THE USE OF HUMAN HAIRS AS A FIBER-REINFORCEMENT IN CEMENT-BASED MORTARS

A. P. Fantilli*, B. Chiaia
Politecnico di Torino, DISEG, Corso Duca Degli Abruzzi 24, Torino 10129, Italy
*Corresponding author; e-mail: alessandro.fantilli@polito.it

Abstract
Fiber-reinforced mortars are widely used in the construction industry due to the better mechanical performances at both fresh and hardened stage. Not only industrial fibers can be added to the cementitious matrix, but also bio-based materials can be effectively used as fiber-reinforcement. Among all the natural fibers, human hairs are herein proposed as a possible alternative to the current polymeric fibers. Accordingly, three point bending tests have been performed on three series of beams: plain mortar, mortar reinforced with 10 grams of human hairs, and mortar reinforced with 10 grams of industrial polyethylene fibers. In all the cases, flexural strength is not modified by the presence of fibers or hairs. Conversely, with respect to plain mortars, the flexural toughness increases of more than 5 times when human hairs or plastic fibers are added. In other words, animal fibers, like hairs, do improve the toughness performances of cementitious mortars, and can effectively substitute industrial fibers made with fossil-based materials.

Keywords:
Fiber-reinforced mortar, Polypropylene fibers, Three point bending tests, Flexural strength, Fracture toughness.

1 INTRODUCTION

Cement-based manufacts are designed to fulfil one or more functions and, contemporarily, guarantee the current safety standards. Nevertheless, in the last years, also the environmental impact of concretes and mortars has been considered a key aspect of the design process. For these reasons, new models, capable of taking into account both the sustainability issues, at material [Damineli 2010] or structural [Fantilli 2013a] levels, and the traditional requirements have been introduced. In all the cases, it has been proved that the higher the fracture toughness of cement based materials, the higher the durability, and thus the sustainability, of the manufacts [Fantilli 2013b, Fantilli 2015].

The addition of fibers to the cementitious matrix of concrete and mortars is frequently the simplest, and also the most convenient, way to increase fracture toughness in tension, bending, and compression [Mehta 2014]. However, the fibers currently used as reinforcement are made with fossil-based materials, such as steel and polymers. When such fibers are substituted by bio-based filaments, the new reinforcement can acquire more functionalities. Indeed, it (1) increases the fracture toughness and, thus, (2) increases the sustainability of cement-based composites, and, contemporarily, (3) reduces the use of fossil resources.

The current scientific literature reports several research projects in which cementitious mortars have been reinforced with bio-based materials, such as hemp [Hamzaoui 2014]. Recently, a large number of researches have focused on the use of animal biopolymer fibers, like the wool of sheeps [Fantilli 2016], pig hairs [Araya-Letelier 2017], or human hairs [Nila 2015]. As in most of the cases such bio-materials are special wastes (e.g., wool needs a sterilization treatment at 130 °C before its disposal), incorporating them into concrete and mortars avoid their landfill.

In all the above-mentioned studies, the performances of cement-based composites, having a bio-based fiber-reinforcement, are compared with similar, but unreinforced, concrete and mortars. Conversely, the capability of the animal fibers to substitute the current industrial fibers has not been investigated. For this reason, the behavior of traditional mortars, reinforced with polypropylene fibers, are herein compared with those reinforced with human hairs. The aim is to demonstrate the competitiveness of some biopolymers, like human hairs, and expand their market application far beyond the current state-of-play.

2 EXPERIMENTAL PROCEDURE

The results of an experimental campaign, performed on cementitious mortars reinforced with human hairs and with polymeric fibers, are described in the following sections. The experimental procedures are in accordance with the rules reported by EN 196-1 [EN 196-1 2005].

2.1 Materials

The main components of the mortars herein investigated are:

- Cement CEM II/B-LL 32.5 R
- Drinkable water
- CEN Standard sand, consisting of siliceous rounded particles, whose size distribution lies within the limits given by EN rules.

