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Experimental characterization of the post-cracking response in Hybrid Steel/Polypropylene Fiber-Reinforced Concrete

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HIGHLIGHTS

- This paper deals with Hybrid Steel/Polypropylene Fiber-Reinforced Concrete (HyFRC).
- It focuses on five HyFRC mixtures made with an invariant volume fraction of fibers.
- Experimental results from tests under both compression and bending are reported.
- Steel fibers mainly contribute to strain re-hardening force-crack response.
- Specimens with more polypropylene fibers exhibited a less variable response.

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ABSTRACT

This paper presents and discusses the results of experimental tests performed on concrete specimens internally reinforced with polypropylene and steel fibers. Specifically, samples of five mixtures (plus a reference plain concrete), characterized by the same total volume of fibers, but different fractions of polypropylene and steel fibers, were tested under compression and in bending. This study was aimed to clarify the influence of different combinations of these fibers on the resulting fracture behavior of Hybrid Fiber-Reinforced Concrete (HyFRC). As expected, the results obtained from compression tests highlighted a negligible influence of fibers in terms of strength and, hence, FRC specimens exhibited a post-peak response more ductile than the reference ones. Conversely, the overall shape of the stress-crack-opening-displacement curves of HyFRC tested in bending was highly influenced by the type of fibers. On the one hand, FRC specimens made of only polypropylene fibers exhibited an excellent post-cracking toughness for the small crack opening ranges of relevance for the Serviceability Limit State, while an apparent decay was observed in terms of post-cracking response, especially at wide crack openings. On the other hand, a marked re-hardening response was observed in the post-cracking behavior for specimens with higher percentage of steel fibers; however, at the same time, the corresponding results showed a relevant scatter.

1. Introduction

Fiber-Reinforced Cementitious Composites (FRCCs), obtained by mixing short fibers within conventional cement-based matrices (i.e., mortar or concrete), can be considered as structural materials featuring both post-cracking tensile strength higher than the corresponding matrices and enhanced toughness (in terms of absorbed strain energy) due to the bridging actions developed by fibers across the opening crack surfaces [1,2]. Among these materials, Fiber-Reinforced Concrete (FRC) is commonly used for structural purposes, such as strengthening existing members [3] and controlling crack opening in new ones [4].

Main concepts behind the structural rules for FRC structural design are commented in several studies and have been well focused in [5]. Among the high performance properties of FRC, the most appealing is its “re-hardening” capacity in tension and bending: a comprehensive classification between strain-hardening (multi-cracking) vs. strain-softening composites has been reported in [6]. It is worth noticing that the bond behavior

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is of key importance for controlling the good features of FRC [7,8]. Steel, glass, synthetic as well as natural fibers can be adopted: their performances and classification are discussed in several scientific papers, technical documents and guidelines [10–14].

Although steel fibers are the most widely used, in the last years, innovative solutions, obtained by combining different fiber types and/or materials are getting more and more common. They are generally referred to as Hybrid FRC (HyFRC): their behavior was specifically investigated with the aim of understanding the possible synergistic action of different fibers on the resulting post-cracking response of FRC members. Applications in this field are based on employing fibers of the same material, such as 1) polypropylene hybrid Fiber-Reinforced Concrete including coarse monofilament and staple fibers [15], 2) micro and macro steel fibers considering smooth, hooked-end and twisted macro fibers [16]; 3) short and long hooked-end steel fibers [17] and 4) micro and macro steel fibers [18].

Moreover, plenty of studies deal with HyFRCs made of fibers of different geometries and materials such as polypropylene and steel [19]. It should be noticed that other combinations of those fibers have been also studied: Steel/Carbon/Polypropylene FRC [20] and Steel/Palm/Synthetic FRC [21] may be mentioned among the others. Recently, the combination of steel fibers with fly ash [22] or silica fume [23] have been considered in Self-Compacting Concrete (SCC) mixtures and a blend of steel and polypropylene fibers with fly ashes [24] have been employed for SCC exposed to high temperature.

Besides these studies about the material behavior, contributions about the macro-scale response of structural members made of FRCCs have been recently published [25]. More specifically, a great interest has been devoted to estimating the capacity of plate members [26], also made out of fiber-reinforced SCC [27]. Moreover, the shear behavior of FRCC beams is a subject of current relevance for the scientific community [28].

Furthermore, some experimental results on the so-called ecofriendly FRCs, such as those made with either Natural Fibers (NFRC) [29] or Recycled Steel Fibers (RSFs) obtained from recycled waste tires and often referred to as Recycled Steel Fiber-Reinforced Concrete (RSFRC) [30], are also available in the literature. Furthermore, RSFs were also employed in combination with conventional or so-called Industrial Steel Fibers (ISFs) in a class of materials often referred to as Hybrid Industrial/Recycled Steel Fiber-Reinforced Concrete (HIRSFRC) [31,32]. Some of the aforementioned studies focused on the synergic effects of combining different fiber typologies, but further experimental studies aimed at investigating the performance of HyFRCs are still needed.

