



Combined Effect of Low and High Rate of Corrugated Steel Fiber and Stirrups on Mechanical Performance of SFSCC Beams

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Abstract – To improve the fragile nature of concrete, its low tensile strength, and a view to giving it the desired properties, which serve to build more durable structures at less cost, the association of a self-consolidating concrete with fiber, is considered a wise combination. However, given the limited amount of research on the response of SFSCC structures, designers and engineers do not use this material with confidence. In the present work, an experimental companion was conducted to examine the combined effect of fibers and stirrups, including the low and high rate of steel fiber, on the behavior of SFSCC beams. This choice allowed working on economically viable SFSCC. Beams were also made with ordinary concrete and others with self-consolidating. Thirty-six beams were of identical cross-section 10x20cm and length of 120cm; carried out with or without longitudinal and transverse reinforcement. Before proceeding with the main part of the research program, the concrete mixtures were characterized first in the fresh state by the following tests: Slump Flow, Time Flow T500; J-Ring, L-Box, V-Funnel, and Sieve stability, and then in the hardened state: compressive and tensile strengths. In the light of the results obtained, it was found that adding steel fibers to fresh self-consolidating concrete decreased its workability and fluidity but improved its hardening properties. Subsequently, the addition of the steel fibers increased the flexural capacity of the beams significantly and enhanced their ductility. Also, an addition of the steel fibers in an adequate percentage, in this case at 0.90%, made it possible to replace the shear reinforcements and can lead to changing the mode of failure from a collapse by brittle shear to a mechanism of ruin in ductile bending.

Keywords: Corrugated steel fibers, Self-consolidating, Stirrups, beams, Overall behavior, Failure behavior.

Introduction

Concrete has been regarded as the quintessential building material for over a century. It is still undergoing continuous evolutions and techniques for new compositions to remedy its fragile nature and low tensile strength. These two essential material weaknesses are the causes of concrete breaking shortly after the first crack occurrence (Fritih *et al.*, 2013), precisely after the sudden birth and propagation of a diagonal crack in the region near the beam support; this is a shear damage ruin mode and considered as high-risk mode. To impart the desired ductile properties and improve the intrinsic performance of this multiphase material, designers are attempting to reinforce beams with transverse reinforcement. However, reasons for cost and public safety have led to the study of other alternatives, residing in the use of fiber-reinforced concrete (Aoude *et al.*, 2014). The addition of elements of the same scale as the aggregates, fibers of different types and sizes, to improve as a primary purpose the fragile behavior of this composite material, both in tension and in shear, and avoid abrupt breaking mode, becomes a major challenge. However, even if since their appearance, these composites materials have not ceased to develop. Nevertheless, this progression is marked out by some constraints to be overcome. For example, the addition of fibers in ordinary concrete can induce a reduction of its maneuverability as well as a difficulty in concreting. The association of self-consolidating concrete with fibers has been proposed as a solution to these problems. Fibers and SCC could be considered as a judicious combination, since the composite self-consolidating fiber-reinforced concrete offers the

advantage of limiting the problem of workability due to friction between fibers and aggregates and maintaining the desired performance, which makes SFSCC very viable, as well allowing a higher fiber content needed for structural applications (Fritih, 2009). An experimental investigation panel has been carried out to date by various researchers to study the possibility of improving the performance of the SFSCC by analyzing a variety of parameters involved. (Hai *et al.*, 2010) based their research on two major points: the behavior of steel-fiber reinforced concrete FRC beams concerning shear and the possibility of using steel fibers as minimum shear reinforcement. Three types of steel hook fibers were considered to analyze 28 flexed beams, in proportion varying from 0.75%, 1%, and 1.5%. The study also included an analysis of the effect of beam depth and the rate of longitudinal reinforcement. Test results showed that using hooked steel fibers with a volume fraction equal to or greater than 0.75% resulted in multiple diagonal cracking and increased shear strength compared to reinforced concrete beams without reinforcement shear. The test results also indicated that the hooked steel fibers could be used safely as minimum shear reinforcement in BRF beams obtained from normal strength concrete and throughout the depth of the studied elements. (Ding *et al.*, 2012) studied the effect of reinforcement combining steel fibers, longitudinal reinforcements, and shear reinforcements on self-consolidating concrete beams' mechanical behavior. They evaluated the effect of this combination on shear strength, strain and cracking, ultimate loads, and failure mode. The investigation showed that the shear strength increased with increasing fiber content. The combination of steel fibers and transverse reinforcement demonstrated a positive composite effect on the studied specimens' ultimate load, ductility, and failure mode. (Fritih *et al.*, 2013) carried out an experimental program, focusing on the influence of the low proportion of stainless steel fibers 0.25%, the control of the opening of the crack, and the consequences on the response of mechanical post-cracking due to bending of the beams. The authors concluded that this type of fiber reinforcement is a suitable solution to control the width of cracks in reinforced concrete members. The performance, ductility, and load capacity are not affected; its effects were limited to the kinetics and distribution of cracks. They also noted that the used fiber content reduces the stresses in the transverse reinforcement, but it cannot be considered as a solution to replace them. (Aoude *et al.*, 2014), focused on the test of eleven slender beams using two types of SFSCC, with three sorts of fibers with different volume contents, subjected to four-point bending loading. However, with two longitudinal reinforcement ratios i.e. $\rho = 1.55\%$ and $\rho = 2.33\%$, no transverse reinforcement was foreseen. Further increase in fiber content up to 1.0% produced a 63% improvement in shear strength than the control beam element. 1.5% fibers fraction did not increase flexural capacity compared with the beam having 1.0% fibers. The investigation by (Cuenca *et al.*, 2015) is based on the study of the effect of the quality of fibers and the level of compressive strength of the analyzed concrete on the behavior of the tested beams. The specimens have a constant fiber content of 50 kg/m³, but of different qualities (fiber strength), with concrete strength thresholds, 40-50 MPa or 80-100 MPa at 28 days. Researchers observed that the contribution of the resistance of the fiber to the ductility of the concrete is more important than the contribution of the resistance of the concrete. The medium resistance concrete combined with the high resistance fibers has ductile behavior. The combination of high-strength concrete and medium strength fiber showed brittle behavior. (Zarrinin *et al.*, 2016) examined the impact of the densities of the steel fibers and the super-plasticizer on the rheological and mechanical properties of traditionally reinforced self-consolidating concrete. Two volume fractions of super-plasticizer, respectively 1% and 2%, were considered. To achieve the desired mechanical performance of SCC beams, different percentages of steel fibers at 0%, 1%, 1.5%, and 2% have been studied. The test results revealed that increasing the steel fibers volume fraction slightly improved compressive and flexural strengths. Energy absorption capacity and toughness were increased, too, with a decrease in inconsistency and other rheological properties. (Kannam *et al.*, 2018) have investigated the contribution of two grades of self-consolidating concrete, namely M30 and M70. The effect of the shear ratio throughout the effective depth on the shear behavior of 16 SFSCC beams, two a/d ratios, respectively 2 and 3, were taken into account. The steel fibers dosage was considered constant, 0.5% by volume of concrete. The experimental results demonstrated that as the ratio of a/d increased from 2 to 3, the ultimate shear strength decreased. It was noticed an improvement in the ultimate load capacity of SCC specimens

