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THE USE OF WOOL AS FIBER-REINFORCEMENT IN CEMENT-BASED MORTAR

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Abstract

As the mechanical response is better than in plain cement-based mortars, fiber-reinforced mortars are widely used in the construction industry. Specifically, the fracture toughness in tension increases with the volume and the aspect ratio (i.e., the ratio between length and diameter) of the fibers, which are generally made with polymeric (e.g., polyethylene, polyvinylchloride, etc.) or inorganic (e.g., glass, carbon, etc.) materials, or with steel. However, some vegetal fibers, such as bamboo and hemp, have been also introduced in the last decades. To produce new mortars with animal fibers, the use of wool as fiber-reinforcement is investigated for the first time in the present paper. According to UNI EN 196-1-2006, three point bending tests have been performed on three series of beams: plain mortar, mortar reinforced with 1% in volume of wool, and mortar reinforced with 1% in volume of treated wool. In the latter case, wool is previously treated with atmospheric plasma in order to modify the nano-metric properties of the fiber surface. As a result, both the flexural strength and the ductility increase when wool, plain or treated, is added to cementitious mortars. In other words, wool does improve the mechanical and ecological performances of cementitious mortars and creates a link between textile and construction markets.

Keywords:

Cement-based mortar; Fiber-reinforced mortar; Wool fiber; Plasma treatment; Three point bending tests.

1 INTRODUCTION

The production of Portland cement, the main component of the modern concretes and mortars, is not environmental friendly. To fabricate one ton of cement, about one ton of carbon dioxide (CO_2), a major greenhouse gas, is released in the atmosphere. According to the estimation given by the World Business Council for Sustainable Development [WBCSD 2005], nowadays the cement industry produces about 5-7% of the global man-made CO_2. Moreover, to tailor cementitious concrete, the most used artificial material, a huge amount of raw materials is needed, such as stone aggregates and water. Thus, the production of concrete and mortar contributes to the depletion of natural resources [Sakai 2013].

As a consequence, the construction industry has adopted eco-friendly practices to reduce this environmental impact. Among them, vegetal fibers, made with bamboo and hemp, have been used to reinforce some cement-based composites [Pacheco-Torgal 2011]. Indeed, these natural fibers are usually stronger and more environmental friendly than synthetic fibers (e.g., PVA or polypropylene), and can improve the mechanical performances of cementitious mortars [Hamzaoui 2014].

In the same way, some animal fibers, such as sheep's wool, have begun to be marketed and promoted as an alternative insulating material in building constructions [Corscaddena 2014]. In fact, wool is a renewable resource, as the average sheep produces between 2.3 and 3.6 kg of raw wool annually that must be sheared (removed) for the health of the animal. However, about 75% of the wool produced by the European sheep farms cannot be used by the textile industry. It has to be considered a special waste, which needs a sterilization treatment (at 130 °C) before its disposal.

The amount of this unused wool is around 150 million tons per year, to which the wool contained in other end of life products (e.g., fitted carpet), and in the waste of the textile industry, has to be summed [Schokker 2010]. Due to some mechanical treatments, performed in order to improve the workability, the quality of this wool is generally high. For instance, Ceria et al. introduced an atmospheric plasma jet treatment to modify the physical and mechanical properties of wool fabric [Ceria 2010]. It produces a nano-metric modification of the wool fiber surface and increases the wettability without modifying the main properties of the wool filaments (e.g. the flakes on the fiber surface).

In the past, also Wu and Li proved that plasma treatment can effectively modify the surface characteristics of polyethylene fibers that reinforce concretes [Wu 1999]. The resulting surface modifications can lead to significant improvement in the interfacial properties fiber-cementitious matrix.

In other words, a huge amount of waste, composed by wool, is similar to the reinforcement used in some cement-based building materials. For this reason, the aim of the present paper is to investigate the performances of mortars reinforced with wool fibers, in order to create an additional and more sustainable market for a valuable resource.

2 EXPERIMENTAL PROCEDURE

The results of an experimental campaign, performed for the first time on cementitious mortars reinforced with wool fibers, is 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 in Tab.1 [EN 196-1 2005].

To the traditional mixture suggested by EN 196-1 [EN 196-1 2005], a suitable amount of ordinary (Fig.1) and plasma treated fibers (Fig.2) are added.

