IOP Conf. Series: Materials Science and Engineering **431** (2018) 042004 doi:10.1088/1757-899X/431/4/042004

Effects of Steel Fibre Addition on the Mechanical Properties of Steel Fibre Reinforced Self-Compacting Concrete (Sccfibre)

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Abstract. Self-compacting concrete (SCC) mix that is highly workable has the ability to fill formworks and tight spaces between rebars under its own weight without applying any vibration. In this research, normal strength steel fibre reinforced self-compacting concrete (SCCFibre) of grade C30 was produced with the addition of Stahlcon HE 0.55/35 steel fibres at volume fraction of 1% (80 kg/m^3). The effect of the steel fibre addition on the SCCFibre mix was investigated in terms of its rheological properties (slump flow diameter and time, J-ring) and mechanical properties (compressive strength, splitting tensile strength, flexural strengths and moduli of elasticity). The compressive strength test was carried out using cubes of 150 x 150 mm, splitting tensile and MOE were performed using 150 x 300 mm cylinders while the flexural strength test was using beams of 150 x 150 x 550 mm. The results from the tests revealed that the workability and the rheological properties of the SCC mix specified by the EFNARC were decreased with the 1% addition of steel fibres. Similar decrement was also discovered in the compressive strength and the MOE value. In contrast, the splitting tensile strength, flexural strength and toughness showed significant increase with the introduction of the fibres.

1. Introduction

Self-compacting concrete (SCC) has the ability to be properly poured in place, filling the formwork corners and small voids between reinforcement bars by means of its own weight without any compaction. Its rheological property allows SCC to be effectively applied in complex shaped elements and congested reinforcements [1]–[5]. The SCC mix has been developed in Japan back in the 1980s with the flow ability that offers advantages to the construction process, whereas the needs of skilled workers were minimized. Furthermore, it leads to a reduction of costs as well as time needed to construct a structure [6].

The introduction of steel fibres to concrete material was essential in order to significantly improve the brittle behaviour of plain concrete. Positive effects of the steel fibres by the ability to bridge cracks in the matrix and contributing to the ductile behaviour of the concrete preventing brittle failures. The combination of these two materials; the self-compacting concrete and the steel fibres produces an effective material of steel fibre reinforced self-compacting concrete that has high flow ability and offers a ductile characteristic. Nowadays, this material is utilized in various civil engineering applications such as road pavements, tunnel segment linings [7] as well as reinforcements in slab structures [8].

This present research is aimed to investigate the influence of 1% steel fibre addition to the rheological and mechanical properties of the normal strength grade C30/37 self-compacting concrete.

2. Experimental studies

Similar concrete grade C30 of plain self-compacting concrete (SCC) was used for all material properties experiments. The experiments were divided into 2 phases: (1) tests on fresh concrete for the slump flow and J-ring test; (2) tests on hardened concrete for the compressive strength, splitting tensile, flexural strength and moduli of elasticity.

2.1. Mixing and testing procedures
The steel fibre volume fraction used in this current study was 1% or 80 kg/m^3. The material composition of plain SCC mix design for concrete grade C30 is shown in Table 1. The design flow of the mix was designed to produce a slump flow diameter of 650 ± 100 mm. In order to ensure a constant flow of the mix, high range superplasticizer (ADVA Flow 222) and cohesion agent (VMAR 10P) was incorporated. The type of steel fibre added to the SCC to produce SCCFibre was hooked end. It was chosen since the geometry of the fibres contributes to higher anchorage and friction between the fibres with the aggregates in the aggregates in the matrix in comparison to straight fibres [9]. In addition, the hooked end also yields greater pull out forces [10] and contributes to higher toughness as well as residual strength [2,15]. The characteristics of the used hooked end steel fibres is shown in **Table 2**. The steel fibres were glued in bundles were added to the mix at the end of the mixing process. It was produced in the bundled manner in order to evade the fibre balling effect [4, 6, 7]. This type of fibres conforms to the requirement of BS EN 14889-1[14].

