Effectiveness of Synthetic Structural Fibers for Self-Compacting Fiber Reinforced Concretes

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ABSTRACT: This paper presents the results of an experimental work in which two different types of synthetic structural fibers were employed in order to obtain Self-Compacting Fiber Reinforced Concretes (SCFRC) with an improved post-cracking behavior, similar to that obtained by means of steel fiber addition. SCFRC mix design was optimized by varying the dosage of both synthetic fibers and crushed gravel in order to maintain self-compactability at the fresh state, but improving hardened concrete mechanical performance. Compression tests, splitting tension tests, and 3-point bending tests were carried out at 28 days of curing. Also drying shrinkage of SSFRC was evaluated up to 90 days of exposure to 50% relative humidity. A reference mixture without fibers, and one mixture prepared by using steel instead of synthetic fibers were tested, in order to compare the effectiveness of the different kinds of fibers. The experimental results obtained by using synthetic structural fibers were extremely encouraging.

1 INTRODUCTION

Self-Compacting Concrete (SCC) offers substantial benefits over conventional concrete (CC), including reduced labor, increased ease of placement, a better surface finish and reduced noise levels at construction sites, etc. High flow ability, better resistance to segregation and bleeding provides larger degrees of freedom to the architects in complex shapes of concrete structures, densely arranged bars and areas where it is more difficult to use vibrators. To achieve these properties, the design of SCC mix involves lower coarse aggregate content, increase fines content, relatively low water / powder ratio, superplasticizing admixtures, and supplementary cementitious materials.

The use of fibers might extend possible fields of application of SCC. Fibers are added not only to improve the mechanical properties, but also to control cracking, to prevent coalescence of cracks, and to change the behavior of the material by bridging of fibers across the cracks. Fibers are produced in a wide range of materials, in different shapes with different properties concerning their affinity to paste or water. They are known to affect the workability and the flow characteristics of concrete. The degree to which workability decreases does depend on the type and content of fibers used and the properties of the constituents of the matrix. Concerning Self-Compacting fiber - reinforced concrete (SCFRC), higher aspect ratio (L/D) and volume concentration (V_f) of fibers improve the performance of SCFRC in the hardened state but also adversely affect its workability. Thus, the product of these two parameters, which is termed as the “fiber factor”, has become a key index in SCFRC mix. The size and amount of aggregate content also influences the workability of SCFRC (Grunewald & Walraven, 2001; Corinaldesi & Moriconi, 2011a).

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2 SCC PREPARATION

2.1 Materials

As binder, commercial portland-limestone blended cement type CEM II/B-L 42.5 according to the European Standards EN-197/1 was used. The Blaine fineness of cement was 0.42 m^2/g and its relative specific gravity was 3.05.

As filler, commercial limestone powder was used, obtained as a by-product of quarry activity. Its Blaine fineness resulted 0.61 m^2/g, and its relative specific gravity was 2.65. In limestone quarries, considerable amounts of limestone powders are being produced as by-products of stone crushers. High amounts of powders are being collected and utilization of this by-product is a big problem from the aspects of disposal, environmental pollution and health hazards. Previous studies showed the feasibility of the use of limestone powders for SCC (Corinaldesi & Moriconi, 2011b).

As aggregate, quartz sand (0-4 mm) and crushed aggregate (2-10 mm) were used. Their specific gravity values were 2610 and 2660 kg/m^3 for quartz sand and crushed aggregate, respectively; while their water absorptions were 2,6% and 3,1%.

As water reducing admixture, a 30% aqueous solution of carboxylic acrylic ester polymer was added to the mixtures.

As reference, hooked steel fibers were employed at a dosage of 0.6% by volume, replacing the same volume of crushed aggregate. This dosage was decided on the basis of experimental results reported in the literature (Khayat & Roussel, 1999), which showed that an increase in fiber content from 0.5% to 1% resulted in lower concrete performances as a consequence of the negative influence on concrete workability. As synthetic structural fibers, Poly-Vinyl-Alcohol (PVA) fibers were added with two different dosages of roughly 0.6 (PVA-low) and 0.8% (PVA-high) by volume, respectively. Alternatively, bicomponent (BIC) fibers were used (sheath made of polypropylene and core made of glass) with two different dosages of roughly 0.5 (BIC-low) and 0.7% (BIC-high) by volume, respectively. Information concerning the main fiber properties are reported in Table 1. Moreover, their morphology is shown in Figure 1.