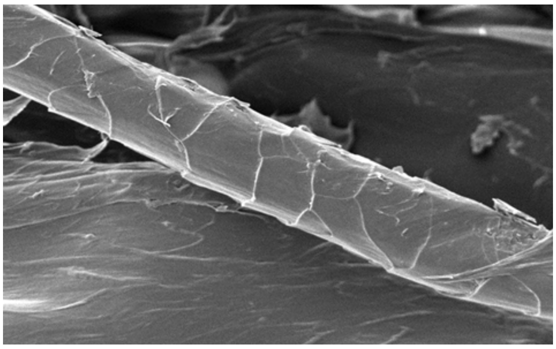

Fig. 1: Ordinary wool filament.

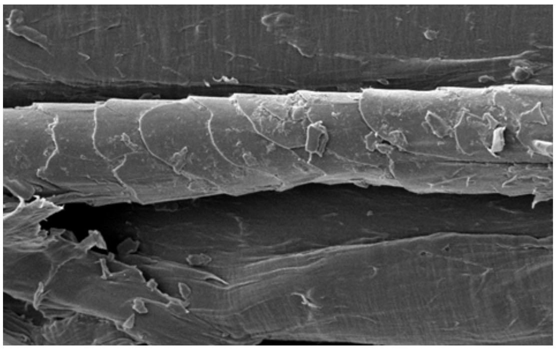

Fig. 2: The wool filament treated with atmospheric plasma [Ceria 2010].

The plasma treatment of the wool fabric is performed in the special pilot unit produced by Grinp s.r.l. in the frame of the research project PLAFI financed by the Piedmont Region. The pilot unit is based on an innovative mobile plasma electrode able to treat directly a bed of fibers coming from a carding machine, which promotes a relevant penetration of plasma through all the bed height. The wool fiber bed was processed in the pilot plasma unit at a rate of 5 kg/h.

The density of both the ordinary and the treated wool fibers is 1.32 g/cm^3 (at 17% of humidity).

With these materials, the following mortars were cast:

- M= Plain mortar, in which the sand/cement and water/cement weight ratios are 1:3 and 1:2, respectively [EN 196-1 2005].
- L = Fiber-reinforced mortar, containing ordinary wool (Fig.1). This mortar is prepared with sand/(cement + fibers) and water/(cement + fibers) weight ratios of 1:3 and 1:2, respectively. As wool fibers absorb water, the fiber content is subtracted from the cement content [Hamzaoui 2014].
- LT = Treated Fiber-Reinforced Mortar, prepared with sand/(cement + fibers) and water/(cement + fibers) weight ratios of 1:3 and 1:2, respectively. This mortar is reinforced with wool fibers previously subjected to the plasma treatment (Fig.2).

As shown in Tab.2, which reports the weight composition of all the mortars, the L and LT mortars are reinforced with 10 grams (1% in volume) of ordinary and treated wool.

Tab. 1: Particle size distribution of the sand[EN 196-1 2005].

Square mesh size (mm)	2.00	1.60	1.00	0.50	0.16	0.08
Cumulative sieve residue (%)	0	7 ± 5	33 ± 5	67 ± 5	87 ± 5	99 ± 5

Tab. 2: Compositions of the mortars.

Type of mortar	**Cement** (g)	**Water** (g)	**Sand** (g)	**Wool** (g)	**Treated wool** (g)
M	450	225	1350	-	-
L	440	225	1350	10	-
LT	440	225	1350	-	10

2.2 Specimens and test setup

Three specimens were cast per each mortar described in Tab.2. According to EN 196-1 [EN 196-1 2005], all the nine specimens are prisms with the dimensions of 40 × 40 × 160 mm (Fig.3). The specimens were cast on October 23, 2014 and have an alphanumeric label, composed by the name of the mortar (i.e., M, L, and LT) and by the date of casting (i.e., 23_10). Finally, a number (i.e., 1, 2, and 3) is used to distinguish the three specimens made by the same mortar.

