FRC MATERIALS: SOME ISSUES FROM THE EXPERIMENTAL BEHAVIOUR IN COMPRESSION AND FLEXURE

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Abstract

In this paper the results obtained from compression and four-point bending tests carried out on Steel Fibre-Reinforced Concrete (SFRC) specimens according to UNI 11039 (2003) are critically examined. The objectives of this research are: to analyse and compare the experimental behaviour in compression and in tension in terms of peak load, post-peak behaviour and residual strength; and to assess fibre contribution and distribution in Mode I – fracture of SFRC material. It is shown that plain concrete and fibre concrete have a comparable peak load/strength but the post-peak response of fibre concrete exhibits a more extended softening branch with a significant residual strength and increased fracture energy compared to those of plain concrete.

Keywords: Bending tests, Compression tests, Fibre reinforced concrete materials, Post-peak behaviour.

1 Introduction

Fibre-Reinforced Concrete (FRC) is a cementitious composite whose behaviour is improved by means of the activation of fibre pull-out mechanism. The mechanical behaviour of this material is influenced by the properties of each component and of many parameters as mix design, cast procedures and member geometry. In particular, when fibres are added in a concrete mix, their type, shape, aspect ratio (L_f/D_f) and volume content (V_f) play an important role (Swamy and Mangat, 1974). Consequently, the structural design based on the use of FRC requires the knowledge of the mechanical and fracture properties.

When FRC came on the stage in the ’70s and ’80s and, the enhanced mechanical properties due to fibres were first tentatively evaluated by using the mixture law. However, the general applicability of this approach was questionable, because of the several empirical coefficients that had to be introduced to take into account the shape, the length and the orientation of the fibres; since some of the parameters were not well defined, only qualitative conclusions could be drawn. Further investigations suggested to consider FRC

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as a single material characterized by a residual strength (both in tension and in compression), whose values had to be identified by means of suitable tests.

In order to give a contribution to this topic, at the University of Calabria a set of compression tests on cube and cylinder specimens loaded uniaxially, and four point bending tests on prismatic notched specimens were carried out. The influence of steel fibre contents on some of the major parameters namely peak load, peak stress and post-peak response were analyzed in compression and in tension. The distribution of the steel fibres on the specimen's fracture surface was also evaluated for estimating the consistency and quality of Steel Fibre-Reinforced Concrete (SFRC) materials and its influence on the mechanical tensile parameters. The main idea is also to prove how it could be possible to produce and place on site FRC materials with significant fibre contents with high toughness. This paper is a part of an extensive experimental/theoretical study on the overall behaviour of FRC material and structural members (Bencardino et al., 2008a; 2008b).

2 Specimen geometry and test programme

The experimental investigation was carried out on cubes, cylinders and notched prisms made from plain concrete (PC) and SFRC. The volume fractions of steel fibres were 1%, 1.6% and 3%. In each group of tests, the specimens were indicated by means of a set of letters and numbers (PC=ordinary-concrete; S1%, S1.6%, S3%=reinforced-concrete with 1%, 1.6%, 3% of steel fibre content). Each set of letters and numbers was followed by a number like 1, 2, and 3, for the identification of each particular specimen. Three tests were carried out for each concrete mix and test specimen size.

2.1 Details of materials, concrete mix design, casting and curing

The following components were used: Portland cement ASTM type I, crushed coarse aggregates, quartz sand, water, condensed silica fume and superplasticizer. The maximum size of the coarse aggregates was 15 mm. The steel fibres have hooked ends, a tensile strength of 350-400 MPa, a length of 22 mm, and an aspect ratio of 40. Table 1 shows the PC, and SFRC (S1%, S1.6% and S3%) composition for 1m^3 of concrete batch. Plain concrete was designed for a 28-day cubic strength of 65 MPa. The actual compressive strength varied between 64 and 70 MPa. In order to obtain a cohesive and flowable mix and a uniform fibre distribution, gap-grading of the aggregates was avoided. When fibres were added to the mix, the same weight of coarse aggregate was removed to keep the same fineness modulus. The mixes were prepared by using a conventional mixer. The prismatic specimens were cast by filling the moulds according to UNI 11039-2 (2003), and then were vibrated on a shaking table. All test specimens were removed from the moulds after 24 hours and were cured for 27 days under water- saturated sand.