Table 1. Main characteristics of the fibers used.

Fiber type	Hooked steel fiber	PVA fiber	Bicomponent (PP/glass) fiber
Length (mm)	30	12	50
Diameter (mm)	0.7	0.2	0.5
Aspect Ratio (AR)	43	62	100
Young modulus (GPa)	170	30	72
Tensile strength (MPa)	450	1000	510

2.2 SCC Mixture Proportions

The SCC mixtures proportions are reported in Table 2. All concretes were prepared with the same water to cement ratio of 0.55. In order to optimize the grain size distribution of the solid particles in the concrete, quartz sand and crushed aggregate fractions were suitably combined, keeping into account also the suggestions reported in the literature concerning the mixture proportion of self-compacting concrete, particularly in terms of maximum dosage of coarse aggregate, that is 340 l/m^3 (Saak et al., 2001).

In order to achieve a volume of very fine particles of about 180 l/m^3, it was necessary to employ limestone powder besides cement, at a dosage of 180 kg. In this way, a water to very fine material ratio of 1.05 in volume was obtained.

Superplasticizing admixture was dosed at 1.2% by weight of cement plus limestone powder, in order to fit the slump flow range of 650÷660 mm (see Table 3).

A reference mixture (Ref) without fibers was firstly prepared. Then, different kinds and/or amount of fibers were added to the mixture, by replacing the same volume of crushed aggregate in order to avoid (or to limit) workability loss due to fiber addition.

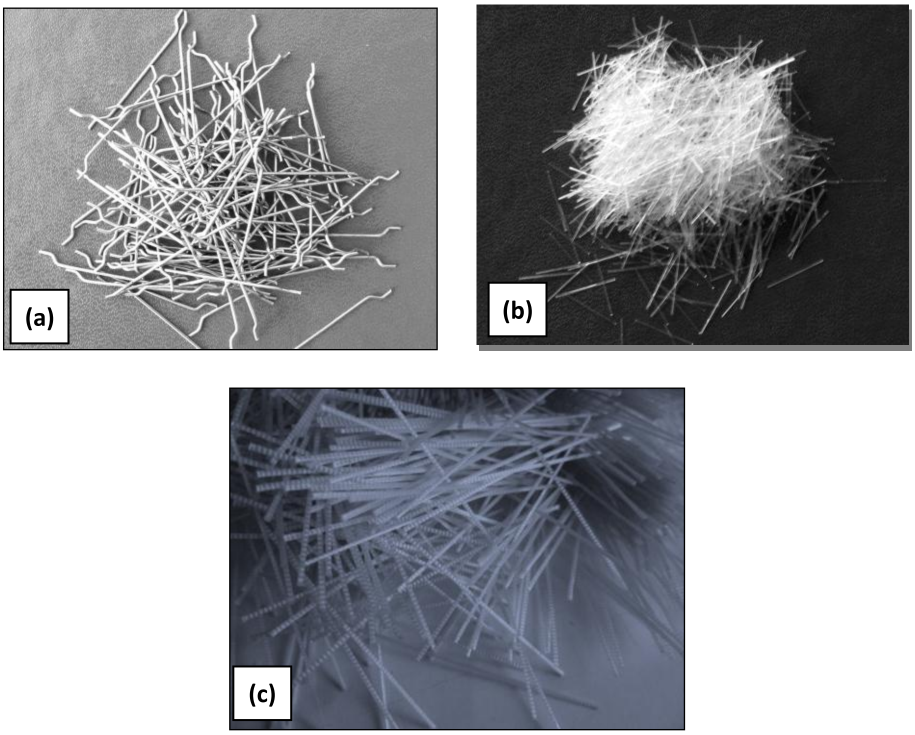

Figure 1. Pictures of steel fiber (a), PVA fibers (b), and bicomponent fibers (c).

Table 2. SCC mixture proportions.