and the shear behavior with the addition of steel fibers. Also, this addition induced a sudden and brittle failure mode change of the specimens to a ductile mode. The investigation (Nikbakhta *et al.*, 2019) focused on studying the shear and bending behavior of high-performance self-consolidating concrete beams without coarse aggregate and with a compressive strength value less than 100MPa. The influence of different types of steel fibers, the ratio a/d , and the longitudinal and transverse reinforcement rates on the behavior of the HPSCC samples, the mechanical properties, and the modes of damage were considered. The results showed that the type of steel fiber is greater than that of the longitudinal reinforcement ratio. In addition, the ultimate load and strain capacity of HPSCC beams has increased significantly by adding the steel fibers. However, non-fiber beams with transverse reinforcement spacing $d/4$ have shown greater flexibility than steel fiber beams with $d/2$ transverse spacing reinforcements and the same longitudinal reinforcement ratio. Moreover, transverse reinforcement has a greater influence than steel fiber on the ductility of HPSCC beams.

To summarize, concrete is the most used building material in the field of civil engineering. This is due to its mechanical qualities and its economic aspect 'relatively low cost'. This mixture must then obey more severe requirements in materials workability, durability, and shapes. Associated with this, current progress has allowed the emergence of special concretes, which increase the cost and design, for example, for self-placing concrete reinforced with SFSCC fibers. These concrete types have both qualities of self-compacting concrete and fiber concrete; however, there are few structural applications to date. This is mainly due to the lack of information concerning their mechanical properties, such as their behavior in bending rarely studied (Frith, 2009; Aoud; 2014 and Mahir *et al.*, 2018). The application of SFSCC to real structures has been obstructed until today because of the limited information about its inflectional behaviors. This present study was carried out to fill this gap. It was carried out to improve the extent of knowledge on the mechanical behavior of SFSCC beams to optimize their use in structural applications. The data presented here are considered unique because they provide information on the effect of parameters such as concrete type, longitudinal and transverse reinforcement, fiber volume fraction on bending behavior, failure mode, and ductility of SFSCC beams.

Materials and Methods

Materials

Before starting a concrete formulation, it is necessary to identify the materials used for this purpose. The components are a Portland cement CPJ-CEMII/A 42.5 from the cement plant GICA, Hamma Bouziane, East Algeria; Class F10 limestone filler; aggregates as crushed materials of granular classes: sand (0-4) and gravel of classes (4-8, 8-15) from the ENG Giant-Quarry, Constantine, East Algeria; ordinary drinking water supplied to laboratory LMDC; adjuvant GLENIUM27 (a highly water-reducing super-plasticizer).

The choice of concrete has focused on ordinary concrete, self-consolidating concrete, and self-consolidating concrete reinforced with steel fibers. Compared to SCC mixtures, SFSCC is characterized by lower gravel content, i.e., a decrease in the volume of the coarse aggregate compensating the volume of the steel fibers incorporated in the concretes to minimize the loss of workability due to the addition of fiber. The mixing proportions of these concretes are detailed in Table 1.

Table 1. Compositions of tested mixtures

Material	Cement kg	Limestone powder kg	Sand kg	Gravel (3-8) kg	Gravel (8-15) kg	Water kg	Super- plasticizer kg	Fibers %
NC	390	/	819.00	234.00	749.00	200.00	/	/
SCC	400	80	737.94	368.97	368.97	169.64	7.40	/
SFSCC0.3%	400	80	737.94	368.97	354.92	169.64	7.40	0.30
SFSCC0.6%	400	80	737.94	368.97	348.94	169.64	7.40	0.60
SFSCC0.9%	400	80	737.94	368.97	342.92	169.64	7.40	0.90
SFSCC1.2%	400	80	737.94	368.97	336.90	169.64	7.40	1.20

Steel fibers are the basic materials in the study. Corrugated steel fibers marketed MEDAFAC supplied by GRANITEX have been used, not only because of their availability and their suitable price, but also for their characteristics, resulting in improved mechanical performances of concrete structures, while respecting the dosages that can be easily practiced in the structural elements. The fiber content per cubic meter concrete was varied between 0.3%, 0.6%, 0.9% and 1.2%. This choice allowed working on economically viable fiber-reinforced concrete to democratize its use among professionals (Fritih, 2009).

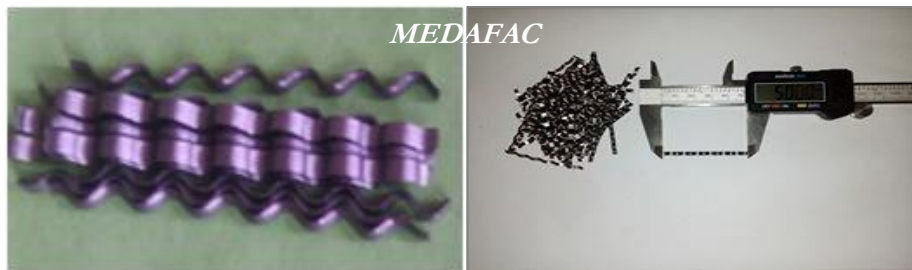


Figure 1. Corrugated steel fiber

Table 2. Geométrical and chemical composition characteristics of steel fibers MADAFAAC

Characteristics géométrical		Chemical Composition	
Shape	Corrugated	Carbon	0.08-0.12%
Length	50 mm	Manganese	0.8-1%
Width	2 mm	Silica	0.06%
Depth	0.6+0.09mm	Phosphorus	0.06-0.08%
Density	0.3	Souffre	00

Before accepting a composition as that of an SCC and before proceeding with the main part of the research program, the mixtures were first characterized in the fresh state to ensure that the fresh concrete properties obey certain criteria established according to the recommendations.