2.2 Test procedure

The compressive strength tests were carried out at 28 days on 150mm cubes and 150x300mm cylinders, according to UNI EN 12390-3 (2003). A Zwick/Roell servo hydraulic closed-loop test machine with a capacity of 3000kN was used. The loads were increased at a rate of 0.05mm/min. Three HBM WA20 LVDTs with a gauge length of

100mm were used to measure strains on the cylindrical specimens. They were mounted at 120-degree intervals on a circular tie placed on the specimen surface at 100mm from the top of the specimen. A second tie was placed on the specimen at 100mm from the bottom and provided the reaction frame for the three LVDTs. Each tie was made of two aluminium half rings connected by springs. These aluminium ties were able to support the measuring devices, to allow lateral deformations when they occurred, and did not give confinement effect on the specimens.

The bending tests were performed at 28 days on 150x150x600mm prismatic specimens, according to UNI 11039 (2003). A single notch with a depth of 45mm was sawn at mid-span to allow the crack to localize. The displacement rate of the crosshead testing machine was 0.05mm/min. A 100kN INSTRON 1195 electromechanical testing machine fitted up with a 100kN C1 HBM load cell was used. The vertical displacement was measured in the mid-span section by means of two LVDTs placed along the front and back faces of each specimen. The transducers were fixed to a rigid yoke in order to minimize the effect of the rotations during the test. Furthermore, two LVDTs were placed at the notch tip on the two faces of the specimen to measure Crack-Tip Opening Displacement (CTOD). The Crack-Mouth Opening Displacement (CMOD) was measured as well, by a TML resistive full bridge transducer astride the notch. In all tests, data acquisition and signal control were carried out by using an HBM Spider 8 control unit.

Tab. 1 Mixture proportion – per cubic meter of concrete

Material	Symbol	Unit	PC	SFRC		
				S1%	S1.6%	S3%
Cement	c	(kg)	500	500	500	500
Quartz	q-0/2mm	(kg)	377	377	377	377
	q-3/6mm	(kg)	273	273	273	273
Aggregate	a-0/5mm	(kg)	693	615	567	458
	a-5/10mm	(kg)	290	290	290	290
	a-10/15mm	(kg)	317	317	317	317
Fibre	-	(kg)	-	78	126	235
	V_f	(%)	0	1	1.6	3

Silica fume	-	(kg)	30	30	30	30
	sf/c	(%)	6	6	6	6
Superplasticizer	-	(kg)	7.5	7.5	7.5	7.5
	sp/c	(%)	1.5	1.5	1.5	1.5
Water	-	(l)	175	175	175	175
	w/c	-	0.35	0.35	0.35	0.35

3 Test results and analysis

3.1 Compressive strength

The strength test results are summarized in Tables 2 and 3. The graphical representation of the typical stress-strain curves is shown in Figure 1. Test results confirm that the addition of fibres, compared to plain concrete, affects the compressive strength value only slightly but influences the post-peak response in a more positive way. The mean value of the ratio between the cylinder and the cube compressive strength is 0.93. Concrete reinforced with a medium content of steel fibres (V_f=1%) shows only a minor improvement in the descending or softening branch of the stress-strain curve compared to plain concrete. Concretes reinforced with higher contents of fibres (V_f=1.6%, 3%), on the other hand, show a more extended softening branch. The ultimate strain reached values of about 0.012 to 0.018 for SFRC with 1.6% and 3% of fibre content, about five times the ultimate strain of plain concrete. It is worthwhile to note that SFRC with 1.6% and 3% of fibre content have a residual stress of about 74% and 78% respectively of their peak stress at a strain of 0.01. These results also highlight that the most predominant role of steel fibres is to modify the failure mode of plain concrete from a brittle to a more ductile failure pattern. The post-test aspects of the failed specimens showed that, in the case of plain concrete, either a single shear plane or a cone-type failure occurred. By contrast, SFRC specimens showed a large number of longitudinal cracks near the failure zone, which were oriented in the parallel or nearly parallel direction to the applied compressive stresses.