Therefore, the present work aims to give a specific contribution for understanding the behavior of FRC with Steel (S) and Polypropylene (P) in a constant total volume fraction and different proportions/substitutions of S and/with P fibers. Specifically, SFRC with 0.75% of fiber volume fraction (equivalent to 60 kg/m^3 of steel fibers) and four more mixtures were prepared by replacing higher and higher volume percentages of steel fibers with an equivalent volume of polypropylene fibers. Hence, the paper aims to compare the mechanical performance and the cracking behavior of conventional Steel Fiber-Reinforced Concrete (SFRC) with both Hybrid Steel Polypropylene Fiber-Reinforced Concrete (HySP-FRC) and pure PFRC. The experimental study consists of both cylinders tested under compression and pre-notched beams tested in four-point bending (4PB).

2. Experimental program

The experimental tests were carried out at the Structural Engineering Testing Hall (Str.Eng.T.H.) of the University of Salerno, Italy, in collaboration with the Department of Structural and Geotechnical Engineering of “La Sapienza” University of Rome.

As mentioned above, the FRC specimens were obtained by mixing two types of fibers (Fig. 1):

- Steel fibers (S), labeled *Wirand*® *FS7* [33];
- Polypropylene fibers (P), labeled *Fibromac*® *12* [34].

Table 1 summarizes their geometric and mechanical properties. P fibers present an aspect ratio (AR) l_f/d_f (equal to 375) higher than the S ones (AR = 60), being the latter characterized by significantly higher tensile strength and elastic modulus.

Five FRC mixtures were prepared, having a constant global volume percentage (0.75%) of fibers and different proportions of S and P fibers (see Table 2).

In addition, a Plain Concrete mixture was prepared as a reference (see Table 2). The concrete mixture composition is reported in Table 3: the same composition was retained for the concrete matrix in all the FRCC mixtures realized as part of this research.

A total number of 18 prismatic (150 × 150 × 600 mm^3) specimens (3 for each mixture) were prepared for the four-point bending (4PB) tests. Moreover, 21 (6 for the plain concrete and 3 for each FRC mixture) cylindrical specimens (300 mm in height and 150 mm in diameter) were realized for the uniaxial compressive tests. All specimens were tested at 28 days of curing.

The compressive tests were performed in displacement control (0.005 mm/min rate) according to EN 12390-4 [35] provisions. Three vertical and three horizontal strain gauges were glued at mid-height of each specimen, alternately arranged every 60°, in order to measure the evolution of the local strains during the tests. Fig. 2 depicts the experimental set-up adopted for these tests.

The 4PB tests were carried out according to UNI039-2 [36] and definitions, classification and designation reported in UNI039-1

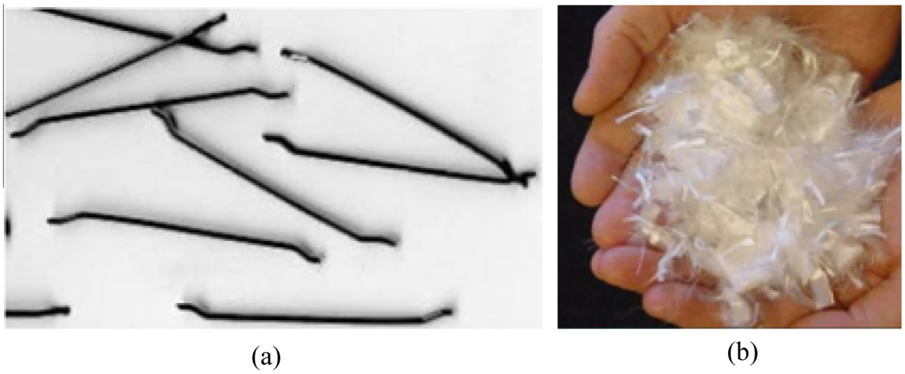
(a) (b)

Fig. 1. (a) Steel and (b) Polypropylene fibers.

Table 1
Relevant properties of fibers [33,34].

Fibers		Diameter [mm]	Length [mm]	Tensile strength [MPa]	Elastic Modulus [GPa]
Steel (S)	WIRAND$^{\circledR}$ FS7	0.550	33	>1200	210
Polypropylene (P)	FIBROMAC$^{\circledR}$ 12	0.032	12	400–500	3.5–3.9

Table 2
FRC mixtures: composition of the fiber phase.

Mixture	Steel fibers (S)		Polypropylene fibers (P)	
	Volume fraction [%]	In weight [kg/m^3]	Volume fraction [%]	In weight [kg/m^3]
HySP-FRC-0.75-0	0.75	60	–	–
HySP-FRC-0.55-0.20	0.55	45	0.2	1.7
HySP-FRC-0.375-0.375	0.375	30	0.375	3.4
HySP-FRC-0.20-0.55	0.2	15	0.55	5.1
HySP-FRC-0-0.75	–	–	0.75	6.8

Table 3
Concrete mix composition.

