Effect of Steel Fiber Volume on Fiber Reinforced Concrete Post-Cracking Behavior

V. Corinaldesi[1] and G. Moriconi[2]

ABSTRACT: In structural elements steel fibers can be used instead of or in addition to reinforcing bars, in order to bear tensile loads. The addition of steel fibers to plain concrete changes its mechanical behavior, since, depending on the type and amount of fibers, an increase in ductility can be achieved. Hooked steel fibers were employed for reinforcing concrete at different dosages in order to evaluate their effect on the post-cracking behavior of concrete. The fiber reinforced concrete was characterized at the fresh state by means of slump test, and after hardening by means of compression, tensile and bending tests. In every case, for equal strength class mixtures, the same first cracking strength was obtained whichever the dosage of fibers. On the other hand, softening or hardening post-cracking behavior was detected depending on the amount of fibers. In order to quantify this effect, toughness was calculated for each mixture, with the aim of identifying the critical volume of fibers.

1 INTRODUCTION

Structural elements made of steel fiber reinforced concrete are becoming increasingly common. Indeed, steel fibers dispersed in the cement matrix allow to limit the concrete brittleness and induce some ductility in the concrete itself, besides definitely increasing its durability and toughness. The addition of steel fibers to plain concrete does not significantly contribute to improve its mechanical behavior before cracking nor its compressive strength. The advantages originated by fiber addition are evident only after concrete cracking, since fibers are able to bridge cracks, allowing concrete to develop a residual strength. However, this residual strength depends on the fiber volume introduced in the concrete mixture (Velazco et al. 1980, di Prisco et al. 2009), which affects the post-cracking behavior of the fiber reinforced concrete (FRC), by changing it from softening to hardening when the fiber volume exceeds a critical value.

In this work, hooked steel fibers were used for reinforcing concrete at different dosages in order to evaluate their effect on the post-cracking behavior of concrete, tested for both a low and a high concrete strength class. Steel fibers were added to the concrete mixtures by replacing the same volume of coarse aggregate, and the same workability level was guaranteed for all the mixtures. The steel fiber reinforced concretes were characterized at the fresh state by means of slump test, and after hardening by means of compression, tensile and bending tests.

In every case, for equal strength class, the same first cracking strength was obtained whichever the dosage of fibers. On the other hand, softening or hardening post-cracking behavior was detected depending on the amount of fibers. In order to quantify this effect, toughness was determined for each concrete mixture. On the basis of the results

[1] *Assistant Professor, Università Politecnica delle Marche, Ancona, v.corinaldesi@univpm.it*
[2] *Full Professor, Università Politecnica delle Marche, Ancona, g.moriconi@univpm.it*

obtained, the critical dosage could be identified, in order to optimize the design of structural elements.

2 EXPERIMENTAL

Cement type CEM II-A/L 42.5 R was used to prepare concrete manufactured with a natural sand (0-6 mm) and a fine coarse crushed aggregate (5-15 mm) assorted according to Bolomey. Two different water to cement ratios were adopted, equal to 0.55 and 0.35, in order to achieve C25/30 and C50/60 concrete strength class, respectively. For the higher strength concrete a superplasticizer (30% aqueous solution of carboxylic acrylic ester polymer) was added to the concrete mixture as water reducing admixture at the dosage of 1.2% by weight of cement, in order to limit the cement amount. Taking into account the workability loss due to fibers addition, in this case the superplasticizer helped also to reach the same workability level of the fresh concrete planned for all the concretes.

Hooked steel fibers in accordance with UNI EN 14889-1 requirements were used for fiber reinforced concrete. Their technical properties are summarized in Table 1.

Table 1. Technical data of steel fibers.

Length	30 mm
Diameter	0,50 mm
Aspect Ratio	60
Tensile Strength	>2500 MPa
Elongation	<1%
Elastic Modulus	190 GPa

Moreover, fibers were slightly brass-plated in order to prevent steel oxidation as well as to improve the bond between steel fibers and cement matrix.