Tab. 2 Cube compressive strength

	R_c
	MPa
PC_1	75.5
PC_2	67.9

Tab. 3 Cylinder compressive strength

	f_c
	MPa
PC_1	64.1
PC_2	66.3

PC_3	71.1	PC_3	69.8
Mean	71.5	Mean	66.7
S1%_1	69.8	S1%_1	67.2
S1%_2	79.0	S1%_2	71.9
S1%_3	73.6	S1%_3	69.8
Mean	74.2	Mean	69.6 (+4.3%)
S1.6%_1	62.8	S1.6%_1	61.1
S1.6%_2	54.3	S1.6%_2	55.7
S1.6%_3	64.5	S1.6%_3	57.7
Mean	60.5	Mean	58.1(-12.9%)
S3%_1	64.4	S3%_1	59.8
S3%_2	62.8	S3%_2	54.2
S3%_3	61.2	S3%_3	61.5
Mean	62.8	Mean	58.5 (-12.3%)

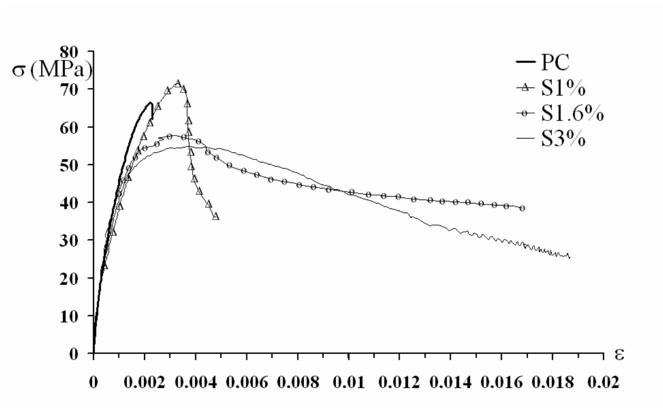


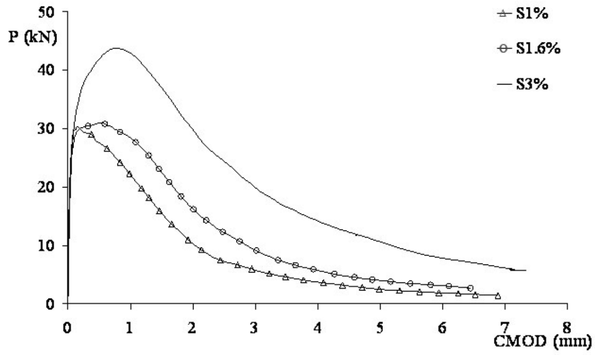
Fig. 1 Typical stress-strain curves of cylindrical specimens

3.2 Bending tests and tensile strength parameters

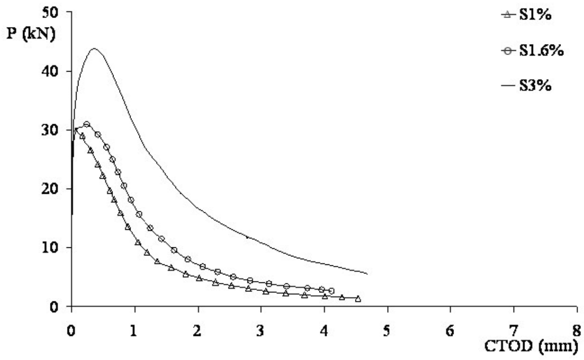
The behaviour of PC specimens was linear-elastic up to failure; thereafter the complete separation of each specimen into two parts occurred. The typical load-CMOD, load-CTOD, and load-deflection curves of the SFRC specimens are shown in Figure 2.