To the traditional mixture suggested by EN 196-1 [EN 196-1 2005], a suitable amount of hairs (Fig.1) or polypropylene fibers (Fig.2) are added.

As shown in Fig.3, which reports the length distribution measured on 100 samples (average length = 53 mm), human hairs do not have a constant length, or fiber aspect ratio, as industrial fibers

Fig. 1: The human hairs used to reinforce mortars.

Fig. 2: Polypropylene fibers used to reinforce mortars.

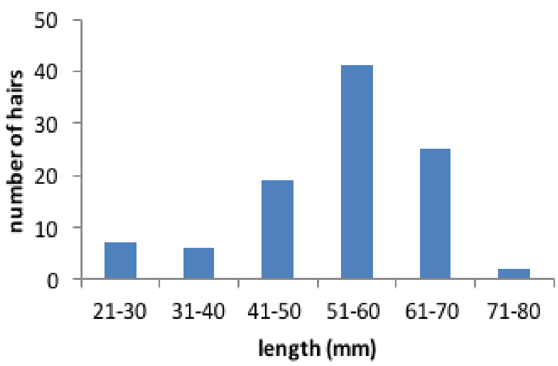

Fig. 3 Length distribution of human hairs.

In addition, 0.4 mm is the average diameter measured through a laser scanning technique on 8 hairs. This value is more or less similar to the diameter measured by Chou et al. [Chou 2015] with a SEM. The same Authors also evaluated the main mechanical and geometrical properties of the human hairs (fiber aspect ratio = 132). Such values, and those of polypropylene fibers (fiber aspect ratio = 600), are reported in Tab. 1.

Tab. 1: Properties of polypropylene fibers and human hairs

	Human hairs	Polypropylene fibers
Strength (MPa)	200	400-500
Average diameter (mm)	0.4	0.02
Length (mm)	53	12

The industrial fibers, industrially produced from a monofilament made with 100% of virgin polypropylene, are generally used to mitigate the effect of plastic shrinkage in cement-based mortars and concretes. The density of both polypropylene fibers and human hairs are the same (i.e., about 0.9 g/cm^3), even if the fiber aspect ratio is completely different.

With these materials, two series of tests were performed. The specimen of the first series, cast on December 21, 2015, consist of:

- M·21·12 = Plain mortar, in which the sand/cement and water/cement weight ratios are 1:3 and 1:2, respectively [EN 196-1 2005].
- C·21·12 = Fiber-reinforced mortar, containing human hairs (Fig.1). This mortar is prepared with sand/(cement + fibers) and water/(cement + fibers) weight ratios of 1:3 and 1:2, respectively. As hairs absorb water, the fiber content is subtracted from the cement content [Hamzaoui 2014].

The second series of tests, cast on March 7, 2016 were composed by the following mortars:

- M·7·3 = Plain mortar having the same composition of M·21·12.
- F·7·3 = Fiber-Reinforced Mortar containing polypropylene fibers (Fig.2), and prepared with sand/(cement + fibers) and water/(cement + fibers) weight ratios of 1:3 and 1:2, respectively. Also in this case, the fiber content is subtracted from the cement content.

As shown in Tab.2, which reports the weight composition of all the mortars, the C·21·12 and F·7·3 mortars are reinforced with 10 grams (about 1% in volume) of human hairs and polypropylene fiber, respectively.

2.2 Specimens and testing procedure

Three specimens were cast per each mortar described in Tab.2. According to EN 196-1 [EN 196-1 2005], all the 12 specimens are prisms with the dimensions of 40 × 40 × 160 mm (Fig.4). The specimens have an alphanumeric label, which coincides with the name of the mortar. Nevertheless, in the following sections a number (i.e., 1, 2, and 3) is used to distinguish the three specimens made by the same mortar.

