIC-0.00 specimen with only 1% macro steel fiber had highest normalized shear stress value with 0.176 MPa while the value of normalized shear stress of B.CONTROL without steel fiber was lowest with 0.143 MPa. As for the beam specimens with hybrid steel fiber, the maximum value of normalized shear stress for B.SCC.MIC-0.25, B.SCC.MIC-0.50 and B.SCC.MIC-0.75 specimens was about 0.159, 0.165 and 0.167 MPa, respectively. The normalized shear stress of beam specimens with only macro steel fiber and beam specimens with hybrid steel fiber indicated approximately an increase of 23% and 11%, respectively, compared to B.CONTROL specimen while B.SCC.MIC-0.00, B.SCC.MIC-0.25, B.SCC.MIC-0.50 and B.SCC.MIC-0.75 exhibited similar normalized shear stress. It should also be emphasized that the normalized shear stress of beam specimen containing only 1% macro steel fiber was higher than that of beam specimens with hybrid steel fiber though there were no significant difference between the normalized shear stress of the beam specimens with only macro steel fiber and hybrid steel fiber. This may be attributed to the length of fibers because Sahoo et al. [18] also found that the beam specimens with 1% macro steel fiber had higher normalized shear stress than that of the beam specimens with a total of 1% hybrid fiber. In consideration of all fiber reinforced beam specimens, B.SCC.MIC-1.00 beam specimens indicated deflection-softening behavior while other beam specimens with steel fiber exhibited deflection-hardening behavior after first crack. Because, the micro fibers could not bridge macro cracks. The curves in Figure 9 showed that the addition of fiber into mixtures had positive effect in terms of the shear stress compared to beams with only shear stirrup. Similar results were found by some researchers [18,19,28–31].

Crack Patterns (Mode of Failure)

Figure 10 indicates the propagation of cracks in reinforced beam specimens. The first crack in the control specimen was observed at the mid-span at a load of 55.68 kN while macro shear cracks spreading from the support to the loading point were observed at 70 kN load magnitude. With the ascending in the load level, shear cracks were observed at the mid-span for the B.CONTROL specimens while the

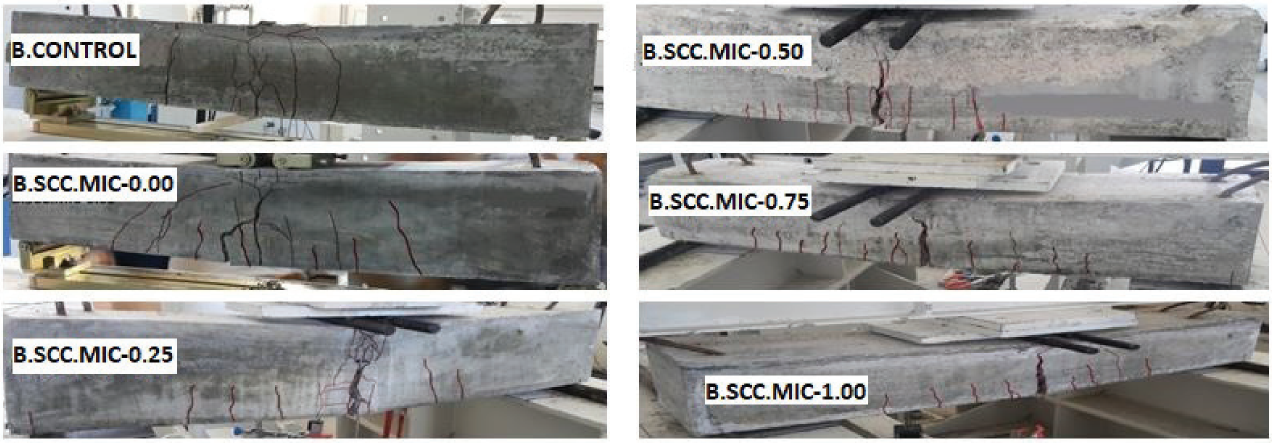


Figure 10. Cracking Pattern for tested beam specimens.