Namely, the characterization tests of fresh self-compacting concrete carried out in this work were Slump Flow test; Time Flow T500; J-Ring test; L-Box test (filling rate $H2 / H1$); V-Funnel test; Sieve stability test.

Hardened concrete

In order to promise the good quality of the composites in question, their characterization in the cured state was thus developed. The mechanical compressive and tensile strengths are essential characteristics of concretes and fundamental parameters of the study. Therefore they were evaluated for all the used concrete batches. These parameters were obtained by testing standard cylindrical specimens 16×32 cm. All samples were demoulded 24 hours after manufacture. They were then placed in ambient conditions of the laboratory until the time of the test, which takes place at 28 days and the days of the bending test.

Configure bending tests

The advantage of bending tests is that it gives a more realistic picture, of what is happening in many structural elements. So this part of our work was carried out to understand the mechanisms involved in the bending behavior of self-compacting concrete reinforced with steel fibers and assess the role that the diversity of the number of parameters involved can play. Three series of 36 beams were made with different types of concrete. Each series consisted of ordinary concrete beams without fibers and beams with self-consolidating concrete reinforced with varying volumes of steel fibers. All the beams have rectangular cross-sections of 10×20 cm and a length of 120 cm. The beams of the first series were made without any ordinary reinforcements, neither longitudinal nor shear reinforcements, but only with a variety of fiber volume fractions, 0%, 0.3 %, 0.6%, 0.9, and 1.2%. The beams of the second series were designed with a longitudinal reinforcement bed of T12 placed in the lower part of the beam with density $\rho_1 = 2.26\%$. Low-density constructive reinforcements were placed on the upper side of the beams to facilitate the placement of the

lower longitudinal reinforcements. Beams of the last series were made with transverse reinforcements with $\rho_t = 0.27\%$, whose function is to counter the shearing force. The concrete cover was kept constant and equal to 20mm for all test specimens. The test consisted of loading the beams to bending at three points under a progressive monotonic load until failure, with a shear span equal to 50cm and a depth shear span ratio a/d corresponding to 3.125 (see Figure 2).

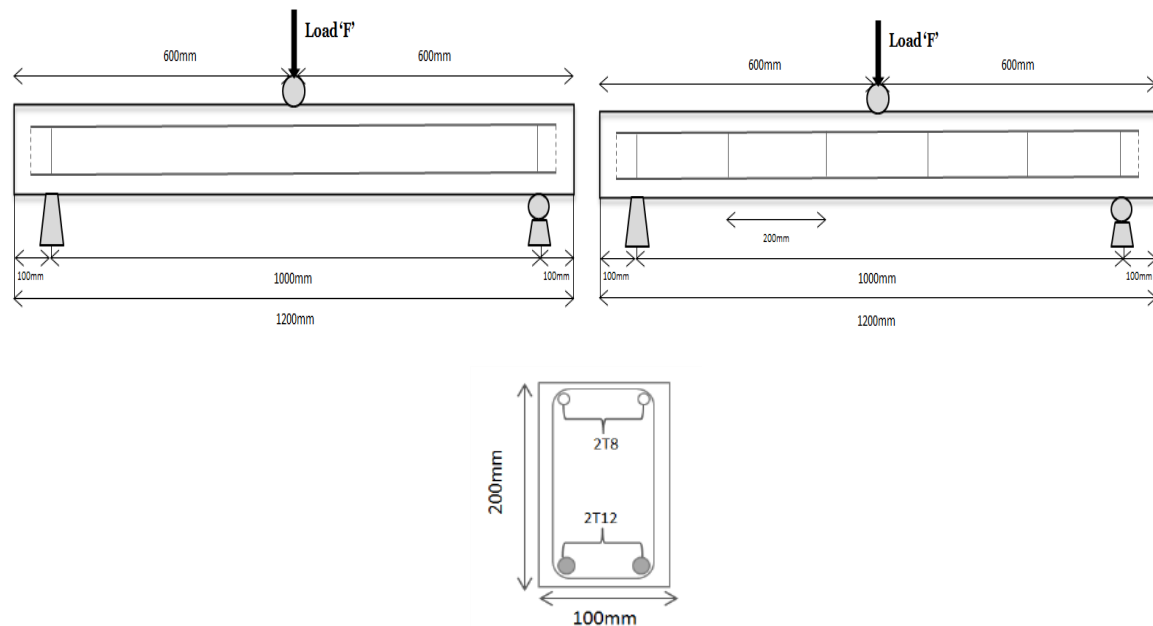


Figure 2. Geometric details of beams and configuration of the three-point bending

Table 3. Geometric and mechanical details of the tested beams

Beams ID	Concrete type	ρ_l (%)	Stirrups ρ_t (%)	Steel fiber rate (%)
Series 1				
NC S1	NC	0.00	0.00	0.00
SCC S1	SCC	0.00	0.00	0.00
SFSCC 0.3% S1	SFSCC	0.00	0.00	0.3
SFSCC 0.6% S1	SFSCC	0.00	0.00	0.6
SFSCC 0.9% S1	SFSCC	0.00	0.00	0.9
SFSCC 1.2% S1	SFSCC	0.00	0.00	1.2
Series 2				
NC S2	NC	2.26	0.00	0.00
SCC S2	SCC	2.26	0.00	0.00
SFSCC 0.3% S2	SFSCC	2.26	0.00	0.30
SFSCC 0.6% S2	SFSCC	2.26	0.00	0.60
SFSCC 0.9% S2	SFSCC	2.26	0.00	0.90
SFSCC 1.2% S2	SFSCC	2.26	0.00	1.20
Series 3				
NC S3	NC	2.26	0.27	0.00
SCC S3	SCC	2.26	0.27	0.00
SFSCC 0.3% S3	SFSCC	2.26	0.27	0.30
SFSCC 0.6% S3	SFSCC	2.26	0.27	0.60
SFSCC 0.9% S3	SFSCC	2.26	0.27	0.90
SFSCC 1.2% S3	SFSCC	2.26	0.27	1.20

The simply supported beams were tested at three-point bending, using a 200kN capacity hydraulic press, equipped with force and displacement sensors. The bending tests were displacement controlled with a speed of 0.2mm/s to ensure quasi-static conditions. The machine output data were deflections at the mid-span of the beams as a function of the applied load up to failure (see Figure 3).