Tab. 2: Compositions of the mortars investigated in the present project.

Type of mortar	Cement (g)	Water (g)	Sand (g)	Human hairs (g)	Polypropylene fibers (g)
M·21·12	450	225	1350	-	-
C·21·12	440	225	1350	10	-
M·7·3	450	225	1350	-	-
F·7·3	440	225	1350	-	10

All the prisms shown in Fig.4 were demolded one day after casting and stored at 20°C (RH = 90%).

As suggested by EN 196-1 [EN 196-1 2005], three point bending tests (Fig.5) were carried out 28 days later. The external load *P* was applied through a Baldwin-Zwick loading machine, having a load capacity of 500 kN. Tests were performed by driving the displacement of the loading cell, whose stroke moved at a velocity of 0.5 mm per minute.

Both the applied load *P* and the midspan deflection δ□ of the beam, were recorded during the tests, till the complete failure of the specimen.

3 TEST RESULTS

The results of the three point bending tests, regarding both the human hair reinforced mortars, and those reinforced with polypropylene fibers, are described in the following two sections, respectively. In each section, the performances of fiber-reinforced mortar are compared with those of the corresponding unreinforced mortar.

3.1 Mortars M·21·12 and C·21·12

Tab.3 reports the main data measured in the tests performed on the first series of tests. In particular, the value of the flexural strength, σ_F, also known as modulus of rupture, is calculated, in the linear elastic regime, by using the following formula:

$$\sigma_F = 1.5 \frac{P_{max}\, l}{B^3} \quad (1)$$

where, l = 100 mm and B = 40 mm (see Fig.5). In Eq.(1), P_{max} is the maximum value of the load *P* measured during the test. All the values of P_{max} and σ_F are reported in Tab. 3.

In the same Table, the deflections of the beam, δ_P, corresponding to the maximum load, are also indicated.

Fig. 4: The specimens tested in the present research project.

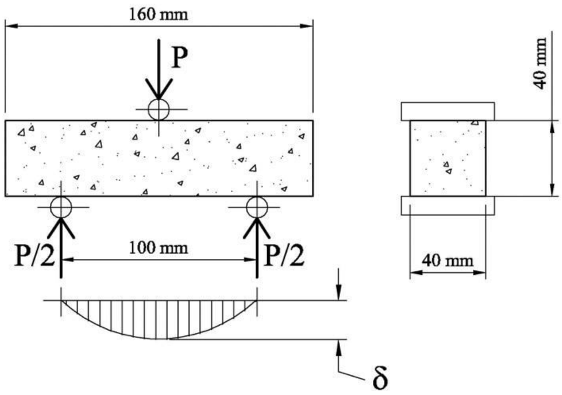

Fig. 5: Three point bending tests for cementitious mortars [EN 196-1 2005].

Tab. 3: Results of the three point bending tests on the specimens made with the mortars M·21·12 and C·21·12.

Specimen	Type of mortar	P_{max} (N)	σ_F (MPa)	δ_P (mm)
M·21·12_1	M·21·12	2.64	6.20	0.240
M·21·12_2		2.52	5.92	0.175
M·21·12_3		2.66	6.24	0.181
C·21·12_1	C·21·12	2.39	5.59	0.302
C·21·12_2		2.86	6.71	0.172
C·21·12_3		2.23	5.24	0.161