Table 1: SCC mix composition

Cement CEM I 42.5R	315 kg/m^3
Pulverized fuel ash (Class F)	105 kg/m^3
Coarse aggregate (10 mm)	830 kg/m^3
Fine aggregate	865 kg/m^3
Water	185 kg/m^3
Water/cement	0.44
Steel fibre content (1%)	80 kg/m^3

Table 2: Characteristics of the steel fibre

Type of steel fibre	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (N/mm^2)
Hooked end (Stahlcon HE 0.55/35)	35	0.55	65	1250

The fresh concrete tests were carried out to determine the rheological properties of the SCC and SCCFibre mix. Two types of tests were performed, i.e. slump flow diameter/time and J-ring. The slump flow test was performed to determine the flow characteristics on a horizontal surface in accordance to BS EN 12350-8 [15]. It is to ensure that the mix has the ability to fill spaces in the formwork under its weight and have acceptable resistance level against segregation. The J-ring test on the other hand is to assess the ability of the mix to flow through opening between reinforcing bars or other obstacles without any segregation or blocking in accordance to the and BS EN 12350-12 [16].
Upon completion of the tests on the plain SCC and SCCFibre mix, the fresh concrete was poured into 150 mm cubes, 150 x 300 mm cylinders and 150 x 150 x 550 mm beam moulds for the mechanical properties tests. Samples were demould after 24 hours and submerged in water for curing. The compressive and splitting tensile strength test was carried out based on BS EN 12390-3 [17] and BS EN 12390-6 [18], respectively.
The flexural strength test was performed at 28 days under three point bending at the age of 28 days based on the specifications given in RILEM TC162-TDF [19]. Samples were tested under displacement control at a constant rate of 0.2 mm/min. A 25 mm notch was sawn to the sample as a guide for the crack initiation.

Table 3 : Slump flow test results

Designation	Slump flow	
	SFD (mm)	T_{500} (sec)
Plain SCC	620	4.5
SCCFibre	610	5

SFD = Slump flow diameter; T_{500} = Slump flow time to reach 500 mm flow diameter

3. Results and discussion

3.1. Fresh concrete properties

3.1.1. Slump flow test

The slump flow test of both plain SCC and SCCFibre mix showed satisfactory performance based on the visual performance. Both mixes flowed smoothly without any of segregation. The steel fibres were also observed to be evenly dispersed without any signs of fibre balling or flow blockage. According to European Guideline for Self-compacting Concrete [20], the slump flow diameter has to at least reach 550 mm diameter. The slump flow of the plain SCC reached an average spread of 620 mm while the SCCFibre mix with 1% of steel fibres spread 610 mm, only 10 mm lesser. Thus, the two mixes was classified under SF1 category [20] which is suitable for unreinforced structures or structures that is lightly reinforced and vertically cast. In terms of the viscosity, the T_{500} flow time requirement stated by the EFNARC [21] has to be within the 2 to 5 seconds range. The results showed that the viscosity of both mixes fulfilled the requirement by meeting this criterion. The details of the slump flow test results are presented in

Table **3**.

3.1.2. J-ring

The passing ability of the plain SCC and SCCFibre mix were measured using the J-ring test in accordance to the BS EN 12350-12 (2010). The J-ring test results is shown in Table 4. The passing ability ratio (PJ) of the plain SCC mix calculated was 5 mm which satisfies the EFNARC requirement. The flow of the mix was smooth and produce no blockage as it passes the reinforcement barrier. The flow spread measured was 625 mm. The flow spread for this type of mix was 625 mm, which is within the EFNARC (2002) requirement.

Subsequently, blockage between the barriers was clearly observed upon the addition of 1% steel fibres for the SCCFibre mix. The steel fibres were found to restrain the mix from easily flowing through the gaps of the J-ring equipment. Only a part of the concrete matrix (aggregates, sand, cement and water) managed to flow through. The flow spread measured was 505 mm, which was lower than the requirement. However, this result was acceptable considering that the slab sample for the experimental work was lightly reinforced with appropriate space to allow the SCFibre mix to flow through. The PJ of SCCFibre increased to 43 mm, which exceeded the EFNARC requirement. Nonetheless, the results from this test is accepted since this SCCFibre mix was designed to be used for a lightly reinforced slab structure as a replacement to the reinforcement, therefore the risk of blockage is minimal.

Furthermore, based on the guideline (“The European Guidelines for Self-Compacting Concrete,” 2005; Steffen Grunewald & Walraven, 2009), the gaps for the J-ring apparatus was too narrow for high amount of long fibres to pass through. For this test, the gap of the J-ring apparatus was 59 ± 1 mm. The length of the steel fibres used in this study was 35 mm. Therefore, wider gap of at least 3 times wider than the length of the steel fibres was required in order for the SCFibre mix to pass through without blockage [7]. Therefore, the test using the standard equipment is only applicable for plain SCC mix or SCC mix with low volume fraction of small fibres [22].