Table 7. Experimental test results for beam specimens

No.	Beam Specimen Name	Load Capacity (kN)		Deflection (mm)		Yield Stiffness (kN/mm)	Energy Absorption Capacity (kN.mm)	Failure Mode
		First Crack	Ultimate	At first crack	At failure			
1	B.CONTROL	55.68	72.51	2.30	20.07	24.20	1252.80	Shear
2	B.SCC.MIC-0.00	75.73	86.30	2.95	30.05	25.67	2275.98	Flexural-Shear
3	B.SCC.MIC-0.25	76.33	82.99	2.10	23.58	36.34	1425.01	Flexural
4	B.SCC.MIC-0.50	77.50	88.25	3.05	32.44	25.40	2600.91	Flexural
5	B.SCC.MIC-0.75	67.20	90.10	1.55	23.93	43.35	1810.16	Flexural
6	B.SCC.MIC-1.00	80.95	86.50	2.98	26.12	27.16	1838.05	Flexural

beam specimens with steel fiber exhibited flexural cracks at mid-span due to delayed the formation of the diagonal cracks by steel fibers though a few shear cracks formed around mid-span for the beam specimens with only macro steel fiber. The first crack in the B.SCC.MIC-0.00 specimens was seen at a load of 75.73 kN load magnitude and additional flexural cracks were also observed close to the mid-span regions before 80 kN load magnitude. The crack pattern and the failure mode of the B.SCC.MIC-0.00 specimens were almost identical to the B.CONTROL specimen. Similar finding was found from study executed by Sahoo et al. [18]. As for the beams with hybrid steel fibers, first flexural cracks were observed at load magnitudes of 76.33, 77.50 and 67.20 kN for the B.SCC.MIC-0.25, B.SCC.MIC-0.50 and B.SCC.MIC-0.75 specimens, respectively. The crack pattern and the failure mode of beam specimens with hybrid fiber were almost similar with one other. Moreover, many flexural cracks were observed in the beam specimens with hybrid fiber before failure indicating better redistribution of stresses on account of uniform distribution of macro and micro steel fibers [18,31,32].

Ultimate Shear Resistance and Displacement Ductility

The shear strength of test specimens was calculated as the half of the maximum load carried by the beam specimens during the tests. As shown in Table 8, B.SCC.MIC-0.75 specimens had highest shear strength with 45.05 kN followed by B.SCC.MIC-0.50, B.SCC.MIC-1.00, B.SCC.MIC-0.00 and B.SCC.MIC-0.25 while B.CONTROL specimens had lowest shear strength in all beam specimens. Moreover, the use of steel fiber in producing of beam specimens had positive effect on the shear strength of beam specimens compared to B.CONTROL specimens. However, the shear strength values of beam specimens with only macro steel fiber and hybrid steel fiber were close to each other. Therefore, it can be said that the aspect ratio and combination of steel fibers did not have an important effect on the shear strength of beam specimens.

Although the compressive strength value of B.SCC.MIC-0.00 specimen was the lowest in all specimens, it had higher shear strength than that of the B.CONTROL specimen. Because, macro steel fibers contributed the shear strength capacity of beam specimens due to its crack bridging capability. These findings were also obtained by some researchers [18,32] that the crack bridging property of steel fibers helped the mechanism of shear strength. Also, beam specimens with hybrid fiber showed higher shear strength capacity than B.CONTROL specimen. The shear strength capacity of hybrid fiber reinforced beam specimens increased about 14%, 22%, and 24% for B.SCC.MIC-0.25, B.SCC.MIC-0.50 and B.SCC.MIC-0.75, respectively, compared to B.CONTROL specimens. Similar results were also obtained from study conducted by Sahoo et al. [18] and Kamal et al. [30].

Table 8. Ultimate shear strength and ductility ratio of specimens

No.	Beam Specimen Name	Shear Strength (kN)	Ductility
1	B.CONTROL	36.25	8.47
2	B.SCC.MIC-0.00	43.15	10.17
3	B.SCC.MIC-0.25	41.49	10.23
4	B.SCC.MIC-0.50	44.12	10.55
5	B.SCC.MIC-0.75	45.05	9.03
6	B.SCC.MIC-1.00	43.25	8.96

The displacement ductility ratios for beam specimens were given in Table 8. The displacement ductility ratios were calculated by dividing the displacement at failure to the displacement at the yield point. The level that beam specimens fall down to 85% of their ultimate load capacities was used as the failure point. The displacement ductility of the B.CONTROL specimen was calculated as 8.47. The displacement ductility of beam specimens with only macro steel fiber and beam specimens with only micro steel fiber indicated almost an increase of 20% and 6%, respectively, compared to B.CONTROL specimen. As for the displacement ductility of hybrid fiber reinforced beam specimens, it increased approximately 21%, 24%, and 7% for B.SCC.MIC-0.25, B.SCC.MIC-0.50 and B.SCC.MIC-0.75, respectively, compared to B.CONTROL specimens.