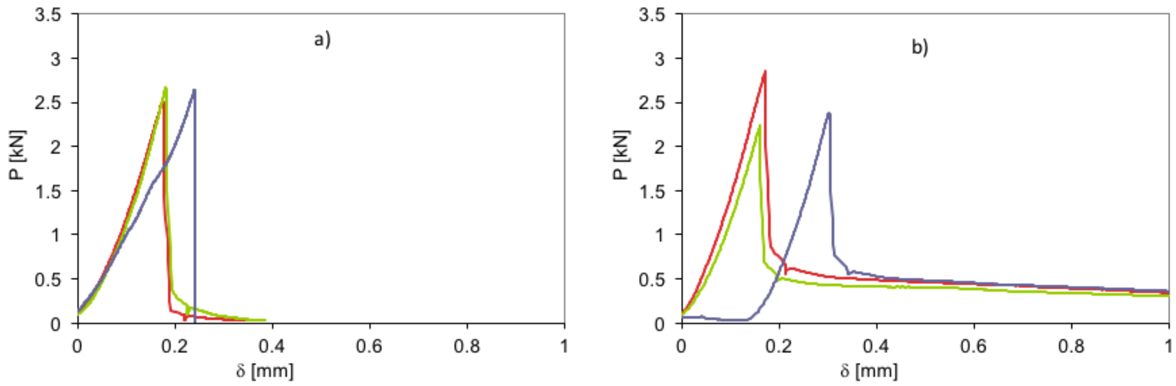

Fig. 6: The results of the three point bending tests in terms of load - midspan deflection (P-δ): a) plain mortar M·21·12; b) mortar reinforced with human hairs C·21·12.

The data reported in Tab.3 are not particularly interesting. Indeed, in terms of P_{max} or σ_F , there is no difference between plain and fiber-reinforced mortars. With respect to plain mortar, fiber-reinforced mortars exhibit more or less the same value of the maximum applied load, and of the corresponding flexural strength.

Conversely, the whole load-deflection (P-δ) diagrams of the nine tests are undoubtedly more relevant. They are reported in Fig.6 and grouped for each type of mortar (plain mortar – M·21·12 – in Fig.6a, and fiber-reinforced – C·21·12 – mortar in Fig.6b). After the peak of stress, residual tensile stresses vanish in the plain mortar specimens (Fig.6a). This is not the case of the specimens reinforced with human hairs, which show significant residual tensile stresses even for large deflection of the post-peak stage (see Fig.6b).

Similarly to other cement-based mortars reinforced with animal fibers [Fantilli 2016], the fracture toughness in bending (i.e. the ductility) increases with the content of human hairs. Thus, it is worth comparing only the post-peak stages of the mortars M·21·12 and C·21·12.

3.2 Mortars M·7·3 and F·7·3

Tab. 4 reports the main results (i.e., the value of the flexural strength, σ_F, calculated with Eq.(1), the maximum value of the load, P_{max}, and the corresponding deflections, δ_p) obtained with the second series of tests. Also in this case, the data reported in Tab. 4 are not so significant. Indeed, with respect to plain mortar, fiber-reinforced mortars exhibit more or less the same value of the maximum applied load, and of the corresponding flexural strength.

Conversely, the load-deflection (P-δ) diagrams of the nine tests, reported in Fig.7 and grouped for each type of mortar (plain mortar – M·7·3 – in Fig.7a and fiber-reinforced – F·7·3 – mortar in Fig.7b), reveal the higher ductility in presence of fiber-reinforcement. In the post-peak stage of plain mortars, residual stresses are not detected (Fig.7a). On the contrary, the presence of polypropylene fibers guarantees the existence of tensile stresses also for large deflections (Fig.7b), as in the case of human hairs. As only the flexural fracture toughness (i.e. the ductility) increases in presence of fibers, the sole post-peak stages of the mortars M·7·3 and F·7·3 are compared.

4 ANALYSIS OF THE EXPERIMENTAL DATA

To investigate the post-peak stage of all the tests, also in absence of local measurements, a new procedure is proposed. This approach has been already adopted to investigate the effect of a wool reinforcement in the cement-based mortars [Fantilli 2016].

Starting from the P-δ curves depicted in Fig.6 and Fig.7, the new post-peak diagrams reported in Fig.8 can be introduced. On the ordinate of such diagrams, the values of the normalized load (with respect to P_{max}) are reported. Conversely, the difference between the post-peak deflection and δ_p is on the abscissa.