Mixture	Ref	Steel	PVA-low	PVA-high	BIC-low	BIC-high
Water/Cement	0.55	0.55	0.55	0.55	0.55	0.55
Water (kg)	190	190	190	190	190	190
Cement (kg)	345	345	345	345	345	345
Quartz sand (kg)	980	980	980	980	980	980
Crushed aggregate (kg)	612	595	602	599	605	603
Limestone powder (kg)	180	180	180	180	180	180
Steel fibers (kg)	-	50	-	-	-	-
PVA fibers (kg)	-	-	7.5	10	-	-
Bicomponent fibers (kg)	-	-	-	-	4.5	6
Superplasticizer (kg)	6.3	6.3	6.3	6.3	6.3	6.3

3 PROPERTIES OF FRESH CONCRETE

As a first step, properties of the fresh concrete were evaluated through Slump test according to Italian Standards UNI 11041. The attention was focused on the measurement of the slump flow, which is the mean diameter ($\O_{FIN}$) of the slumped concrete. Then, also the elapsed time to gain the final configuration (t_{FIN}) was detected. Then, time elapsed for the SCCs passing through V-funnel was also detected, according to Italian Standards UNI 11042. Results obtained are reported in Table 3.

All concretes had enough deformability under their own weight (strictly related to the value of the mean diameter), and quite a high viscosity (related to the value of the elapsed time to stop), which is necessary to avoid segregation of fibers and coarse aggregate particles. In fact, neither the presence of a halo of cement paste around the slumped concrete or the so-called 'sombrero effect' were observed. Almost the same values of slump flows and elapsed times were detected for all the mixtures, and the effect of both the different kind and the different amount of fibers was insignificant.

Table 3. SCC fresh workability.

Mixture	Ref	Steel	PVA-low	PVA-high	BIC-low	BIC-high
Slump flow, $Ø_{FIN}$ (mm)	650	650	660	650	660	650
Slump flow, t_{FIN} (s)	14	13	12	13	12	13
V funnel, t_{FIN} (s)	10	9	9	10	10	11

4 PROPERTIES OF HARDENED CONCRETE

4.1 Compression Tests

Nine cubic specimens, 100 mm in size, were cast for each concrete mixture for compression tests, according to Italian Standards UNI EN 12390-1. These specimens were cast in PVC forms and wet cured at 20°C (UNI EN 12390-2). Compressive strength was evaluated after 1, 7 and 28 days of curing according to Italian Standards UNI EN 12390-3. Results obtained are reported in Fig. 2. The target strength class (C 25/30) was achieved in every case, even if the fiber addition caused a certain strength loss (never higher than 10% indeed). The reason probably lies in a slight different water dosage (probably in the presence of fibers some more water was necessary in order to reach the same slump flow).

4.2 Three-point bending tests

Three prismatic specimens, 100 by 100 by 450 mm in size, were cast for each concrete mixture for 3-point bending tests, according to RILEM TC 162-TDF (Rilem, 2002). These specimens were cast in steel forms and wet cured at 20°C (UNI EN 12390-2) for 28 days. In the middle of the span (400 mm) the specimens were notched (the depth of the notch is 25 mm). Flexural strength was evaluated according to RILEM TC 162-TDF by calculating the tensile stress reached at the tip of the notch. Also the areas under the load-deflection curves were calculated (the 'total area' up to a deflection corresponding to 0.1%, and the 'elastic area' up to the first-cracking of concrete). In addition, the fracture energy was calculated according to RILEM TC 50-FMC (1985). Results obtained are reported in Table 4.

The first-cracking strengths were quite similar for all the tested mixtures (± 5% with respect to the reference 'Ref'), but the values of ductility (ratio between 'total area' and 'elastic area') as well as of fracture energy were sensibly different by varying kind and dosage of fibers. In particular, both steel and bicomponent fibers showed to be extremely effective in improving the post-cracking behavior of SCC, due to their optimized geometry in terms of shape (due to the presence of either hooks or scabrous surface for 'Steel' and 'BIC' type, respectively) and aspect ratio (equal to 100 in the case of 'BIC' type), as well as due to the high value of their young modulus (see Table 1).