Energy Absorption Capacity and Yield Stiffness

The energy absorption capacity of reinforced beam specimens was obtained from the area under load-deflection curves. In the energy absorption capacity calculations, only the area equal to the failure point was considered. Failure points were determined identical to those used for displacement ductility ratio calculations, as expressed above. Energy absorption capacities for all reinforced beam specimens were shown in Table 7. As for the energy absorption capacity of the beam specimens with only macro or micro steel fiber, the energy absorption capacity of B.SCC.MIC-0.00 beam specimens was 81% higher than that of B.CONTROL beam specimens while that of B.SCC.MIC-1.00 increased approximately 25% compared to B.CONTROL specimens. The energy absorption capacity of hybrid fiber reinforced beam specimens increased about 14%, 107%, and 45%, for B.SCC.MIC-0.25, B.SCC.MIC-0.50 and B.SCC.MIC-0.75, respectively, compared to B.CONTROL specimens. Moreover, the initial stiffness of all beam specimens with reinforced steel fiber was higher than that of B.CONTROL specimens regardless of the blending of steel fibers. B.SCC.MIC-0.75 specimens containing hybrid steel fiber had highest initial stiffness with 43.35 followed by B.SCC.MIC-0.25, B.SCC.MIC-1.00, B.SCC.MIC-0.0 and B.SCC.MIC-0.50. However, as seen in Table 7, the initial stiffness value of all specimens with/out steel fiber was almost identical except for B.SCC.MIC-0.75 specimens. The load-deflection behavior of B.SCC.MIC-0.75 beam specimen was almost

Table 9. Ultimate shear strength measured and predicted values of SCC beams

Beam Specimens	Measured Ultimate Shear Strength (kN)	Predicted Ultimate Shear Strength (kN)	Measured / Predicted Ultimate Shear Strength
B.CONTROL	36.25	36.25	1.00
B.SCC.MIC-0.00	43.15	42.66	1.01
B.SCC.MIC-0.25	41.49	43.04	0.96
B.SCC.MIC-0.50	44.12	43.41	1.02
B.SCC.MIC-0.75	45.05	43.79	1.03
B.SCC.MIC-1.00	43.25	44.16	0.98

Ultimate shear strength = 36.25 + 641 * Macro steel fiber volume fraction (%) + 791.4 * Micro steel fiber volume fraction (%) (kN) R^2 =0.94

linear up to a mid-span deflection of 3 mm, while the B.CONTROL specimens exhibited linear load-deflection behavior up to a mid-span deflection of 2 mm.

Statistical Analysis of Shear Strength Results

Regression analysis was an effective statistical method which was helpful for interpreting the relation between two or more parameters. It also can be utilized to estimate the ultimate shear strength of a hybrid fiber reinforced self-compacting concrete. The following regression equation measure the mechanical properties of hybrid fiber reinforced concrete based on the volume of macro and micro steel fiber (Table 9). Coefficients of R^2=0.94 for the value of ultimate shear strength indicated a good linear correlation between mechanical properties and macro vs. micro steel fiber volume fraction. R^2 also stand for a statistical measure of how close the test results were the fitted regression line.

As given in Figure 11, contour plots were two-dimensional non-linear curved drawings by using the regression analysis equations obtained from test results. The variation of measured responses with respect to several parameters were symbolized in contour plots, which can ensure a broad band of individual factors that, influence the measured responses. As can be seen from Figure 11, the use of macro steel fiber with micro steel fiber as hybrid importantly enhanced the ultimate shear strength of SCC beam specimens. On the other hand, based on the experimental results, ultimate shear strength value was overestimated with 1.03 for the combination of 0.75% micro and 0.25 macro steel fiber volume fraction.