Fibers dosages of 10, 30, 50, 70 and 90 kg/m^3 of concrete were tested for the C25/30 mixtures, while they were 30, 40, 50 and 60 kg/m^3 of concrete for the C50/60 mixtures. Steel fibers were added to the mixtures by replacing the same volume of coarse aggregate, and the same fluid consistency (slump equal to 160 mm) was guaranteed for all the tested mixtures.

For each concrete mixture, prismatic specimens (10×10×50 cm) middle-notched (notch depth of 25 mm) were manufactured for bending tests, while cubic specimens (10×10×10 cm) were prepared for compressive and tensile tests. The concrete specimens have been wet cured at 20°C until testing. Compression tests have been performed after 1, 7 and 28 days of curing, while tensile and bending tests have been carried out only after 28 days of curing.

3 RESULTS AND DISCUSSION

3.1 Compressive Strength

Compressive strength was evaluated up to 28 days of wet curing according to UNI EN 12390-3 on cubic specimens. The mean values obtained from three specimens of each concrete mixture after 28 days of curing are reported in Table 2, showing that the planned strength class for the two concretes was anyway achieved independently of the fiber dosage in the concrete mixture. The same results are summarized as strength development with time in Figure 1, from which, as expected, no influence of fibers addition on FRC compressive strength can be observed at any level whichever the concrete strength class.

Table 2. 28-day compressive strength of the different FRCs.

Strength class (MPa)	C25/30					C50/60			
Fibers dosage (kg/m^3)	10	30	50	70	90	30	40	50	60
Mean compressive strength (MPa)	35.6	36.0	35.6	36.0	37.1	67.4	64.0	72.6	67.9
Cubic characteristic strength (MPa)	30	30	30	30	30	60	60	67	60

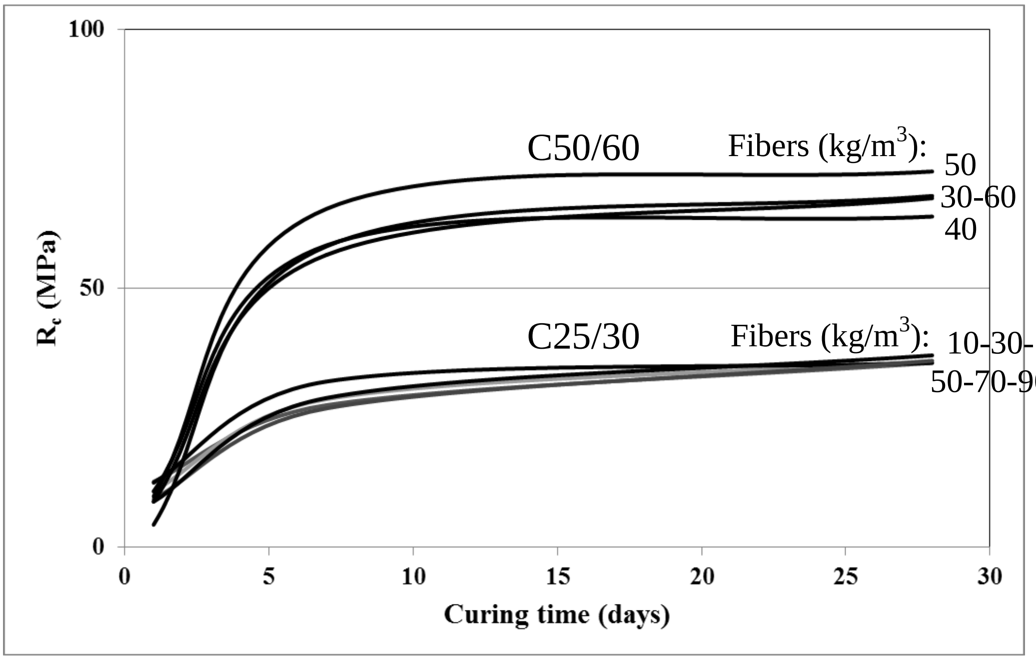

Figure 1. Strength development with curing time of the different FRCs.