Table 4: J-ring test results

Criteria	Plain SCC	SCCFibre	EFNARC requirement
$T_{500\,j}$ flow time (sec)	7	6.7	2- 5 sec
Flow spread, SF_j	625	505	550 - 650
Passing ability, PJ	5 mm	43 mm (blocked)	0 – 10 mm

Figure 1 *:* J-ring test (a) Plain SCC (b) SCCFibre

3.2. Hardened concrete properties

Both mixes, the Plain SCC and SCCFibre were tested for the its hardened mechanical properties, that is the compressive strength, tensile splitting strength, flexural strength test as well as the modulus of elasticity.

3.2.1. Compressive strength

In order to determine the compressive strength of both mixes, twelve (12) numbers of 150 x 150 mm cubes were cast for testing at the sample age of 3, 7, 28 and 42 days. The test was performed based on the standard procedures in BS EN 12390-3 [17]. The results from the compression test are presented in **Table 5** and illustrated in Figure 2. The results revealed that both mixes achieved the designed concrete strength for grade C30/37. In comparison of the two mixes, it can be observed from the results that compressive strength decreases with the inclusion of the steel fibres. This strength reduction might be caused by the effect of the steel fibres on the workability of the mix. Based on the graph, the strength difference was not significant at the early ages of the samples. The difference was most pronounced at the sample age of 28 days with approximately 18% and decreased to 7% at 42 days. This decrement trend of the compressive strength with the addition of the steel fibres was found to be in agreement with findings of previous researchers [22]–[26]. Presence of the steel fibres might cause a localized stress concentration in the hardened cement paste initiating additional weak points in the matrix. Furthermore, the reduction was also due to the matrix disturbance by the steel fibres that induced higher voids. Nonetheless, although the inclusion of steel fibres reduce the compressive strength, it significantly contribute to the improvement of the compressive failure mode by holding the matrix together at crushing point [27].

Table 5: Compressive strength test results for both mixes

Age of sample (days)	3 days (N/mm^2)		7 days (N/mm^2)		28 days (N/mm^2)		42 days (N/mm^2)	
Plain SCC	19.49		26.54		39.73		39.46	
	17.56	18.76	25.26	25.44	37.98	38.74	40.26	40.27
	19.23		24.52		38.52		41.1	
SCCFibre	16.00		23.01		34.46		37.44	
	19.33	17.55	23.37	23.55	32.55	32.72	38.06	37.43
	17.32		24.28		31.16		36.79	

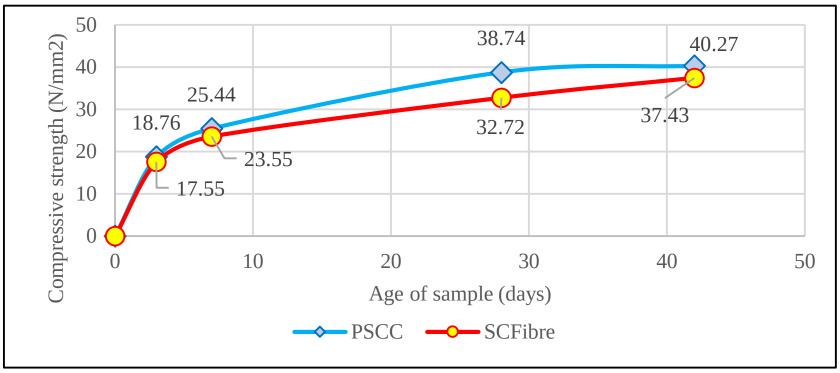

Figure 2 : Compressive strength test results of PSCC and SCCFibre cube samples

3.2.2. Tensile splitting strength

Table 6 exhibits the results of the splitting tensile strengths, f_{ct}. The test was carried out according to BS EN 12390-6 [18] on 150 x 300 mm cylinder samples. Six samples were prepared and tested for the plain SCC and steel fibre reinforced self-compacting concrete (SCCFibre) at 28 days of age. The ultimate load for each mix were recorded from the Universal Testing Machine and the tensile splitting strength values were calculated. Results revealed that the inclusion of the steel fibres had significantly increase the strength of the cylinder samples by 54.72%. The enhanced splitting tensile strength of the SCCFibre was as a result of the bridging mechanism of the steel fibres that secures the gap in the crack openings during loading. The introduced bridging mechanism assist in restraining the micro cracks development within the concrete matrix [22]. Furthermore, the hooked end geometry of the steel fibres also contributes in enhancing the anchorage between the fibres and the concrete matrix resulting in higher splitting tensile strength [24].