Material	Dosage [kg/m^3]
Cement 42.5	420
Water	210
Sand (0–4 mm)	800
Aggregates (6–12 mm)	800

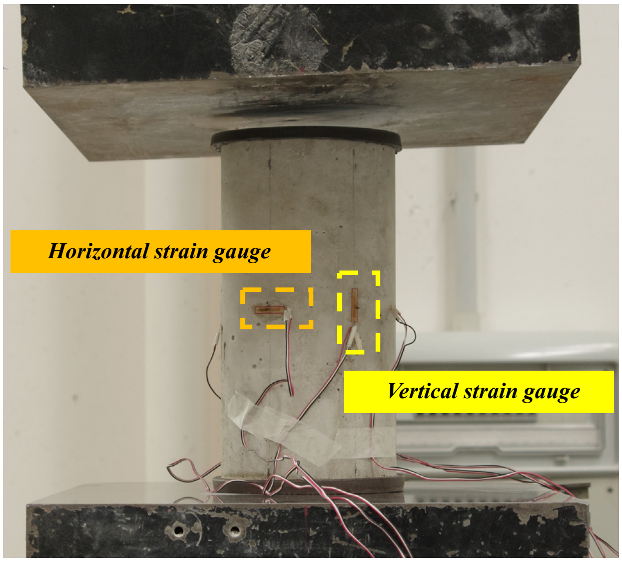

Fig. 2. Experimental set-up for the uniaxial compressive tests.

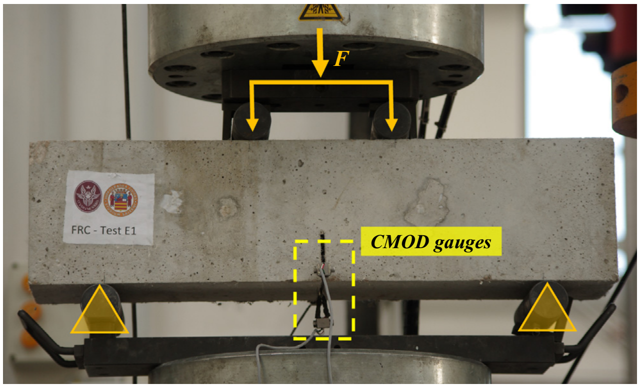

Fig. 4. Experimental set-up for the 4PB tests.

[37] were also considered. Particularly, the displacement rate was set to 0.005 mm/min and three displacement transducers were placed inside the notch to monitor the so-called Crack Mouth Opening Displacement (CMOD), which is defined as the relative displacement between the two points at the bottom sides of the notch (Fig. 3). Then, Fig. 4 shows the aforementioned experimental setup.

3. Results and discussion

3.1. Uniaxial compression tests

Fig. 5 shows the results of the tests in terms of uniaxial compressive strength; error bars indicate the scatter between the

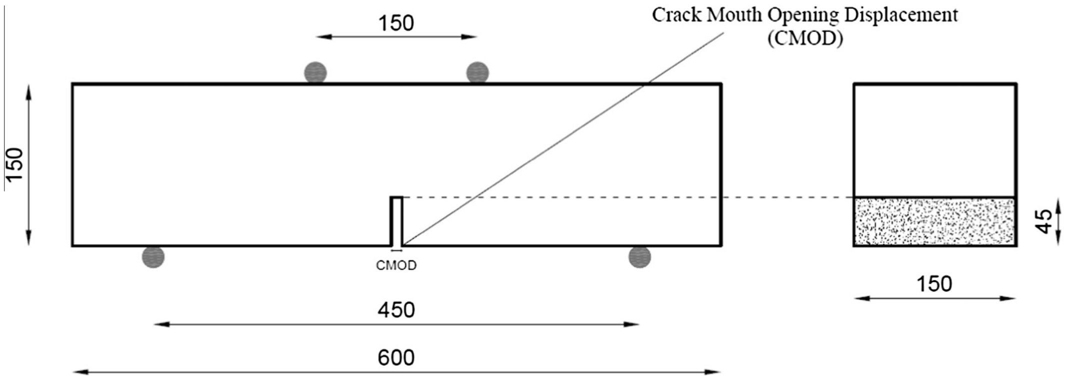

Fig. 3. Geometry of the notched beams.

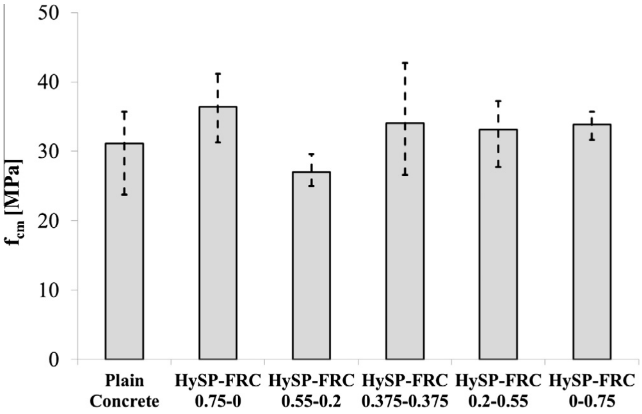

Fig. 5. Cylindrical compressive strengths for HySP-FRCs.

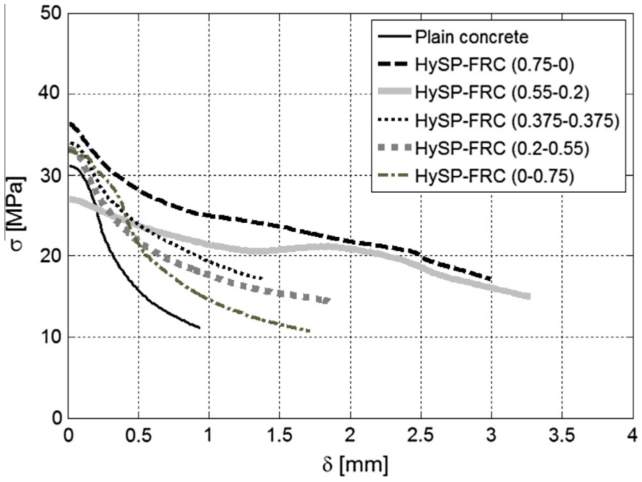

Fig. 6. Compression post-peak behavior: average axial stress vs displacement for HySP-FRCs.

minimum and the maximum values obtained for each mixture. For the sake of clarity, Table 4 reports the numerical values of compressive strength obtained in all tests.