3.2 Tensile Strength

Tensile strength was evaluated according to EN 12390-6 through splitting tension tests on cube specimens. The mean values of the first cracking stresses obtained after 28 days of wet curing are reported in Table 3. Again, as expected, the addition of steel fibers does not significantly modify the maximum value of tensile strength.

Table 3. 28-day tensile strength of the different FRCs.

Strength class (MPa)	C25/30					C50/60			
Fibers dosage (kg/m^3)	10	30	50	70	90	30	40	50	60
Tensile strength (MPa)	2.84	2.74	2.79	2.56	2.81	3.87	3.59	2.76	3.07

In Figure 2 the stress-strain curves under splitting tension for the different FRCs are reported.

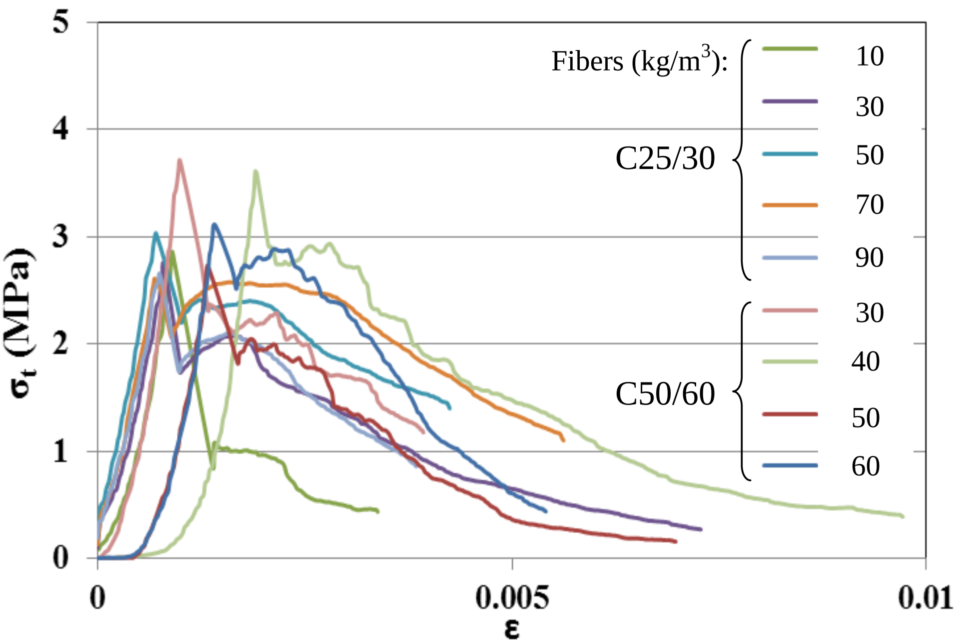

Figure 2. Stress-strain curves under splitting tension of the different FRCs.

3.3 3-Point Bending Tests

Flexural strength was evaluated according to RILEM TC 162-TDF (Vandewalle et al. 2003) by calculating the tensile stress reached at the tip of the notch of the prismatic specimens after 28-day wet curing. In Figures 3 and 4 the force-deflection curves are reported for the concrete mixtures of the two different strength classes. These curves confirm that fibers addition does not practically modify the first cracking stress, which is always limited by the cement matrix properties, but allows different post-cracking behavior of the fiber reinforced concrete depending on the fibers amount. This behavior is just determined by the presence of fibers, which start acting only after the concrete first cracking by developing a crack-bridging action. The main result is a strength recovery after concrete cracking conferring FRC higher ductility with respect to a brittle ordinary concrete, and the ability to absorb higher energy leading to FRC higher toughness.

However, the FRC post-cracking behavior depends on the fibers dosage, since for low fiber amounts a softening behavior is detected, which changes to hardening when high fiber amounts, exceeding a critical value, are added to the concrete mixture.

The residual flexural tensile strengths corresponding to the concrete cracking stress can also be determined as reported in Table 4.

Table 4. 28-day residual strength for the different FRCs.