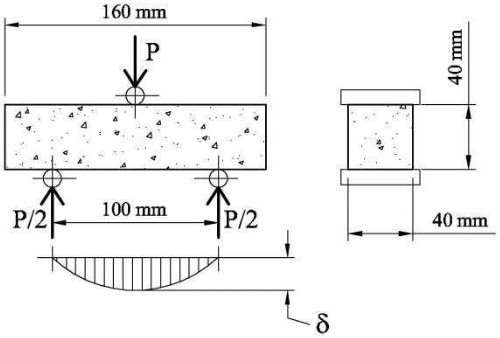

Fig. 3: Three point bending tests for cementitious mortars [EN 196-1 2005].

Fig. 4: The specimens tested in three point bending.

The nine prisms, shown in Fig.4, were demoulded one day after casting and stored in water at 20°C. As suggested by EN 196-1 [EN 196-1 2005], three point bending tests (Fig.3) 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 (Fig.3)

3 TEST RESULTS AND DISCUSSION

Tab.3 reports the main data measured in each test. In particular, the value of the flexural strength, σ_F, also known as modulus of rupture, can be calculated, in the linear elastic regime, by using the following formula:

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

Where l=100 mm and B=40 mm (see Fig.3). In Eq.(1), $P_{\max}$ is the maximum value of the load P measured during the test.

Fig.5 shows the load-deflection (P-δ) diagrams of the nine tests, grouped for each type of mortar (plain mortar – M – in Fig.5a, fiber-reinforced – L – mortar in Fig.5b, and fiber-reinforced – LT – mortar in Fig.5c). During the ascending branch of each curve, elastic modulus cannot be measured. In fact, no local displacements were determined, as prescribed for the characterization of structural concrete [Fib 2013]. However, mortars are not properly used as structural materials, thus from the P-δ curves important information can also be obtained. In particular, as illustrated in Fig.5d, both $P_{\max}$ and the corresponding displacement, δ_p, are detected in all the curves, and their values are reported in Tab.3.

With respect to plain mortar, fiber-reinforced mortars exhibit higher values of the maximum applied load, and of the corresponding flexural strength. This is true both for L and LT mixtures, although the cement content is lower than that of the plain mortars. More precisely, if ordinary wool fibers are added (L mixture), $P_{\max}$ is 18% higher than M mortar. Whereas, $P_{\max}$ is 23% higher when plain mortar is reinforced with wool fibers treated with plasma (LT mixture).

The mechanical performances of cementitious mortars are therefore modified by the presence of wool filaments, similarly to the mortars reinforced with hemp fibers [Hamzaoui 2014]. The better properties of the L and LT mixtures are not only evidenced by the strength. Also the ductility, and the fracture toughness, of the cementitious mortars can be improved by the presence of fiber-reinforcement made by wool.

Tab. 3: Test results of the three point bending tests.

Specimen	**Type of mortar**	**$P_{\max}$** (N)	**σ_F** (MPa)	**δ_p** (mm)	**A_F** (mm)	**G_F** (N/mm)
M23_10_1	M	1773	4.15	0.12	0.012	0.052
M23_10_2		1919	4.50	0.10	0.012	0.055
M23_10_3		1671	3.92	0.10	0.015	0.061
L23_10_1	L	2085	4.89	0.12	0.032	0.158
L23_10_2		2330	5.46	0.15	0.026	0.141
L23_10_3		1926	4.51	0.12	0.027	0.123
LT23_10_1	LT	2266	5.31	0.78	0.024	0.125
LT23_10_2		2162	5.07	0.11	0.029	0.145
LT23_10_3		2183	5.12	0.19	0.035	0.177