As expected from similar studies available in the literature [9,17,31], the tests on HySP-FRC specimens led to results fairly close to the output obtained for the reference plain concrete. The maximum variation was measured for the specimens reinforced with only steel fibers (HySP-FRC-0.75-0): a percentage increment of about 15% was actually observed.

Based on these observations, it may be concluded that the resulting compressive strength of the tested HyFRC is mainly governed by the composition of the concrete matrix. Conversely, as it is well-known, fibers play an important role in controlling the post-peak regime, as they “bridge” the opening cracks. A less softening response in the post-peak region, with respect to plain concrete, characterizes the HyFRC specimens, especially those with higher content of steel fibers, as can be appreciated in Fig. 6, which plots the average axial stress (σ) vs displacement (δ) curves for all the analyzed mixtures.

Each one of the curves reported in Fig. 6 was obtained by averaging the stresses of the tested samples (3 cylinders for the HySP-FRCs and 6 for plain reference concrete): Fig. 7 reports the individual σ-δ curves obtained in each test.

Finally, it is worth highlighting that, in these curves, δ represents the vertical displacement imposed by the testing machine: the curves report the post-peak behavior, starting from the maximum measured stress.

3.2. Four-point bending tests

The 4PB tests were executed on three specimens for each mixture. The typical failure mode of a fiber-reinforced specimen (i.e., HySP-FRC-0.75-0) is shown in Fig. 8. The vertical load (F) and the corresponding Crack Mouth Opening Displacement (CMOD) were monitored during each test. More specifically, the CMOD was evaluated as the average of the three acquired measurements.

The F-CMOD curves obtained for each mixture are shown in Figs. 9a–9e. For a given mixture, the scatter between the curves is very low, confirming the reliability of the acquired data and the symmetry of the loading process.

For each mixture, an averaged Force-Displacement curve has been evaluated by calculating the mean value of the three CMODs measured with the transducers. Thus, a unique curve (F-CMOD$_m$) can be obtained also averaging the forces (of the three tested samples) corresponding to a given CMOD level.

The F-CMOD$_m$ curves evaluated for all the analyzed mixtures are shown in Fig. 10: on each graph, the black line represents the average response of the three tests, whereas the grey area highlights the scatter between the results. This scatter is usually due to various effects (e.g. the irregular space distribution of fibers, variable number and orientation of fibers crossing the crack surface, etc.), which contribute to the natural uncertainty of the experimental behavior.

However, the results generally point out that the post-cracking response of FRC specimens made with only steel fibers is characterized by significant toughness (Fig. 10b), as a result of the significant bridging action exploited by those fibers, which is not present in plain concrete (Fig. 10a).

Furthermore, the effect of replacing part of steel fibers with an equivalent volume of polypropylene fibers, can be easily caught by analyzing Fig. 11. In the post-cracking behavior of HySP-FRC, the following stages can be identified:

Stage I) an early post-peak branch with CMODm lower than 0.8 mm;
Stage II) characterized by CMODm in between 0.8 and 1 mm;
Stage III) with crack opening displacements greater than 1 mm.

Table 4
Experimental results for HySP-FRC specimens tested in compression.

Mixture	Test 1 [MPa]	Test 2 [MPa]	Test 3 [MPa]	Test 4 [MPa]	Test 5 [MPa]	Test 6 [MPa]	f_{cm} [MPa]	Err^+ [MPa]	Err^- [MPa]
Plain Concrete	34.57	33.406	23.722	30.59	35.675	28.711	31.11	4.56	7.39
HySP-FRC-0.75-0	36.64	31.287	41.177	–	–	–	36.37	4.81	5.08
HySP-FRC-0.55-0.2	24.99	29.598	26.445	–	–	–	27.01	2.59	2.02
HySP-FRC-0.375-0.375	32.89	26.595	42.679	–	–	–	34.05	8.63	7.46
HySP-FRC-0.2-0.55	27.75	37.257	34.289	–	–	–	33.10	4.16	5.35
HySP-FRC-0-0.75	31.66	35.712	34.169	–	–	–	33.848	1.86	2.18