Figure 3. Three-point bending test and Flexion test machine

Results

Fresh concrete properties

Table 4 summarizes the experimental results of the workability tests carried out for fresh self-compacting concrete. The D_m factor represents the average final diameter, while the element T500 represents the time required for the mixture to reach the 500mm gap circle in the flow test. The ratio H2/H1 represents the blockage of aggregates and fibers in the L-box test. Different effects of steel fibers addition on the properties of the SCC's studied, were noticed.

Table 4. Fresh tests results

Tests	Slump flow 	Time Flow T500	L-Box H2/H1 	V-Funnel 	Sieve- stability 	J-Ring 
Concrete Type						
SCC	740	3.00	1	10	9.3	740
SFSCC0.3%	700	4.21	1	10.96	10.6	700
SFSCC0.6%	660	5.84	0.9	39	11.21	640
SFSCC0.9%	600	6.62	/	/	12.06	590
SFSCC1.2%	570	6.73	/	/	13.15	540

Mechanical performance

Compressive strength

The results obtained from the compressive strength test are shown in Figure 4.

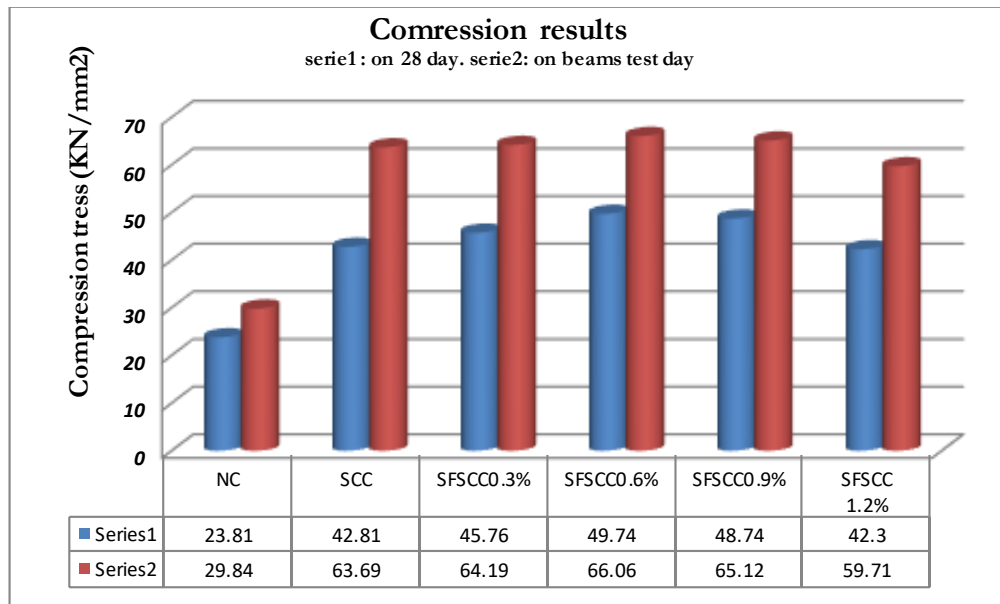


Figure 4.Compression test results

Splitting tensile strength

The results of tensile testing (splitting test) at age 28 are illustrated in Figure 5.

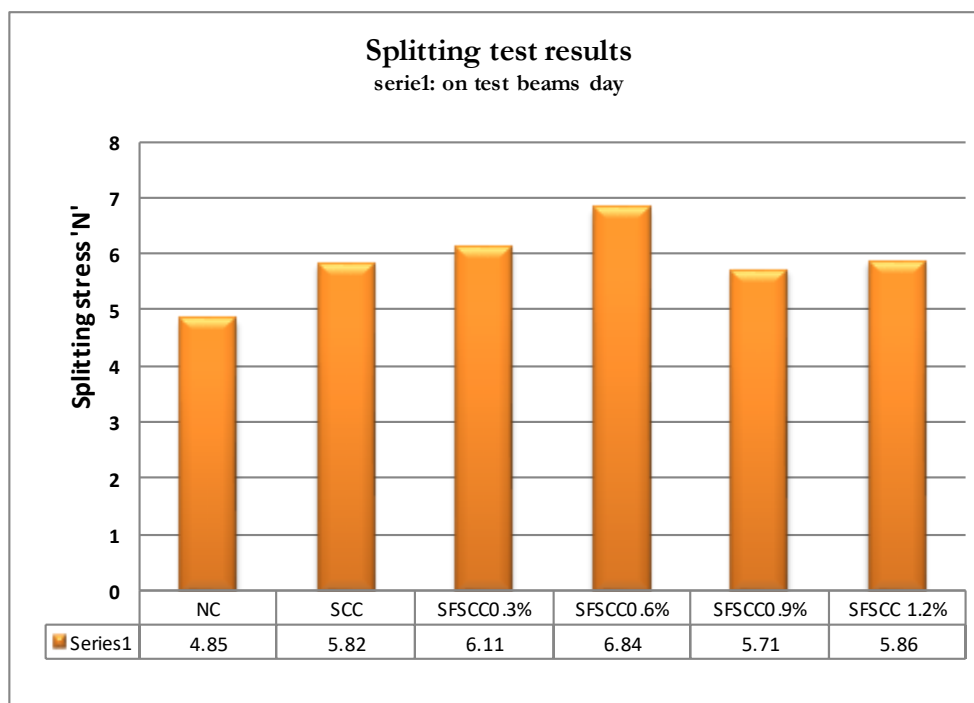


Figure 5.Splitting tensile test results

Bending tests

Lowest steel fibers volume tests beams

Load–Deflection relationships

Results of specimens reinforced with the lowest steel fibers ratios are illustrated in Table. 5., as well as in Figures 7 and 8.