Strength class (MPa)	C25/30					C50/60			
Fibers dosage (kg/m^3)	10	30	50	70	90	30	40	50	60
Residual flexural tensile strength (MPa)	2.57	2.85	4.74	5.92	4.82	3.43	5.15	5.21	6.24
Tensile strength (MPa)	2.84	2.74	2.79	2.56	2.81	3.87	3.59	2.76	3.07

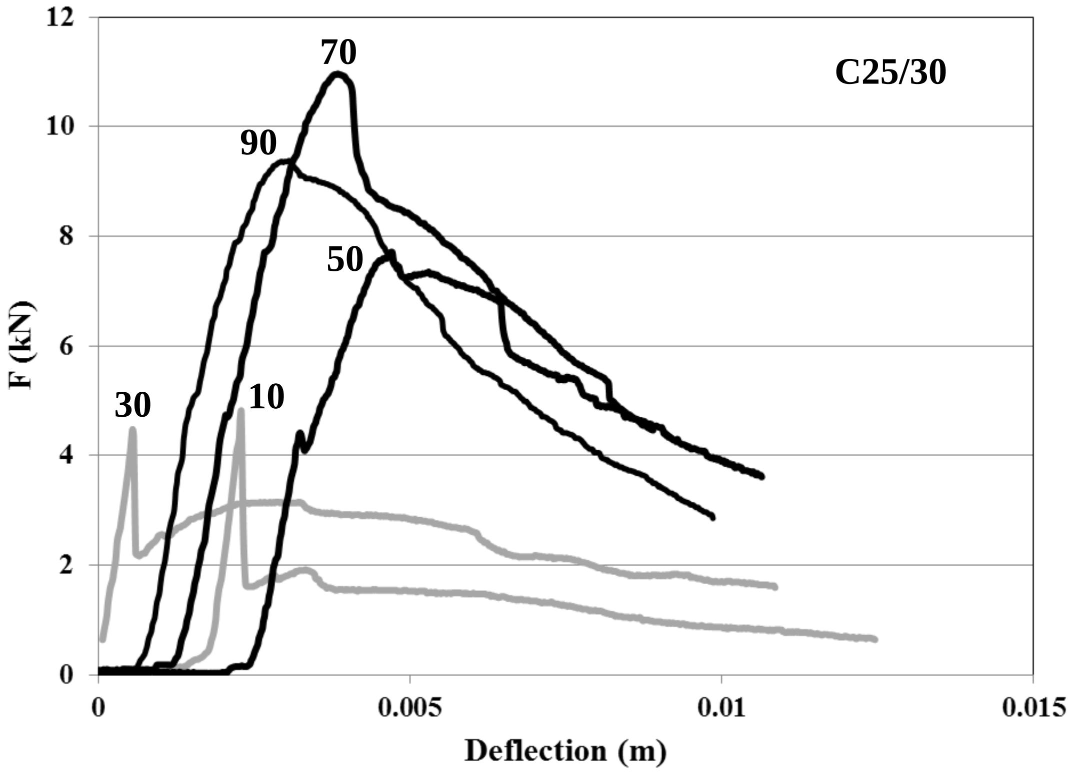

Figure 3. Force vs. deflection curve under flexural stress for C25/30 FRC. Numbers on curves indicate the fibers dosage (kg/m^3).