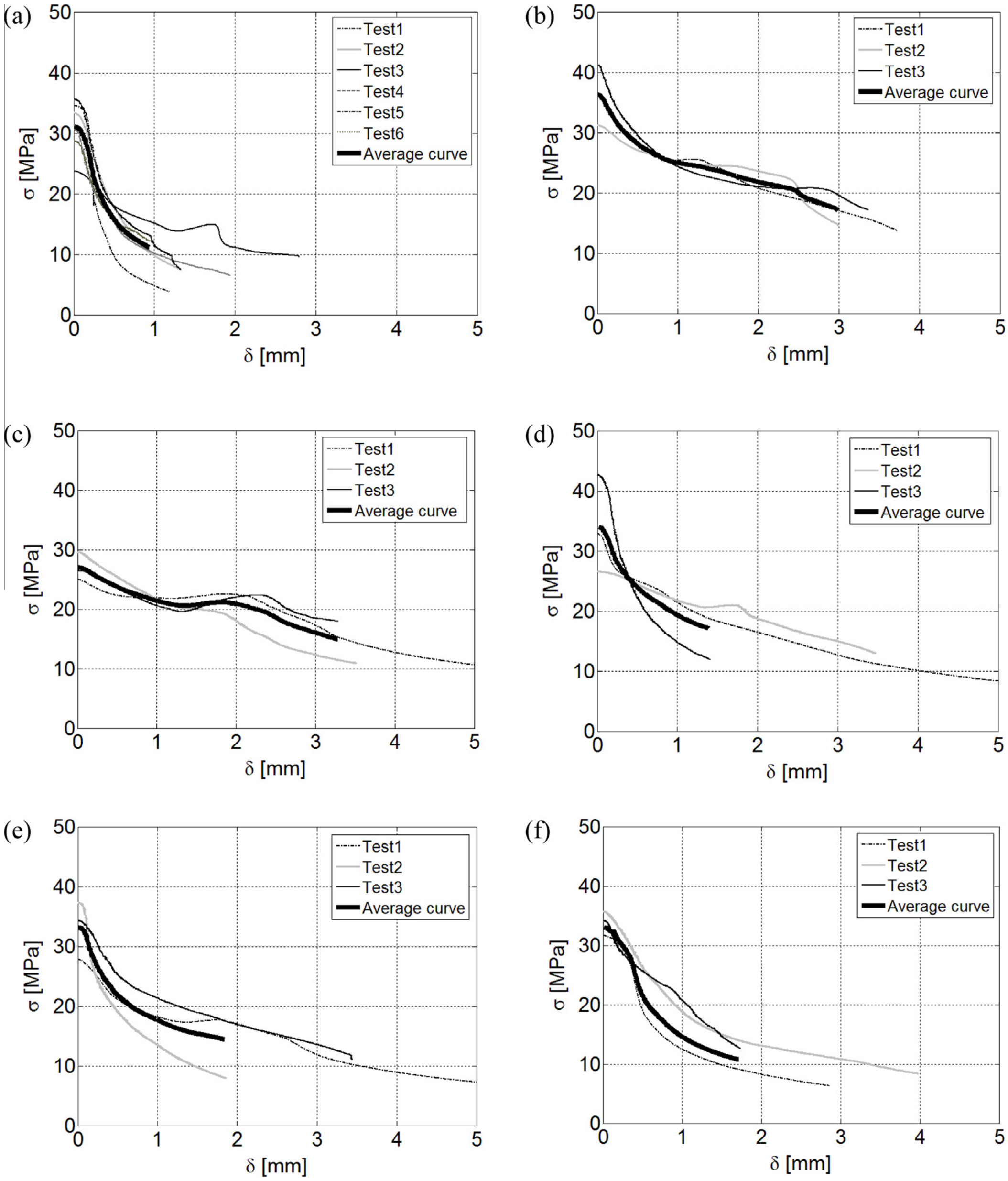

Fig. 7. Compression post-peak behavior in terms of axial stress vs vertical displacement: a) Plain concrete; b) HySP-FRC-0.75-0; c) HySP-FRC-0.55-0.2; d) HySP-FRC-0.375-0.375; e) HySP-FRC-0.2-0.55; f) HySP-FRC-0-0.75.

Fig. 8. Typical failure mode (HySP-FRC-0.75-0).

In Stage I, the slope of the descending (softening) branch is more pronounced for the mixtures with higher content of S fibers, denoting a more delayed activation of such fibers in comparisons to the P-fibers: this is mainly due to the lower number of S fibers corresponding to the same volume of P ones.

In Stage II, steel fibers begin to give a significant contribution, while the P-ones tend to lose their action mainly due to either/both debonding or/and tensile failure mechanisms. Therefore, on the one hand, a re-hardening response can be observed for the specimens characterized by a high amount of S-fibers, while, on the other hand, a crack-softening behavior was obtained for specimens with a predominant percentage of P-fibers (Fig. 11).

In Stage III, the activated P fibers reach their maximum bond strength and react with a constant friction force while a further bridging effect is still offered by S fibers, which actually results in a hardening response as the crack opening increases.

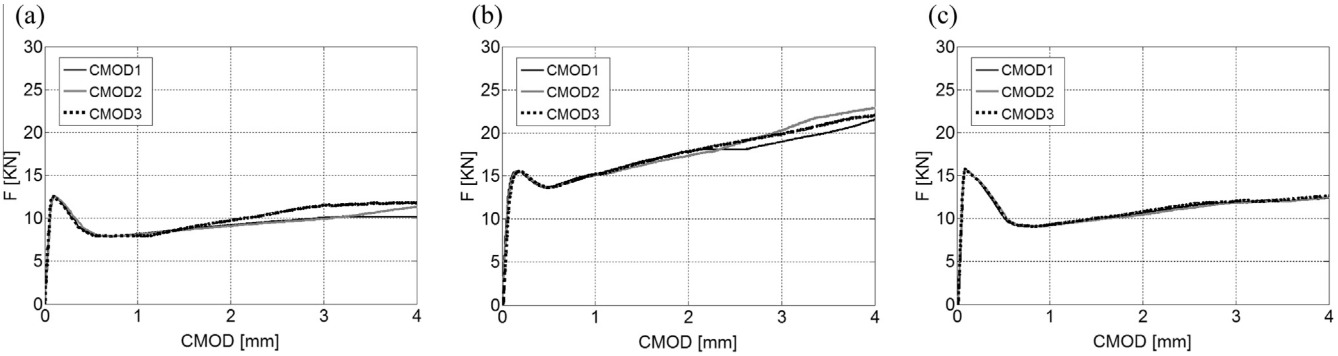

Fig. 9a. HySP-FRC-0.75-0: a) Test1, b) Test2 and c) Test3.