Table 6: Cylinder tensile splitting strength

Type of mix	Maximum load (kN)	Tensile splitting strength, f_{ct} (N/mm^2)
Plain SCC	143.65	2.05
SCCFibre	208.4	3.15

Note: These maximum values were adopted from the average of three samples

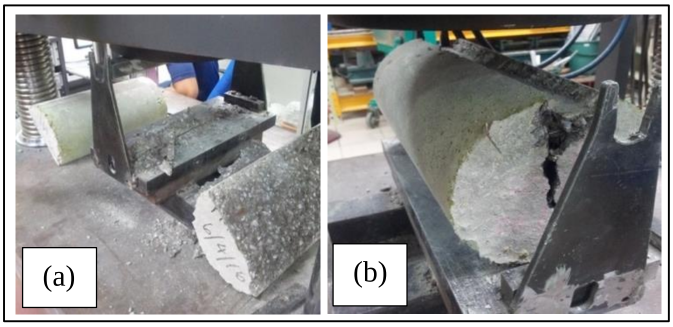

Figure 3: Tensile splitting cylinder sample condition after testing; (a) plain SCC (b) SCCFibre

The conditions of the plain SCC and SCCFibre samples after testing is shown in **Error! Reference source not found.**. The plain SCC sample experienced brittle failure where the sample split into two parts. In contrast, the inclusion of 1% steel fibres has managed to restrain the matrix together by remaining intact after the splitting failure. The steel fibres bridged the cracks and held the two split components of the cylinder. This behaviour was also contributed by the hooked end steel fibre geometry that contributes to the increment of the tensile splitting strength by restraining the internal micro-cracks and also the fibre pull-out strength [16, 18, 22].

3.2.3. Flexural strength test

The ultimate load, flexural strength and moment at mid span of the 550 mm length of beams are presented in Table 7. This flexural strength test was performed according to the test procedures in the RILEM TC 162-TDF [29]. Six (6) notched beams with the dimension of 150 x 150 x 550 mm was loaded under three-point bending and the ultimate loading as well as the deflection values were recorded during the test.

Table 7 : Flexural strength test results

Sample	Ultimate load, F_L (kN)	Flexural strength, F_b (N/mm^2)	Moment at midspan, M_L (kNm)
Plain SCC	10.69	3.42	1.34
SCCFibre	22.94	7.34	2.87

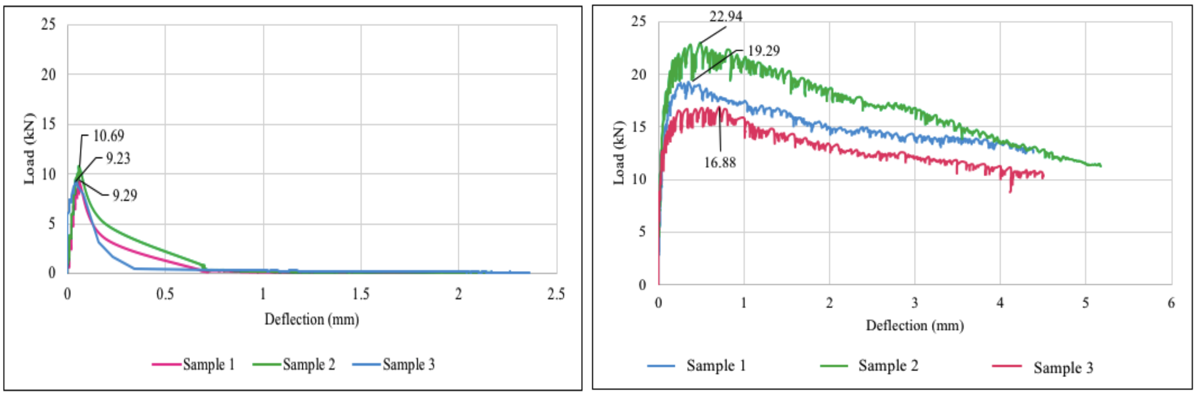

Figure 4. a) Load versus deflection graph of plain SCC beam samples and b) SCCFibre samples

Figure 4a) and (b) shows the flexural behaviour of the both plain SCC and SCCFibre beam samples. The graphs revealed that the 1% inclusion of hooked end steel fibres resulted a significant increase of the ultimate load of more than double in comparison to the plain SCC. The results had proven the effectiveness of the steel fibres in enhancing the flexural strength of plain SCC. Based on the figures, it can be observed that the Plain SCC and SCCFibre graphs ascends linearly until the sample underwent cracking. The line then deviates upon cracking as a result of the micro-crack occurrence as it propagates through the concrete matrix [2], [30].