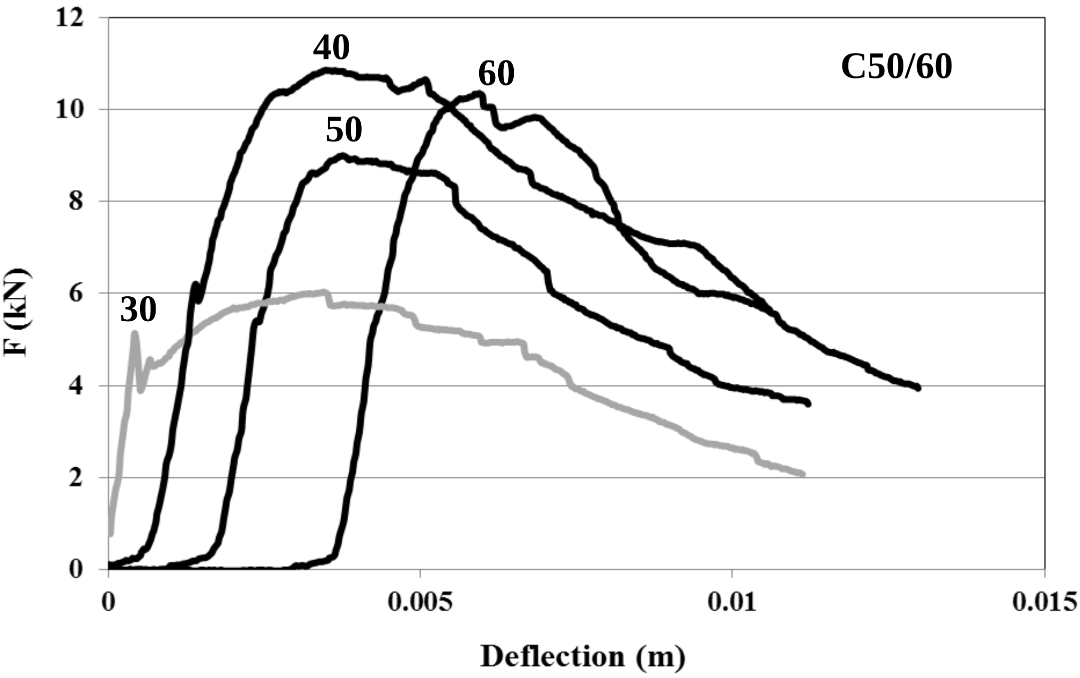

Figure 4. Force vs. deflection curve under flexural stress for C50/60 FRC. Numbers on curves indicate the fibers dosage (kg/m^3).

From Figures 3 and 4, as well as from Table 4, a critical value of fibers volume corresponding to 40 kg/m^3 can be recognized independently od the FRC strength class, clearly discriminating between the softening and the hardening behavior.

3.4 Toughness Improvement

The increase in toughness attributable to fibers addition has been evaluated through the ratio between the areas under the post-cracking and the pre-cracking force-deflection curves, where the former area is unaffected by fibers addition and the latter one, limited to 0.01 deflection, is mainly determined by the amount of fibers dispersed in the cement matrix. In Table 5 the toughness increase factors by this way determined are reported for the different FRCs.

Table 5. Toughness increase factor for the different FRCs.

Strength class (MPa)	C25/30					C50/60			
Fibers dosage (kg/m^3)	10	30	50	70	90	30	40	50	60
Toughness increase factor	7.3	33.0	46.2	47.2	29.4	35.7	41.5	37.4	39.0

Even if the values of the factors reported in Table 5 suffer for uncertainties in the graphic determination of the first cracking strain, making them highly susceptible to even slight variations of the very low values of the pre-cracking areas, all very close to each other, the beneficial effect induced by increasing amounts of fiber in the FRC mixtures appears easily recognizable.

4 CONCLUSIONS

Assuming a relation between the fibers volume added to a concrete mixture and the toughness induced by this addition in the fiber reinforced concrete, an attempt has been made to determine the fibers critical volume, able to change the FRC behavior from softening to hardening, by analyzing the flexural behavior of concretes reinforced with increasing amounts of fibers. This critical value of fibers volume seems to be independent of the concrete strength class.

As expected, fibers addition did not significantly affect the concrete compressive and tensile strength, but decisively contributed to change the FRC post-cracking behavior, developing strength recovery and ductility induced by a remarkable toughness improvement.

REFERENCES

di Prisco, M., Plizzari, G. and Vandewalle, L. (2009). "Fibre reinforced concrete: new design perspectives", *Materials and Structures*, 42(9), 1261-1281.

Vandewalle, L. et al. (2003). "RILEM TC162-TDF: Test and Design Methods for Steel Fibre Reinforced Concrete: sigma-epsilon design method (final recommendation)", *Materials and Structures*, 36(262), 560–567.

Velazco, G., Visalvanich, K. and Shah, S.P. (1980). "Fracture behavior and analysis of fiber reinforced concrete beams", *Cement and Concrete Research*, 10(1), 41–51.