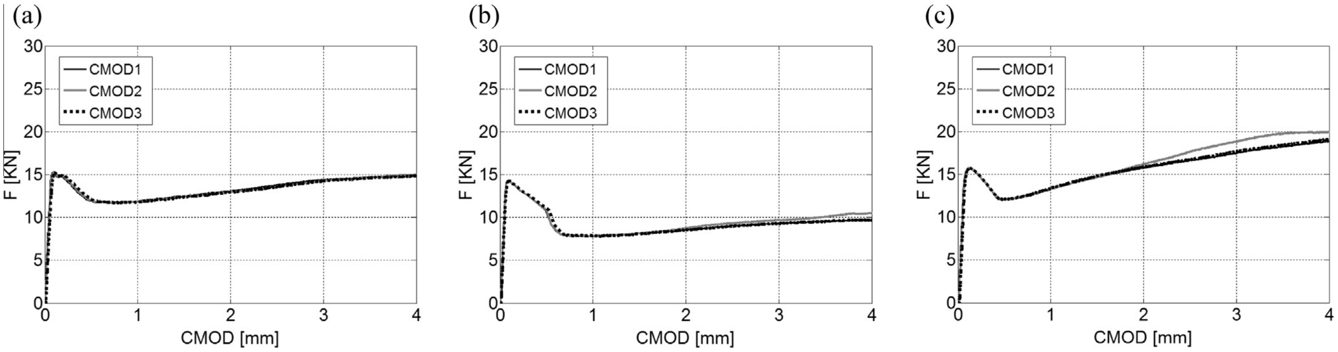

Fig. 9b. HySP-FRC-0.55-0.2: a) Test1, b) Test2 and c) Test3.

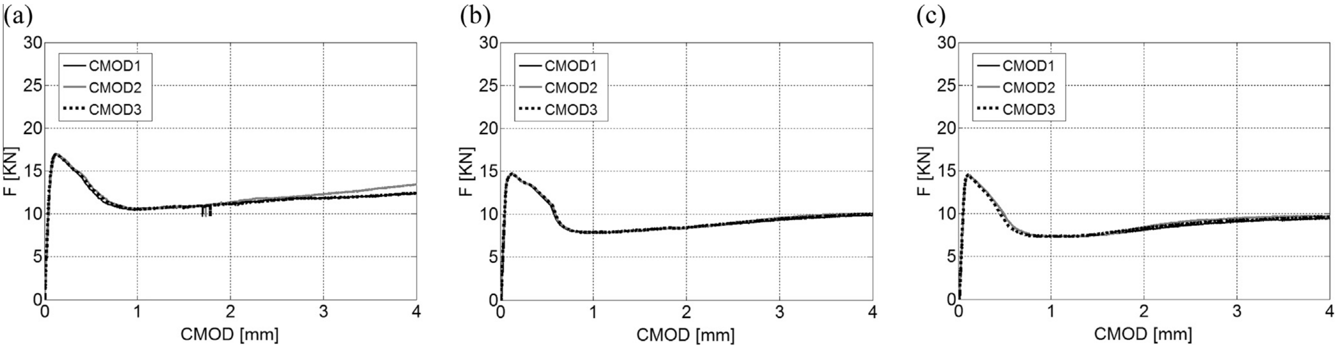

Fig. 9c. HySP-FRC-0.375-0.375: a) Test1, b) Test2 and c) Test3.

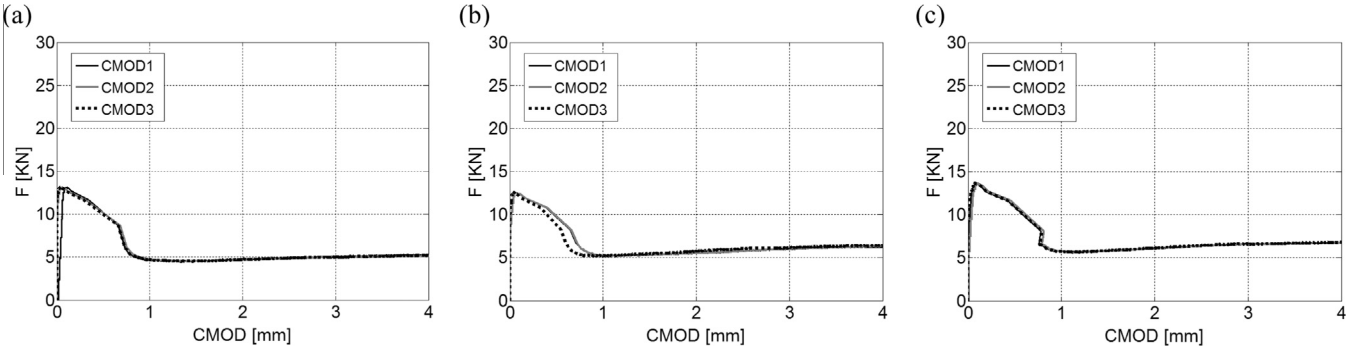

Fig. 9d. HySP-FRC-0.2-0.55: a) Test1, b) Test2 and c) Test3.