CTOD values are the average values between the front and rear measurements. The SFRC curves typically show a linear branch up to first cracking. Close to the peak load, there is stable crack propagation because of the favourable effects that the fibres have on the ligament. Beyond the peak load, there is a mechanical decay that is more or less pronounced depending on fibre content. As micro cracks coalesce into macro cracks, hooked-end fibres become increasingly efficient in crack bridging. The larger the fibre content, the higher the peak load. In fact, concrete specimens with medium content of steel fibre (V_f=1-1.6%) showed an increase of about 19-20% while in those with higher content (V_f=3%) the increase is about of 72%, compared to PC specimens. The residual load evaluated at the CTOD value of 3mm is about 9%, 13% and 11% of the peak load for V_f=1%, 1.6% and 3%. These results make it possible to directly compute the fracture energy, as the area underneath the load-deflection curve or indirectly from the load-crack opening displacement curve. To obtain comparable results the long softening branch should be truncated at the same point. The area under the load-deflection curve evaluated by referring to a limit displacement value of 3.00mm is higher by about 48% in the case of medium content of fibre (V_f=1.6%) and is three times for higher content (V_f=3%) compared to SFRC with 1% of steel fibre content.

According to UNI 11039-2 (2003), the following parameters have to be evaluated in order to describe SFRC behaviour in tension: the load (P_{If}) and the strength (f_{If}) at first cracking, the equivalent strengths ($f_{eq(0-0.6)}$, $f_{eq(0.6-3)}$) and the ductility indexes (D_0, D_1). The nominal strength at first cracking represents the behaviour of the cementitious matrix and, according to UNI 11039-2 (2003), can be computed by means of the expression: $f_{If} = \frac{P_{If}\, l}{b(h-a_0)^2}$ (MPa). Where b (150mm), h (150mm), l (450mm) are the width, height and span of the specimen, respectively; a_0 (45mm) is the depth of the notch; and P_{If} is the value of the load recorded for a Crack-Tip Opening Displacement equal to $CTOD_0$. The parameters $f_{eq(0-0.6)}$ and $f_{eq(0.6-3)}$ are the average nominal stresses in the CTOD range between 0 and 0.6mm, and in the range between 0.6mm and 3mm, respectively. These two parameters are the post-cracking equivalent strengths to be used at the serviceability limit state and at the ultimate limit state, respectively. These parameters can be computed by using the following expressions: $f_{eq(0-0.6)} = \frac{l}{b(h-a_0)^2}\frac{U_1}{0.6}$; $f_{eq(0.6-3)} = \frac{l}{b(h-a_0)^2}\frac{U_2}{2.4}$. Where U_1 and U_2 should be evaluated from the following expression: $U_1 = \int_0^{0.6} P(CTOD)\, d(CTOD)$; $U_2 = \int_{0.6}^{3} P(CTOD)\, d(CTOD)$. The ductility indexes can be calculated by: $D_0 = \frac{f_{eq(0-0.6)}}{f_{If}}$; $D_1 = \frac{f_{eq(0.6-3)}}{f_{eq(0-0.6)}}$. All these expressions were formulated by assuming a linear distribution for the stresses acting on the cross section. The values of the above parameters are given in Table 4. The load/strength values at first cracking are similar for any fibre content. The equivalent strengths $f_{eq(0-0.6)}$ and $f_{eq(0.6-3)}$, and the ductility indexes D_0 and D_1 increase when fibre contents increase.



a)



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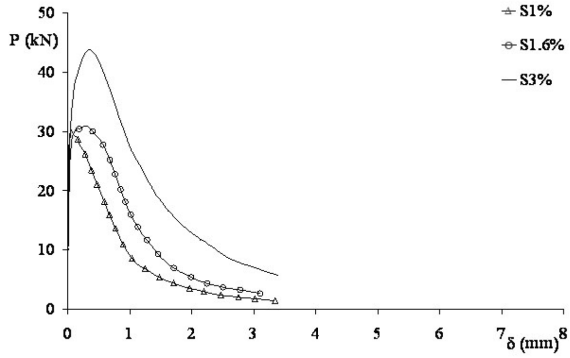

c)

Fig. 2 Bending tests, typical curves: load-CMOD (a); load-CTOD (b); and load-deflection (c)

3.3 Fibre distribution on fracture surface and toughness

In order to evaluate the effect of fibre dispersion in the matrix, as governed by the fresh state properties of concrete through the casting process, on the mechanical performance of the fibre reinforced composite, per each of the three mix described, the specimen's fracture surface of the notched prismatic specimens was discretized in four rows and five columns cells, as it presented in Figure 3 (a). The average number of fibres counted that were visible on the fracture surface is presented in Figures 3 (b) and 3 (c). Quite uniform fibre distributions were obtained without a pronounced fibre percentage in the casting direction.