Tab. 4: Test results of the three point bending tests.

Specimen	Type of mortar	P_{max} (N)	σ_F (MPa)	δ_p (mm)
M·7·3_1		2.85	6.67	0.329
M·7·3_2	M	2.95	6.91	0.355
M·7·3_3		3.14	7.35	0.489
F·7·3_1		2.59	6.08	0.619
F·7·3_2	LT	2.41	5.65	0.220
F·7·3_3		2.24	5.26	0.178

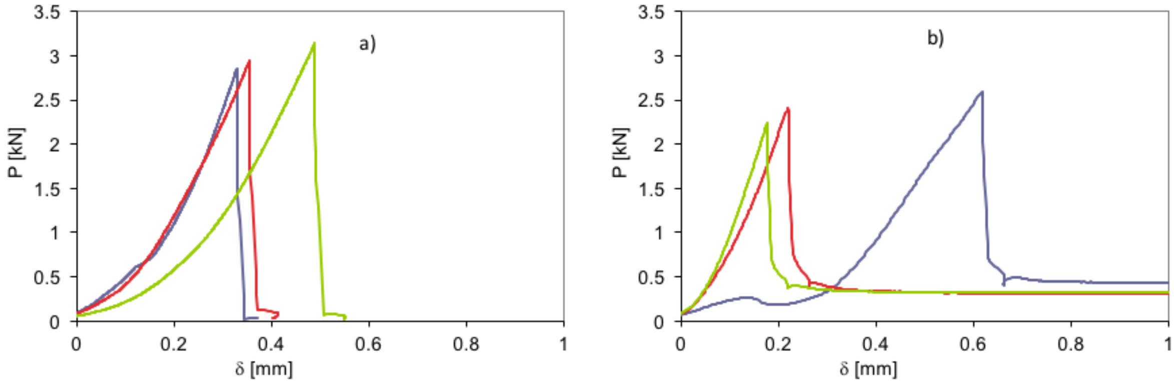

Fig. 7: The results of the three point bending tests in terms of load - midspan deflection (P-δ): a) plain mortar - M·7·3; b) mortar reinforced with polypropylene fibers F·7·3.

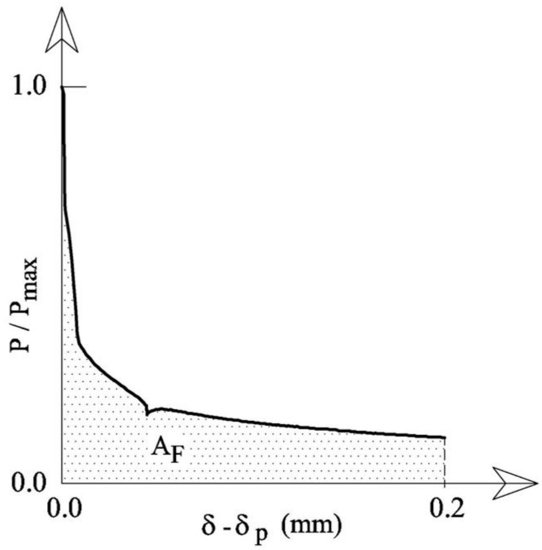

Fig. 8: The normalized post-peak diagram used to compare the performances of the mortars

All the post-peak diagrams are limited to the value $\delta - \delta p$ = 0.2 mm. In correspondence of this deflection, the residual load detected in plain mortars (Fig.6a and Fig.7a) is practically zero.

The ductility of the mortars herein investigated can also be quantified by calculating the area A_F delimited by the post-peak curves (see Fig.8). If this value is multiplied by the flexural strength, σ_F , a sort of fracture toughness in bending, G_F , can be attained.

Fig. 9 shows the normalized post-peak curves of all the 12 bending tests. Only the mortars reinforced with polypropylene fibers or human hairs can show remarkable residual tensile tests, even in presence of large relative deflections.