Table 5. Bending tests Results of beams with lowest steel fibers ratios

ID Beam's	F_{els} (KN)	F_{Max} (KN)	δ_{els} (mm)	δ_p (mm)	δ_{max} (mm)	% $F_{NCS3-Max}$	% $F_{SCCS3-Max}$	$\delta_{max}/\delta_{els}$
NC								
NC S1	/	14.564	/	2.125	2.413	/	/	/
NC S2	36.252	36.252	2.826	2.926	2.954	/	/	1.045
NC S3	56.884	58.92	6.9796	8.926	10.634	/	8.299	1.524
SCC								
SCC S1	/	13.998	/	0.756	0.913	/	/	/
SCC S2	35.96	36.018	3.933	4.167	4.254	/	/	1.082
SCC S3	54.278	54.405	5.6196	7.046	7.127	-0.077	/	1.199
SFSCC 0.3%								
SFSCC 0.3 S1	10.84	10.84	2.536	2.536	3.726	-81.602	-80.075	1.469
SFSCC 0.3 S2	36.489	37.038	3.731	3.912	5.782	-37.138	-31.922	1.549
SFSCC 0.3 S3	53.503	67.245	4.851	6.701	7.817	14.129	23.601	1.611
SFSCC 0.6%								
SFSCC 0.6 S1	18.628	18.628	1.179	1.179	2.531	-68.384	-65.760	2.147
SFSCC 0.6 S2	61.996	65.563	5.8164	6.8401	8.231	11.275	20.509	1.415
SFSCC 0.6 S3	76.604	76.604	7.015	7.494	7.127	30.013	40.800	1.016

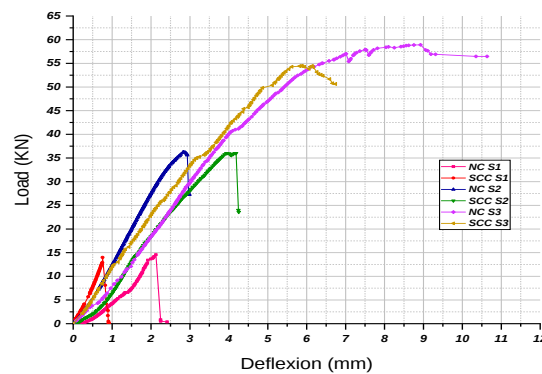
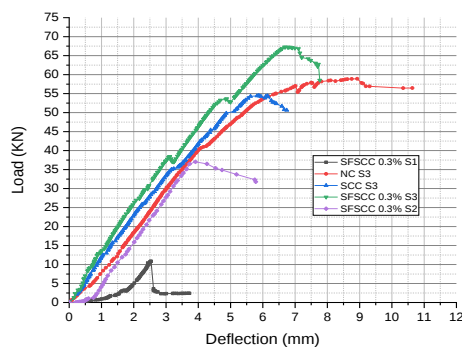
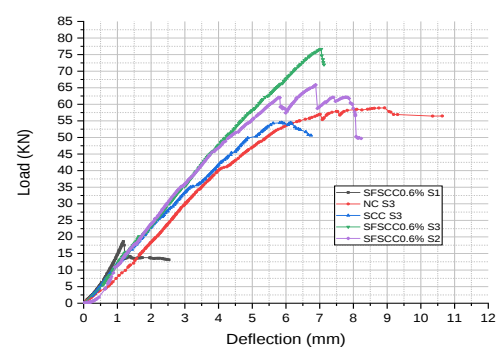


Figure 7. Load-mid span deflection curves of SCC & NC beams



a. SFSCC 0.3%



b. SFSCC 0.6%

Figure 8. Load-mid span deflection curves of tests beams with lowest steel fibers volume

Failure behavior

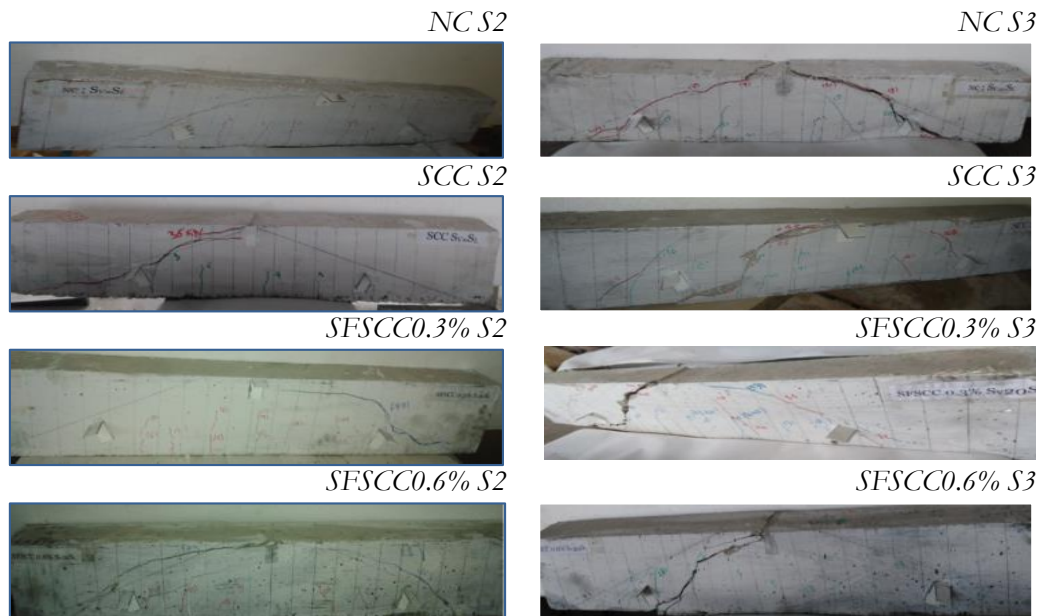


Figure 9..Cracking pattern of beams with the lowest rate of steel fibers

Figure 9 shown that shear failure is dominated for all of the beams reinforced with a low rate of steel fibers.