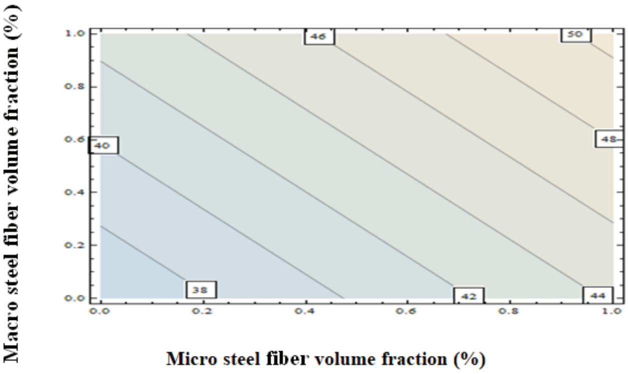


Figure 11. Contour plot variation of SCC beams for ultimate shear strength-macro vs. micro steel fiber volume fraction.

CONCLUSION

In this work, SCC beams with hybrid steel fibers was tested under four-point bending loading to investigate the effect of the blending of the macro and micro steel fibers. The following conclusions were drawn by using the results obtained from experiments:

- The shear failure was prevented by using hybrid fiber in the beam specimens produced from steel fiber reinforced self-compacting concrete, that is, all hybrid reinforced SCC beam specimens reached the ultimate bearing capacity with the mode of flexural failure.
- The beam specimens containing only 1% macro steel fiber had highest normalized shear stress values in all beam specimens though there was no important difference between the normalized shear stress values of the beam specimens with hybrid and 1% macro steel fiber.
- The beam specimens containing 0.25% macro and 0.75% micro steel fiber had highest shear strength while the control beam specimens had lowest shear strength in all beam specimens.
- As for displacement ductility, the beam specimens with only macro steel fiber and micro steel fiber indicated approximately an increase of 20% and 6%, respectively, compared to the control specimens while a further increase in the displacement ductility of hybrid fiber reinforced beam specimens was obtained.
- Hybrid fiber reinforced beam specimens with 0.50% macro and 0.50 micro steel fiber had the highest percentage increase of the energy absorption capacity with 107% followed by the beam specimens containing only 1% macro steel fiber with 81% compared to control beam specimens.

- The beam specimens with hybrid fiber reinforced had higher initial stiffness than the beam specimens with only 1% macro or only 1% micro steel fiber while control beam specimens had lowest initial stiffness.
- Hence, it can be concluded bluntly that the use of hybrid steel fiber in producing of beam specimens had in general positive effect on the shear behavior of beam specimens.
- Empirical equation was derived from regression analysis of the experimental results for ultimate shear strength was applicable to half-scale beams with hybrid steel fiber due to their coefficients of R^2=0.94.

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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.

REFERENCES

[1] Phan TH, Chaouche M, Moranville M. Influence of organic admixtures on the rheological behaviour of cement pastes. Cem Concr Res 2006;36:1807−1813. [CrossRef]

[2] Turk K, Karatas M, Ulucan ZC. Effect of the use of different types and dosages of mineral additions on the bond strength of lap-spliced bars in self-compacting concrete. Mater Struct Constr 2010;43:557−570. [CrossRef]

[3] Karatas M, Turk K, Ulucan ZC. Investigation of bond between lap-spliced steel bar and self-compacting concrete: The role of silica fume. Can J Civ Eng 2010;37:420−428. [CrossRef]

[4] Valcuende M, Parra C. Bond behaviour of reinforcement in self-compacting concretes. Constr Build Mater 2009;23:162−170. [CrossRef]

[5] Turk K, Nehdi ML. Coupled effects of limestone powder and high-volume fly ash on mechanical properties of ECC. Constr Build Mater 2018;164:185−192. [CrossRef]

[6] Turk K, Demirhan S. Effect of limestone powder on the rheological, mechanical and durability properties of ECC. Eur J Environ Civ Eng 2017;21:1151−1170. [CrossRef]

[7] Amed B, Kabay N. Glass Fibre Reinforced Precast Concrete Containing High Content Pozzolanic Materials. Sigma J Eng Nat Sci 2019;37:675−86.

[8] Turk K, Oztekin E, Kina C. Self-compacting concrete with blended short and long fibres: experimental investigation on the role of fibre blend proportion. Eur J Environ Civ Eng 2019;26:905−918. [CrossRef]

[9] Khalil WI, Tayfur YR. Flexural strength of fibrous ultra high performance reinforced concrete beams. ARPN J Eng Appl Sci 2013;8:200−214.