The highest ultimate load achieved by the plain SCC sample was 10.69 kN. Upon reaching the ultimate load, the graph drastically drops, and the beam sample loses its strength. The plain SCC flexural beam experienced a brittle behaviour by splitting into two parts. The SCCFibre beam sample, on the other hand achieved higher ultimate load with a maximum of 22.94 kN. The load-deflection curve was in contrast of the plain SCC beam where the graph experienced deflection-hardening response contributed by the inclusion of the steel fibres [26, 27]. The curve pattern is similar to the findings of Barros et.al [27], and Pajak et.al [28] that also performed similar flexural testing according to the RILEM recommendation [29]. The steel fibres had managed to bridge the cracks and held the matrix together while sustaining the loads. The stresses across the cracks were bridged by the fibres providing resistance to further macro-cracks propagation.

Table 7 presents the values of the flexural strength and the bending moment at mid-span that is calculated based on the ultimate strength values obtained from the flexural test. The flexural strength and bending moment were found to be significantly higher than the plain samples.

3.2.4. Modulus of elasticity (MOE)

The moduli of elasticity values for the plain SCC and SCCFibre were determined by performing the standard test based on BS EN 12390-13 [34]. **Figure 5** showed the stress-strain data that was recorded during the test at the third loading cycle where the value already stabilized. Subsequently, linear trend lines were plotted based on the readings.

Based on the plotted graphs, the modulus of elasticity for the plain SCC and SCCFibre samples are 34.15 kN/mm^2 and 32.25 kN/mm^2, respectively, determined from the slope of the trendlines drawn. The MOE value of the SCCFibre was affected by the presence of the steel fibres, whereas the value is slightly lower than the plain SCC sample by 5.6%. The result is in line with the findings by previous researchers [16, 20, 30]. The steel fibres addition had cause agitation to the concrete matrix causing higher volume of voids initiating micro-crack within the concrete matrix. Moreover, the orientation of fibres that is parallel to the direction of loads also acted similarly as voids causing a reduction in the strength of the sample [26]. The decrease of the MOE value for SCCFibre in comparison to plain SCC was in similar trend as the compressive strength behaviour.

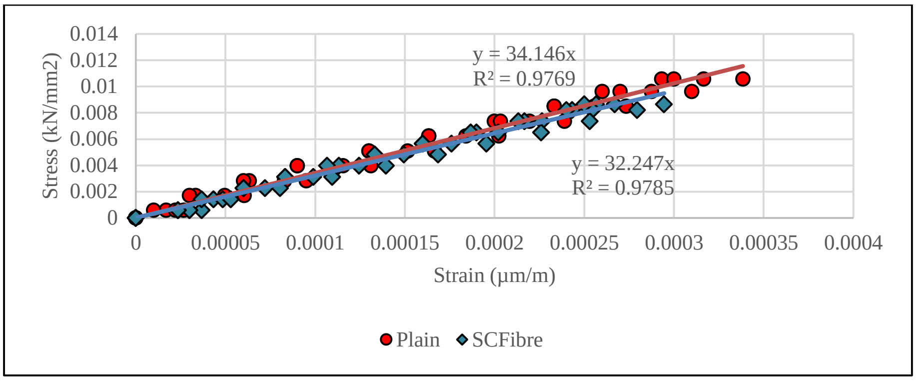

Figure 5 : Stress versus strain graph for the modulus of elasticity

4. Conclusion

The experimental investigation was carried out to study the rheological and mechanical properties of the plain self-compacting concrete (plain SCC) and steel fibre reinforced self-compacting concrete (SCCFibre). The results obtained can be summarized as follows:

- The 1% steel fibre addition decreased the workability of the SCC resulting a reduction in the passing ability of the mix. Although the addition also decreased the flow ability of the SCC mix, however, the SCCFibre mix was still able to flow smoothly without any signs of segregation.
- The compressive strength was decreased with the 1% addition of the steel fibres. This can be related to the workability decrement. At 28 days, the decrease observed was approximately 18%, while as the sample aged to 42 days, the decrease was found to be lower with only 7% lesser than the plain SCC.
- In contrast to the compressive strength, the steel fibre contributed to the increment of the tensile splitting strength. The steel fibres bridged the gap between the two gaps of the crack opening holding the matrix together. The 1% addition has improved the tensile splitting strength by 54.72%.
- Similar enhancement was observed on the flexural strength with more than double increment of the sustained ultimate loading. The steel fibre addition improved the failure mode of the flexural beam sample by bridging the cracks at mid-span evading the brittle failure of the plain SCC matrix.
- The moduli of elasticity (MOE) value follows similar trend as the compressive strength where the MOE values with addition of the steel fibres was 6% lower in comparison to the plain SCC.

5. References

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Acknowledgement
Special thanks to the laboratory staffs of the Faculty of Civil Engineering, UiTM, Malaysia for their technical support in completing this research.