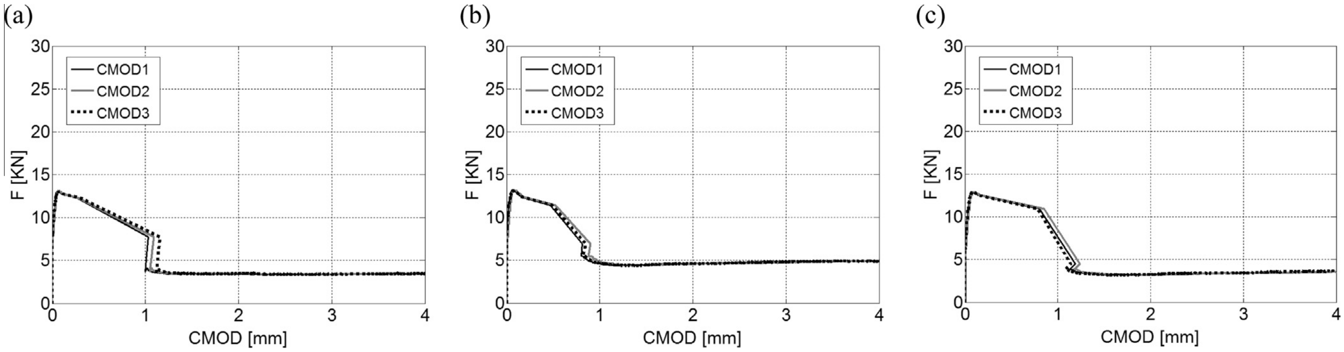

Fig. 9e. HySP-FRC-0-0.75: a) Test1, b) Test2 and c) Test3.

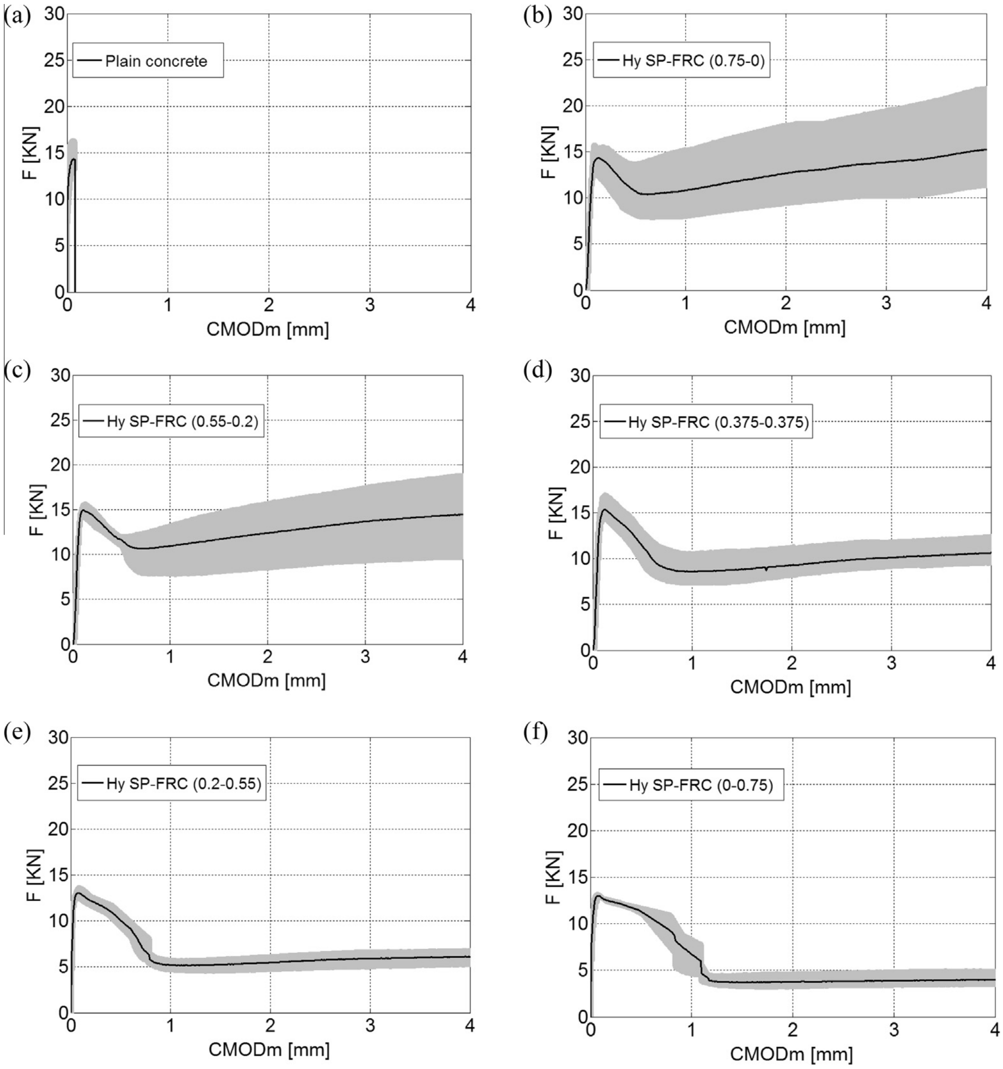

Fig. 10. F vs CMOD$_m$: a) Plain concrete, b) HySP-FRC-0.75,0, c) HySP-FRC-0.55-0.2. d) HySP-FRC-0.375-0.375, e) HySP-FRC-0.2-0.55 and f) HySP-FRC-0-0.75).