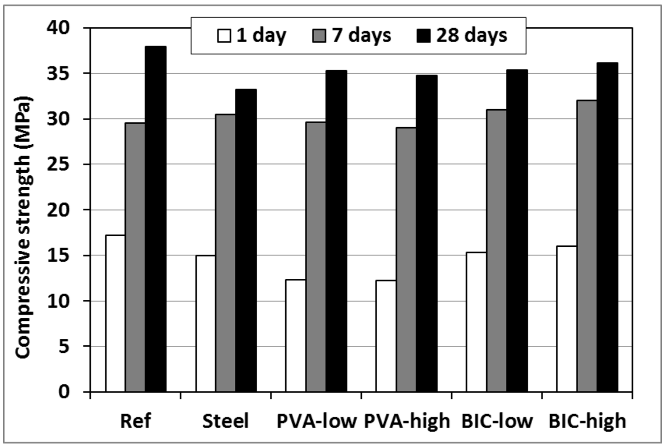

Figure 2. Compressive strength vs. curing time.

Table 4. Results of the 3-point bending tests after 28 days of curing.

Mixture	Ref	Steel	PVA-low	PVA-high	BIC-low	BIC-high
First-cracking strength (MPa)	4.62	4.77	4.49	4.62	4.68	4.85
Ductility (Total area/Elastic area)	1.36	4.95	2.1	2.4	5.43	5.87
Fracture energy (J/m^2)	4464	8664	5690	5780	8135	9870

4.3 Splitting Tension Tests

Five cubic specimens (100 mm in size) were manufactured for each mixture, then wet-cured at 20°C, for splitting tensile strength tests (carried out after 28 days according to EN 12390-6). The mean values of the first-cracking strengths measured on five specimens for each mixture are reported in Table 5. A slight improvement of this value was detected in the presence of fibers (never higher than 10% indeed). Also in this case a positive effect on the post-cracking behaviour has been observed, even if not measured.

Table 5. Results of the splitting tension test after 28 days of curing.

Mixture	Ref	Steel	PVA-low	PVA-high	BIC-low	BIC-high
First-cracking strength (MPa)	2.57	2.81	2.64	2.72	2.81	2.85

4.4 Drying Shrinkage Tests

For free drying shrinkage monitoring, three prismatic specimens (100 x 100 x 500 mm) were prepared for each concrete mixture according to UNI 11307. After one day of wet curing, the specimens were stored at constant temperature (20 ± 2 °C) and constant relative humidity (50 ± 2 %), while measuring drying shrinkage at different curing times up to 90 days of exposure. Results obtained are shown in Figure 3.

With respect to the mixture without fibers, a certain reduction of drying shrinkage was detected (in particular, with steel fibers it was less 25% after 90 days), by confirming previous results (Corinaldesi & Moriconi, 2004). In general, the effectiveness of fiber addition seems to be correlated to their Young’s modulus (the higher is the modulus the lower is the strain).

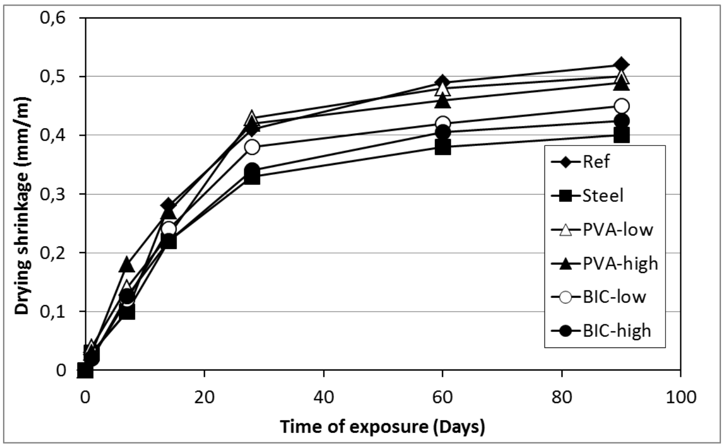

Figure 3. Drying shrinkage vs. time of exposure to 50% R.H. and T=20°C.

5 CONCLUSIONS

On the basis of the results obtained the following conclusions can be drawn:

- FRSCC can be prepared by using synthetic structural fibers instead of steel fibers, showing adequate strength class (C 25/30), as well as sufficiently low drying shrinkage strains;
- concerning FRSCC under bending and tension tests, extremely positive results were found in terms of post-cracking behavior, in particular when the bicomponent fibers were used; the reason lies in their optimized geometry (aspect ratio equal to 100), in the scabrous surface of their sheaths, as well as in their cores (characterized by high young modulus).

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