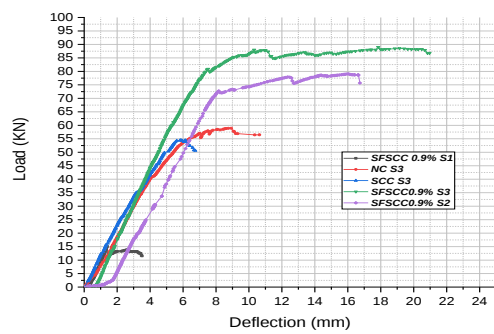
Highest steel fibers volume testes beams

Load–Deflection relationships

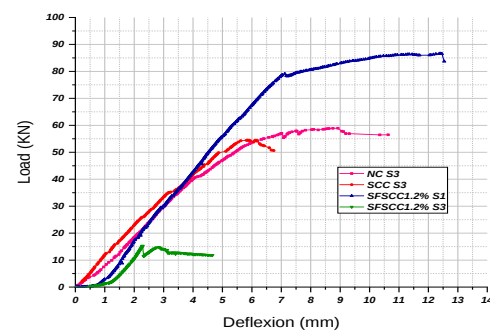
Figure 10 illustrates the bending capacity of beams, made with the highest volume of steel fibers, as a function of the displacement; the results are summarized in Table 6.

Table 6. Bending tests results of highest steel fibers volume

ID Beam's	F_{els} (KN)	F_{Max} (KN)	δ_{els} (mm)	δ_p (mm)	δ_{max} (mm)	% $F_{NCS3-Max}$	% $F_{SCCS3-Max}$	$\delta_{max}/\delta_{els}$
<i>SFSCC 0.9</i>								
SFSCC 0.9 S1	15.086	15.143	1.383	1.3879	3.512	-74.299	-72.166	2.539
SFSCC 0.9 S2	72.741	79.071	8.167	16.051	16.736	34.201	45.338	2.049
SFSCC 0.9 S3	80.68	87.999	7.454	10.317	20.966	49.353	61.750	2.813
<i>SFSCC 1.2 S1</i>								
SFSCC 1.2 S1	15.198	15.198	2.279	2.2786	4.659	-74.171	-72.065	2.044
SFSCC 1.2 S2	/	/	/	/	/	/	/	/
SFSCC 1.2 S3	78.733	86.597	7.0355	12.370	12.537	46.58	58.754	1.782



a. SFSCC 0.9%



b. SFSCC 1.2%

Figure 10. Load-mid span deflection curves of tests beams with highest steel fibers volume

Failure behavior

The cracking pattern and the failure mode for beams contain the highest volume of fibers are presented in Figure 11.

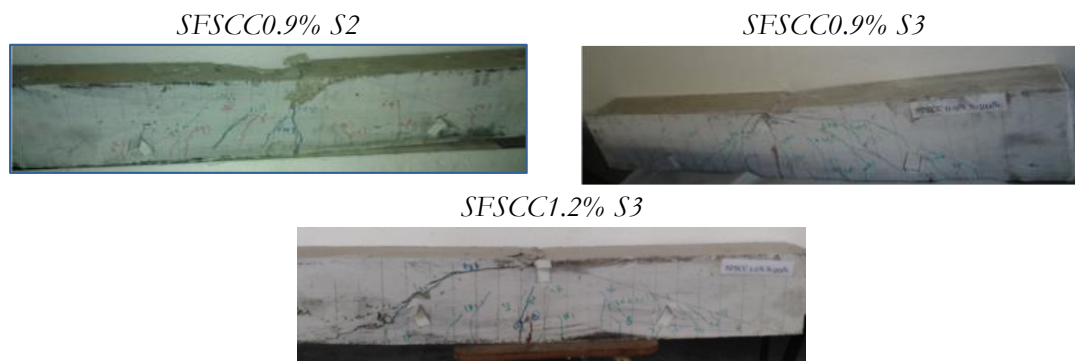


Figure 11. Cracking pattern of beams with the highest rate of steel fibers

Discussion

Fresh concrete properties

A decrease in the workability of the mixtures in question has been observed (Irki *et al.*, 2016; Zarrin *et al.*, 2016; Salem *et al.*, 2017; Mahir *et al.*, 2018; Khaloo *et al.*, 2014). It is easy to notice that the average diameters of the self-compacting concrete slabs obtained by the *Abram-Cone* test and the *J-Ring* test and the *H1/H2* ratio obtained from the *L-Box* test decreased with the increasing volume of added corrugated steel fibers. It should also be noted that the addition of steel fibers reduced the flow rate of SFSCC. The experimental results of the *V-Funnel* and *T500* tests revealed that when more fiber dosage is added, more increase in flow time. Despite the decrease in workability of the mixes when the steel fiber content is 0.3% and 0.6%, the workability parameters remain satisfying the requirements of the SCC according to recommendations.

The strengths of the properties in the SCC state are reflected when the fiber dosage is greater than 0.6%; this content could reach the upper limit of the workability of the SFSCC studied in the present investigation. (Yining *et al.*, 2012; Swamy *et al.*, 1976; You *et al.*, 2010) have shown the existence of a critical concentration of fibers beyond which the material cannot overflow despite its rheological characteristics. This same finding is reported by other researchers (Grunewald *et al.*, 2004) and (As'ad *et al.*, 2011), who has underlined the increased effect of metal fibers on the workability of SFSCC. Beyond a specific fiber concentration, the concrete becomes less dense and has more difficulty flowing between the reinforcements. According to (Salem *et al.*, 2017), the reason for the viscosity degradation of SFSCC for higher fiber content is the unit weight of the steel fibers. Thus, the cause of the decrease in flow acceleration, with the increasing their dosages, the fibers do not allow the aggregates to move more freely.

The addition of steel fibers in SCCs results in decreased workability since the mixes become less dense. This decrease is also influenced by the wavy shape of the fibers (Irki *et al.*, 2016). According to the findings of (Martinie *et al.*, 2010), the shape of the fibers contributed to the reduction of the flow of fiber-reinforced concrete. In addition, depending on the results observed at a higher steel fiber content, one should be aware of the sensitivity of applying these types of SCC to structural members.

Mechanical performance

For the SFSCC0.6% mixture, the maximum value reached at 28 days was 49.74MPa, while at 90 days, it was 66.06MPa, with a 16.27% gain in compressive strength. However, the compressive strength values decreased with 1.2% fiber content fiber (Khaloo *et al.*, 2014; Mohammadi *et al.*, 2008). The reduction in strength of SFSCC1.2% mixtures could be, due to the decrease in the workability of the concrete, as shown by the relevant value of the flow diameter of the slump (Salem *et al.*, 2017). The lower compressive strength of the samples may also be due, to the formation of more voids, at the fiber interfaces in the concrete matrix due to their shape.