Another important evidence of the experimental results is that the scatter between experimental results reduces significantly in specimens with higher contents of polypropylene fibers. This is most likely due to both the higher number of P fibers replacing an equal volume of S fibers and the higher aspect ratio of the P fibers with respect to the S fibers. Thus, a more regular distribution of polypropylene fibers was observed throughout the cracked surface in all tested specimens compared to the usual non-regular distribution of steel fibers. Table 5 summarizes the main parameters evaluated through the experimental test results.

More specifically, it reports the values obtained for:

1) F_{max}, representing the maximum force achieved in the ascending cracking phase;
2) $CMOD_{m,Fmax}$, representing the $CMOD_m$ corresponding to F_{max};

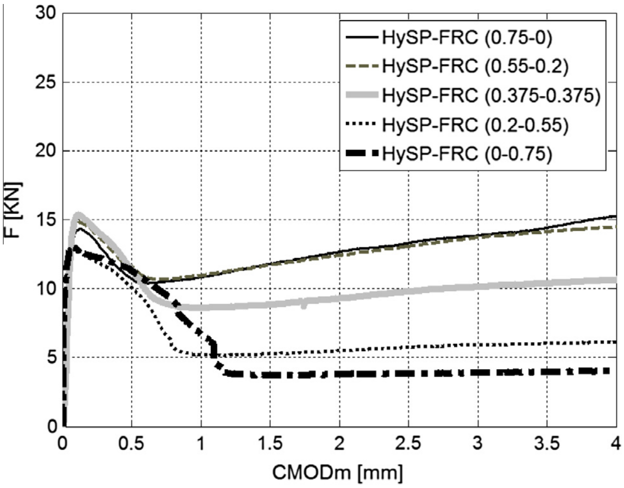

Fig. 11. average F-CMOD$_m$ curves for HySP-FRCs.

Table 5
Experimental results for HySP-FRC specimens tested in bending.

Mixture	$CMOD_{m,Fmax}$ [mm]	F_{max} [kN]	F_{min} [kN]	F_u [kN]	F_{min}/F_{max}	F_{min}/F_u
Plain Concrete	0.070	14.326	0.000	0.000	0.000	0.000
HySP-FRC-0.75-0	0.127	14.335	10.385	15.252	0.724	0.681
HySP-FRC-0.55-0.2	0.108	14.934	10.640	14.471	0.712	0.735
HySP-FRC-0.375-0.375	0.123	15.383	8.575	10.639	0.557	0.806
HySP-FRC-0.2-0.55	0.077	13.066	5.151	6.112	0.394	0.843
HySP-FRC-0-0.75	0.084	12.998	3.711	3.989	0.285	0.930

3) F_{min}, representing the minimum force achieved in the softening phase;
4) F_u, representing the force achieved for $CMOD_m$ equal to 4 mm;
5) F_{min}/F_{max} and F_{min}/F_u.

The following observations can be drawn out of the aforementioned results:

1) as expected, the fibers within the concrete matrix leads to a higher value of the $CMOD_{m,Fmax}$: this value tends to decrease when the polypropylene fibers amount increases;
2) the maximum force achieved in the ascending branch is not influenced by the presence of the fibers but, it is worth noticing that some slight decays are measured when the polypropylene fibers amount increases;
3) the minimum and the ultimate force (F_{min}, F_u) as well as the ratio F_{min}/F_{max} decrease as the polypropylene fibers amount increases.

4. Conclusions

This paper reports the results of experimental tests aimed at characterizing the structural response of HyFRC specimens, obtained by randomly mixing different combinations of polypropylene and steel fibers, with a constant total amount of fibers equal to 0.75% (in volume fraction).

The following comments can be remarked:

- Combining steel and polypropylene fibers is an attractive solution for enhancing the post-cracking behavior of cement-based matrices and possibly tailoring the material response to specific structural requirements;
- Although these fibers do not significantly affect compressive strength in HyFRC, they play a key role on the post-cracking behavior both in compression and in bending;
- HyFRC mixtures with more steel fibers exhibited higher post-cracking bending strengths and a tougher behavior, often resulting in strain re-hardening force-crack response;
- The presence of polypropylene fibers led to lower variability in the experimental results obtained on specimens characterized by the same HyFRC mixture, though resulting in a general reduction in strength and toughness.

Further researches, both experimental and theoretical in nature (i.e., aimed at widening the number of test results and at further exploring alternative formulations for simulating the crack development processes), are needed to make the behavior of these materials fully predictable and, hence, pave the way for using HyFRC in practical applications and, hence, pave the way towards using HyFRC in practical applications such as those concerning both static as well dynamic [38] mechanical properties of HyFRC.

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