Tab. 4 Bending tests: first crack and post cracking equivalent stresses, toughness indicators and specific number of fibres on the fracture surface

	P_{If}	f_{If}	$f_{eq(0-0.6)}$	$f_{eq(0.6-3)}$	D_0	D_1	Specific n.
	kN	MPa	MPa	MPa	-	-	fibres/cm^2
S1%_1	24.6	6.7	7.1	2.0	1.1	0.3	0.67
S1%_2	25.5	6.9	5.3	1.8	0.8	0.3	0.69
S1%_3	24.5	6.7	5.5	1.2	0.8	0.2	0.65
Mean	*24.9*	*6.8*	*6.0*	*1.7*	*0.9*	*0.3*	*0.67*
S1.6%_1	20.3	5.5	7.9	2.8	1.4	0.4	1.02
S1.6%_2	20.1	5.5	7.7	2.8	1.4	0.4	1.21
S1.6%_3	22.4	6.1	7.4	2.6	1.2	0.4	1.08
Mean	*20.9*	*5.7*	*7.7*	*2.7*	*1.3*	*0.4*	*1.10*
S3%_1	24.1	6.6	15.1	8.7	2.3	0.6	2.58
S3%_2	30.6	8.3	11.0	4.8	1.3	0.4	2.20
S3%_3	24.5	6.7	11.2	5.7	1.7	0.5	2.04
Mean	*26.4*	*7.2*	*12.4*	*6.4*	*1.8*	*0.5*	*2.27*

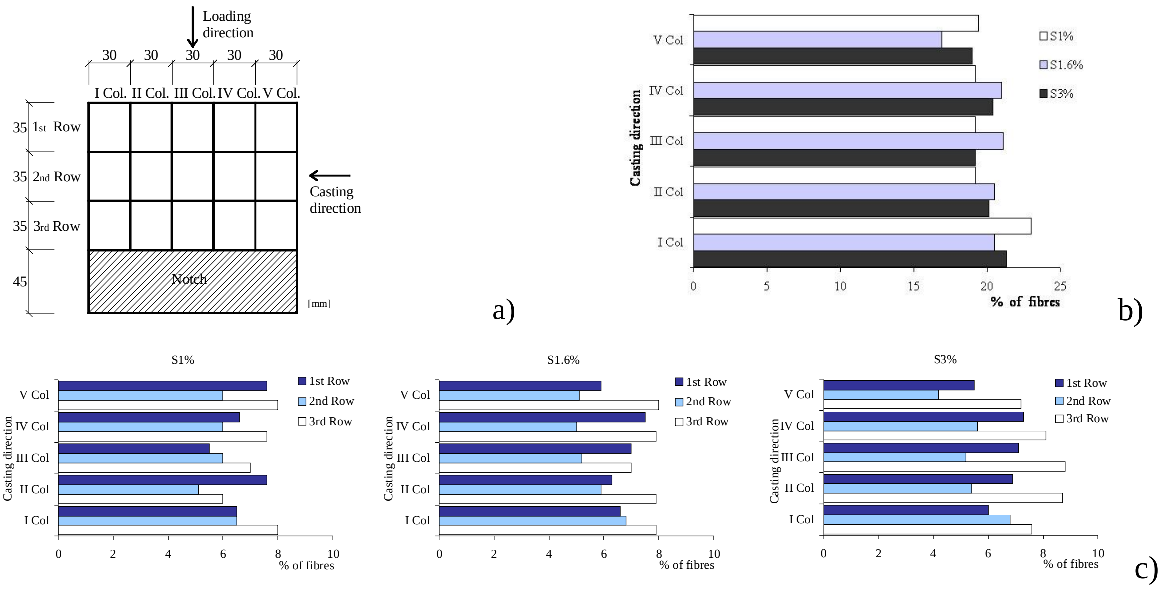

Fig. 3 Prismatic specimens: discretization of the specimen's fracture surface (a); average fibre distribution (b) and (c)