It can be seen that the reference SCC mixture has the lowest tensile strength, compared to other samples, due to its highly fragile nature. However, the mix of SFSCC0.6% underlined the best result of 6.85KN, with a substantial gain of 17.52% compared to the control SCC. The mixtures of SFSCC 0.9% and SFSCC1.2% presented strengths similar to that of SCC, with ductile failure modes.

Bending tests

As showing in Figure7, there are no apparent differences between the behavior of the beams in SCC and those of ordinary concrete of the first series, and even distinctions for the samples of the second series of beams reinforced with longitudinal reinforcement, the bending resistance recorded for SCCS2 beams is 36.018KN and 36.252KN for NCS2 beams. While the bending capacity of NCS3 beams was better than that of the SCCS3 specimens, the detected breaking loads were 58.92KN respectively for the NCS3 samples, with a gain of 8.299% compared to the beams of SCCS3, of which a load of 54.405KN is recorded. This is due to a reduction in aggregate locking due to the lower content of coarse aggregates used in SCC, a typical quality of its own (Lachemi *et al.*, 2005). In terms of elasticity, the NC S3 specimen demonstrated better deformability; the recorded deflection maximum is 10.634mm with the ductility of 1.524, and 7.127mm” with the ductility of 1.016 for the SCCS3 beams.

The combination of longitudinal reinforcements with a low fiber density of 0.3% (Figure 8.a) does not improve the flexural strength of the SFSCC 0.3% S2 samples. Instead, it leads to a decrease in the breaking load of 31.92% compared to SCC S3 and 37.14% compared to NC S3. Flexural strength, plain or self-consolidating concrete with shear reinforcement, remains the better choice than SFSCC 0.3% S2.

A combination of 0.3% volume steel fibers with the transverse reinforcements improves the beams' bending capacity: an ultimate load value of 67.25KN was recorded, with a 23.60% gain than SCC S3 and 14.13% compared to NC S3. SFSCC0.3% S3 beams are more ductile than SCC S3, with a maximum deflection of 7.81mm and ductility of 1.611. They have almost the same ductility then NC S3 beams.

The addition of 0.6% of steel fiber (Figure 8. b) allowed an increase of the ultimate resistance and the ductility of the beams of SFSCC 0.6% S2 compared to SCC S3. Again in terms of a load of order, 20.51% and a maximum deflection of 8.23 were recorded. In addition, it is conceivable to replace the transverse reinforcements in the SCC beams with this fiber rate. Regarding the comparison to NC S3 beams, the ductility of the latter remains the best.

Failure behavior

Mechanisms governing the failure mode, and the stiffness of the beams with a low rate of fibers, designed in this experimental investigation, are also reported in Table 7.

Table 7. Mode of failure of the tested beams reinforced with the lowest rate of steel fibers

Beams	First crack load (KN)	Number of cracks	Break way
NC S2	9.243	06	Oblique stress shear failure
SCC S2	9.536	04	Shear failure due to loss of adhesion between concrete and longitudinal steels
SFSCC0.3% S2	/	11	Oblique stress shear failure
SFSCC0.6% S2	10.8097	09	Oblique stress shear failure
NC S3	8.052	14	Shear failure due to loss of adhesion
SCC S3	8.8097	14	Shear failure due to loss of adhesion
SFSCC0.3% S3	9.1907	14	Shear failure due to loss of adhesion
SFSCC0.6% S3	11.213	17	Shear failure due to loss of adhesion, with the creation of several cracks

A brittle shear failure mode was observed for most tested beams, but it was more pronounced for the reference NC and SCC beams; the failure was accompanied by a very little warning of the eminent shear failure, SCC beams present less tight cracking beam compared to the NC beam. SCC beams are slightly less ductile than regular concrete beams.

Although most beams demonstrated shear failure, the crack patterns for the beams were markedly different. Two types of shear failure were distinguished, by oblique stress shear failure, and for most samples by shear failure due to loss of adhesion. The width of the crack of the beams without the fibers was more pronounced even in the presence of the transverse reinforcement; this crack even matched in the beams reinforced with fibers for higher loads.

It should be noted that the presence of fibers, however, also allowed the development of multiple diagonal cracks and the widening of at least one of them before a shear failure and a cracking pattern developed, first, in the area between the supports, before the diagonal crack had appeared and widened.

Subsequently, a 0.9% fiber addition resulted in a high yield of SFSCC specimen (Figure 10.a); this rate increased the bending capacity and improved the ductility of the beams significantly. It made it possible to increase the ultimate loads of SFSCC0.9% S2 beams. The gains are 45.34% compared to SCC S3 and 34.20% compared to beams in NC S3. The peak deflection recorded is 16.05mm. The volume of 0.9% made it possible to replace the shear reinforcements.

Beams of SFSCC 0.9% S3 assigned performance importantly. There is a gain of 61.75% for SCC S3 beams and 49.35% for NC S3 beams, with a maximum deflection of 20.97mm. The coupling of transverse reinforcement with fibers embodied a significant role in increasing the flexural strengths of test beams, which (Zhiguo *et al.*, 2010; Ding *et al.*, 2012) had also approved.

The combination of transverse reinforcement and fibers at a volume of 1.2% had a significant influence on the increase of the bending strengths of the test specimens (Figure 10.b). SFSCC1.2% S3 beams showed a high efficiency since it has been noted a gain of 58.754% compared to SCC S3 beams and 46.58% compared to NC S3 beams a maximum deflection of 12.54mm and a ductility of 1.78.

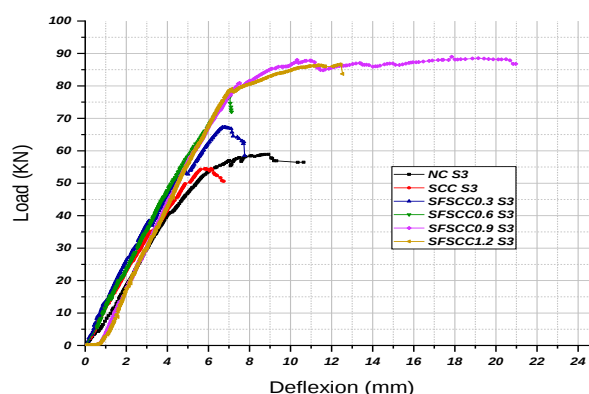


Figure 12. Load-mid span deflection curves of testes beam with shear reinforcement

It emerges very clearly from the above curves (Figure 12) that the load-strain relationship of the beams is modified due to the presence of fibers in the SFSCC mixture. The addition of the fibers ensured a significant increase in the breaking load and an improvement in ductility. Furthermore, this increase in the bending strength of SFSCC beams has been linked to the increase in the volume of the steel fibers (Kannam *et al.*, 2018; Zhiguo *et al.*, 2010; Ding *et al.*, 2012; Zarrin *et al.*, 2016). A better gain is recorded in the case of SFSCC 0.9% S3.