For all the tests, both the values of A_F and G_F are shown in Tab.5, whereas the average values of the main mechanical performances (i.e., A_F and G_F) of the four type of mortars are compared in the histograms depicted in Fig.10.

Due to the presence of polypropylene fibers or human hairs, the values of ductility (A_F in Fig.10b) and of fracture toughness (G_F in Fig.10c) remarkably increase with respect to plain mortar. Conversely, in all the mortars the flexural strength is more or less the same (see the values of σ_F in Tab.3 and Tab.4).

Due to the presence of human hairs, the average values of A_F and G_F are about 5 times higher than those of measures in the corresponding plain mortars M·21·12. Such increment is more or less similar to that observed in presence of polypropylene fibers. More precisely, in the mortars F·7·3, A_F and G_F are, respectively, about 7 times and 6 times those of the mortars M·7·3.

Although human hairs have a lower (of about 5 times) fiber aspect ratio, they can effectively reinforce the cement-based mortars, as the most common industrial fibers do. Indeed, the main mechanical parameters of the mortars reinforced with the same quantity of human hairs or polypropylene fibers are practically identical.

Tab. 5: Post-peak mechanical properties of the mortars

Specimen	A_F (mm)	G_F (N/mm)
M·21·12_1	0.000489	0.052
M·21·12_2	0.0112	0.055
M·21·12_3	0.0143	0.061
C·21·12_1	0.0501	0.158
C·21·12_2	0.0443	0.141
C·21·12_3	0.0452	0.123
M·7·3_1	0.000468	0.158
M·7·3_2	0.00769	0.141
M·7·3_3	0.00697	0.123
F·7·3_1	0.0411	0.125
F·7·3_2	0.0370	0.145
F·7·3_3	0.0378	0.177

5 CONCLUSIONS

From the results of the experimental investigations previously described, in which the application of human hairs as reinforcement is compared with the use of polypropylene fibers, the following conclusions can be drawn:

- The addition of human hairs, can improve the performance of cementitious mortar and, therefore increase the sustainability of such building material.