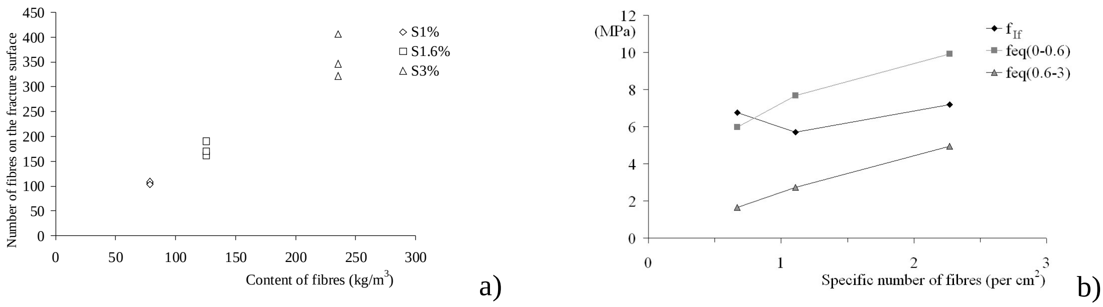

Fig. 4 Relationship between: content vs. number of fibres (a); specific number of fibres

vs. tensile strength parameters (b)

In fact a uniform crack opening on the two faces of the specimens was developed. As it was expected, the number of fibres on the fracture surface increased with the content of fibres (Fig. 4 (a)). The first cracking and the post-cracking equivalent stresses were plotted versus the number of the fibre on the fracture surface (Fig. 4 (b)). The post-cracking equivalent strengths show a quite linear relationship with the fibre content while the first crack strengths exhibit an almost constant relationship.

4 Conclusions

From this study, the following major conclusions can be drawn:

- The addition of fibres does not significantly affect the compressive strength of concrete. The increase in fibre content improves the post-peak behaviour and a more extended softening branch is observed.
- SFRC specimens with fibre content of 1.6% and 3% show, at 0.01 strain, a residual stress of about 74% and 78% of their respective peak stresses. At these fibre volumes, the ultimate strain at failure reaches values of three to five times the ultimate strain values fixed by current guidelines.
- The use of medium-high steel fibres contents significantly improves the post-peak behaviour in tension, by extending the softening branch and reducing the negative slope. Hooked steel fibres give to the concrete a sizable post-peak residual strength. As a result the enhanced toughness given by the fibres results in a greater structural robustness under unexpected or extreme load situations, especially in statically-redundant structures.
- The data obtained emphasize that, through correct mix design, consistent quality of fibre concrete can be produced and placed in the field.

References

[1] Bencardino, F., Rizzuti, L., Spadea, G., Swamy, R.N.: *Stress-strain behavior of steel fiber reinforced concrete in compression*, ASCE, Journal of Materials in Civil Engineering, Vol. 20, No. 3, pp. 255-263, 2008a

[2] Bencardino, F., Rizzuti, L., Spadea, G.: *Three-versus four- point bending tests: an experimental investigation on steel fiber- reinforced concrete*, Studies and Researches, Graduate School in Concrete Structures – Fratelli Pesenti, Politecnico di Milano, Italy Vol. 28, pp. 133-155, 2008b

[3] Swamy, R. N., Mangat, P. S.: *Influence of fiber geometry on the properties of steel fiber reinforced concrete*, Cement and Concrete Research, Vol.4, pp. 451-456, 1974

[4] UNI 11039-1: *Steel Fibre Reinforced Concrete - Definitions, Classification and Designation*, 2003

[5] UNI 11039-2: *Steel Fibre Reinforced Concrete - Test Method for Determination of First Crack Strength and Ductility Indexes*, 2003

[6] UNI EN 12390-3: *Testing Hardened Concrete - Compressive Strength of Test Specimens, 2003*