Despite the gain in breaking load noted by the SFSCC 1.2% beams, compared to the SCC S3 and NCS3 beams, this effect remains insignificant to that recorded by the SFSCC 0.9% beams, especially after the remarkable workability degradation by adding this volume fraction. We can afford to see a limit in fiber density where beyond this fraction, no further improvement is contributed, but instead, additional costs are recorded, even distinctions (Aoude *et. Cohen*, 2014).

Failure behavior

More details of the cracking pattern and the failure mode, for beams containing the highest volume of fibers are presented in Table 8.

Table 8. Mode of failure of the tested beams reinforced with the highest rate of steel fibers

Beams	First crack load (KN)	Number of cracks	Break way
SFSCC1.2%S3	13.459	17	Shear failure with compression of concrete: the delayed shear crack appeared after the appearance of several bending cracks
SFSCC0.9%S2	12.064	17	Flexural failure
SFSCC0.9%S3	12.542	19	Flexural failure

The failure mode gradually changed, from brittle shear failure for the control concretes and SFSCC0.3% as well as for SFSCC0.6%, into ductile bending failure by increasing the fiber dosage to 0.9%, with even denser crack pattern “multiple cracking” compared to the SCC specimen (Dinh *et al.*, 2010; Aoude *et al.*, 2008; Ding *et al.*, 2012). The addition of steel fibers in an adequate percentage leads to change the failure mode, from a brittle shear collapse to a ductile bending failure mechanism (Ding *et al.*, 2012; Kannam *et al.*, 2018; Mohammadi *et al.*, 2008), which has been approved in this present study at a fraction of 0.9%.

The results reveal that the fibers limited the rise of the crack front towards the compressed part of the section. The same results were obtained by (Fritih 2009).

Shear crack openings (diagonal cracks) were considerably restricted by the presence of fibers (Fritih *et al.*, 2013; Casanova, 1996). As well as a late appearance of the latter (Ding *et al.*, 2010; Ding, Y *et al.*, 2011; Fritih, 2009), this type of crack develops for higher forces (Ding, Y *et al.*, 1999-2010); however, the orientation of the diagonal cracks do not appear to be influenced by the action of the fibers.

Closer cracks have been observed in fiber-reinforced beams than in those without fibers (Mahir *et al.*, 2018). The spacing of cracks under the same load decreased with increasing fiber content (Ding *et al.*, 2010). This may be explained by the ability of fibers to transfer stresses to concrete through a crack (Fritih *et al.*, 2013).

The well-distributed fibers in the beam acting as a three-dimensional net can also transfer tensile force (Boulekbache *et al.*, 2010). Therefore, the post-crack behavior of steel fiber reinforced beams shows a significant improvement over SCC and NC without reinforced with transverse reinforcement (Ding *et al.*, 2012). Steel fibers became effective after cracking, with more uniform stress redistribution over the cracking region, and continued to resist tensile stresses until they were torn off (Fritih *et al.*, 2013; Mahir *et al.*, 2018).

Combining shear reinforcement and steel fibers have demonstrated a positive hybrid effect on deformability performance (Kannam *et al.*, 2018; Zhiguo *et al.*, 2010).

According to the results of this work, specific standards in the fresh state for fiber-reinforced concrete have been recommended better to use the latter (Kassimi, 2008).

Conclusion

Various observations were recorded in this study. A decrease in the workability of the blends in question was observed gradually, with the increase in the fiber content. The mixtures become less viscous. Despite

the decrease in the workability of the mixes, when the steel fiber content is 0.3% and 0.6%, the workability parameters remain following the requirements of the SCC according to 'the recommendations'. The strengths of the properties in this state of SCC are reflected when the fiber dosage is more significant than 0.6%. The maximum value of compressive strength was compared for SFSCC0.6%, with a 16.27% gain in compressive strength. However, the compressive strength values decreased when the fiber content was 1.2%. The combination of longitudinal reinforcement with a low fiber density of 0.3% did not intercede to improve the bending strength of the SFSCC0.3% samples but rather a breaking load loss. Flexural strength, plain or self-consolidating concrete with shear reinforcement, remains the better choice than SFSCC0.3%.

Combined, the 0.3% volume steel fibers with the transverse reinforcements highlighted an improvement in the bending capacity of the beams. SFSCC0.3% S3 specimens are more ductile than SCC S3 ones but are less ductile than NC S3 beams. Addition of 0.6% fiber volume made it possible to raise the ultimate resistance of SFSCC 0.6% S2 beams, comparing to SCC S3 ones. Therefore this fiber's rate is sufficient to replace the transverse reinforcements in terms of resistance. Subsequently the addition of 0.9% of fibers assigned a high yield for the SFSCC specimens. This volume increased the bending capacity, improved the ductility of the beams significantly, and changed the failure mode from brittle mode to ductile mode. Thus it is clear that this fiber rate can replace the transverse reinforcements. Coupled reinforcement of transverse reinforcement and fibers embodied a significant role in increasing the bending strengths of the designed beams. Despite the gain in breaking load emphasized by SFSCC beams 1.2%, compared to SCC S3 and NC S3 beams, this effect remains insignificant compared to that recorded by SFSCC0.9% beams, unlike the ductility where the arrow is very limited. Also, degradation in workability is marked by the addition of this volume fraction. SCC beams are slightly less ductile than ordinary concrete beams. The use of fibers with densities of 0.3% and 0.6% was not sufficient to transform the failure mode of beams. The Crack pattern under the same load is widened with increasing fiber content; this can be explained by the ability of fibers to transfer stresses to concrete through a crack. The combination of shear reinforcements and steel fibers has demonstrated a positive hybrid effect on the deformability performance.

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