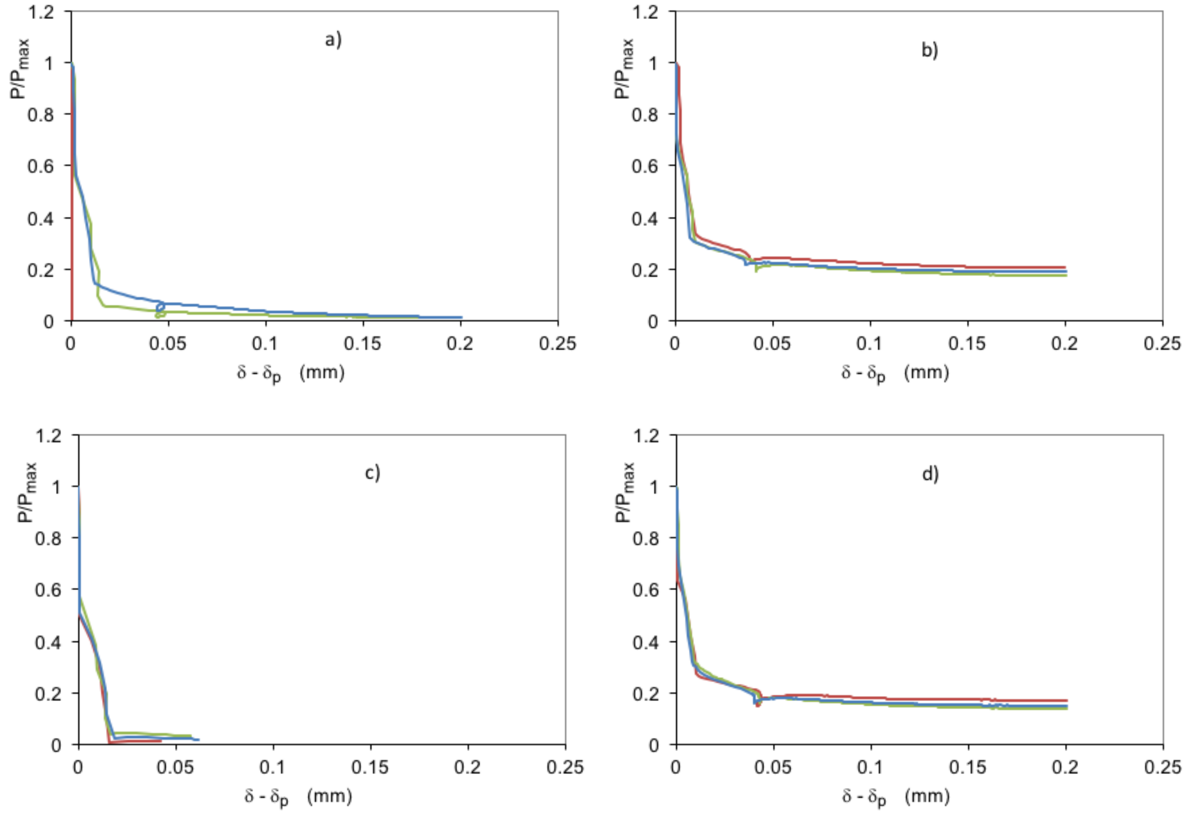

Fig. 9: The normalized post-peak diagrams obtained from the tests: a) mortar M·21·12; b) mortar C·21·12; c) mortar M·7·3; d) mortar M·7·3.

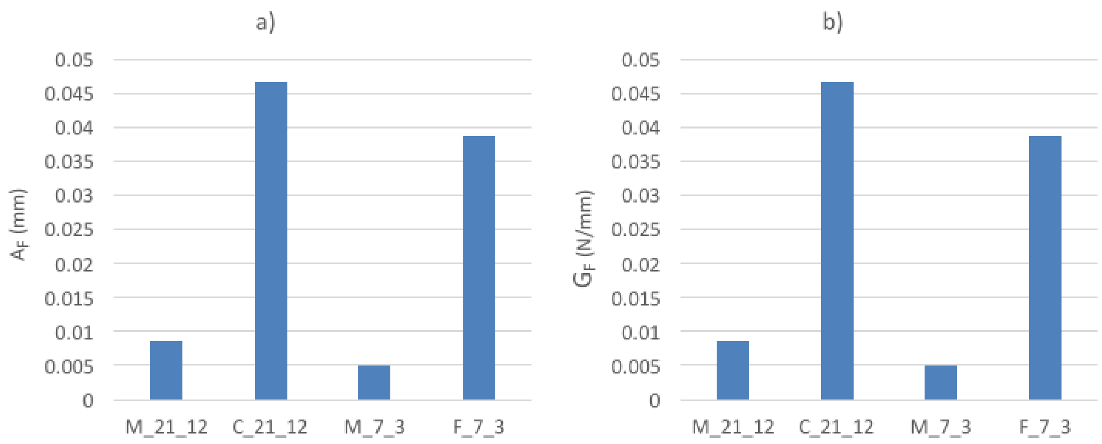

Fig.10. The average values of the main mechanical parameters measured in the post-cracking stage of three point bending tests: a) the ductility A_F; b) the fracture toughness G_F.

- If 10 grams (1% in volume) of human hair substitute an equivalent mass of cement in plain mortar, the flexural strength does not change, but the fracture toughness in bending increase of 5 times.
- A similar behavior can be obtained when 10 grams (1% in volume) of polypropylene fibers are used to reinforce the cementitious matrix.

Further experimental campaigns need to be performed to optimize the tailoring procedure, and to analyze the chemical damage of human hairs in alkaline environments.

6 ACKNOWLEDGMENTS

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