[10] Dancygier AN, Savir Z. Flexural behavior of HSFRC with low reinforcement ratios. Eng Struct 2006;28:1503−1512. [CrossRef]

[11] Turk K, Bassurucu M, Bitkin RE. Workability, strength and flexural toughness properties of hybrid steel fiber reinforced SCC with high-volume fiber. Constr Build Mater 2021;266:120944. [CrossRef]

[12] Bassurucu M, Turk K. Effect of curing regimes on the engineering properties of hybrid fiber reinforced concrete. Int J Energy Eng Sci 2019;4:26−42.

[13] Turk K, Bassurucu M. Bond strength of full-scale beams with blended short and long steel fiber. Pamukkale Univ J Eng Sci 2021;27:274−280. [CrossRef]

[14] Voo YL, Poon WK, Foster SJ. Shear strength of steel fiber-reinforced ultrahigh- performance concrete beams without stirrups. J Struct Eng 2010;136:1393−1400. [CrossRef]

[15] Ozawa K, Maekawa K, Kunishima M, Okamura H. Development of high performance concrete based on the durability design of concrete structures. Proceeding Second East Asia-Pacific Conference on Structural Engineering and Construction (EASEC - 2), vol. 1, Chiang Mai, Thailan: 1989, p. 445−450.

[16] Rossi P, Acker P, Malier Y. Effect of steel fibres at two different stages: The material and the structure. Mater Struct 1987;20:436−439. [CrossRef]

[17] Mobasher B, Li CY. Mechanical properties of hybrid cement-based composites. ACI Mater J 1996;93:284−292. [CrossRef]

[18] Sahoo DR, Maran K, Kumar A. Effect of steel and synthetic fibers on shear strength of RC beams without shear stirrups. Constr Build Mater 2015;83:150−158. [CrossRef]

[19] Alyousif A, Anil O, Sahmaran M, Lachemi M, Yildirim G, Ashour AF. Tests of high-performance

fiber-reinforced concrete beams with different shear span-to-depth ratios and main longitudinal reinforcement. J Reinf Plast Compos 2015;34:1491-1505. [CrossRef]

[20] ACI Committee 318. Building Code Requirements for Structural Concrete. Michigan: American Concrete Institute; 2014.

[21] Dilger WH. Reinforced concrete: mechanics and design. Can J Civ Eng 2000;27:87. [CrossRef]

[22] Test CC, Drilled T, Concrete C, Statements B. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens 1. Concrete 2006;i:1-7.

[23] Song PS, Hwang S. Mechanical properties of high-strength steel fiber-reinforced concrete. Constr Build Mater 2004;18:669-673. [CrossRef]

[24] Haddadou N, Chaid R, Ghernouti Y, Adjou N. The effect of hybrid steel fiber on the properties of fresh and hardened self-compacting concrete. J Build Mater Struct 2014;1:65-76. [CrossRef]

[25] ASTM. ASTM C 496/C 496M-Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. Pennsylvania: ASTM International; 2011.

[26] ASTM. ASTM C78-Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with. Pennsylvania: ASTM International; 2002.

[27] Ghanem H, Obeid Y. The Effect of Steel Fibers on the Rhyological and Mechanical Properties of Self Compacting Concrete. Eur Sci J 2015;11:1857-17881.

[28] Ortiz Navas F, Navarro-Gregori J, Leiva Herdocia G, Serna P, Cuenca E. An experimental study on the shear behaviour of reinforced concrete beams with macro-synthetic fibres. Constr Build Mater 2018;169:888-899. [CrossRef]

[29] Tahenni T, Chemrouk M, Lecompte T. Effect of steel fibers on the shear behavior of high strength concrete beams. Constr Build Mater 2016;105:14-28. [CrossRef]

[30] Kamal MM, Safan MA, Etman ZA, Salama RA. Behavior and strength of beams cast with ultra high strength concrete containing different types of fibers. HBRC J 2014;10:55-63. [CrossRef]

[31] Türker K, Birol T, Yavaş A, Hasgül U, Yazici H. Flexural behavior of beams with ultra high performance fiber reinforced concrete. Tek Dergi/Technical J Turkish Chamb Civ Eng 2019;30:8777-801. [CrossRef]

[32] Xue X, Hua X, Zhou J. Test and prediction of shear strength for the steel fiber-reinforced concrete beams. Adv Mech Eng 2019;11:1-14. [CrossRef]