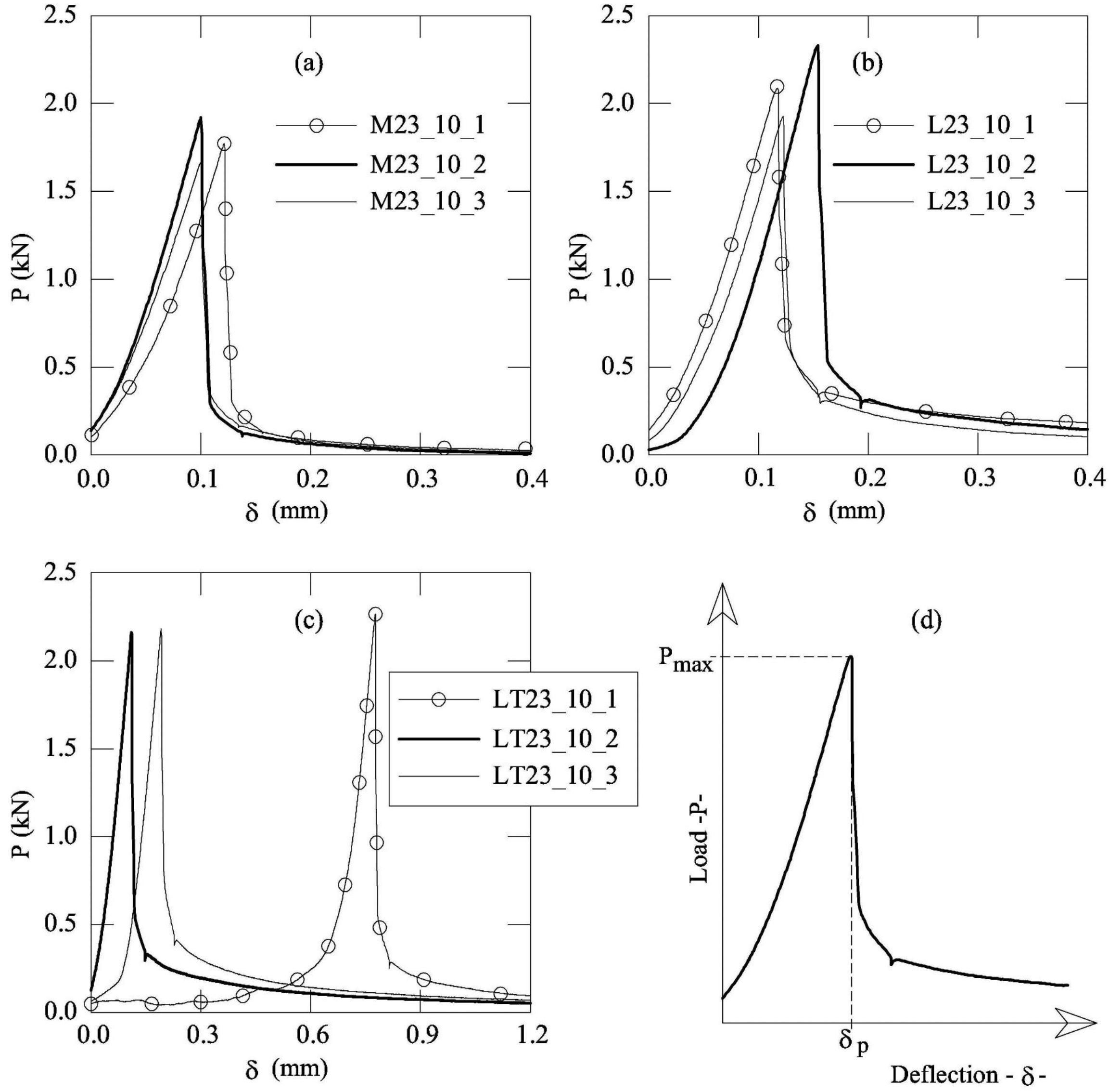

Fig. 5: The results of the three point bending tests in terms of load - midspan deflection (P-δ): (a) plain mortar - M; (b) mortar reinforced with ordinary wool – L; (c) mortar reinforced with wool treated with atmospheric plasma– LT; (d) the main mechanical parameters of the P-δ curves.

To illustrate this aspect also in absence of local measurements, a new approach for defining the post-peak properties of the mortars is proposed in the present paper. Starting from the *P*-δ curves depicted in Fig.5, the new post-peak diagrams reported in Fig.6 can be introduced. On the ordinate of such diagrams, the values of the normalised load (with respect to P_{max}) are reported. Conversely, the difference between the post-peak deflection and δ_p is on the abscissa. 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 (M in Fig.6a) is remarkable lower than those measured in fiber-reinforced mortars (L in Fig.6b, and LT in Fig.6c).

The ductility of the three mortars herein investigated can also be quantified by calculating the area A_F delimited by the post-peak curves (see Fig.6d). If this value is multiplied by the flexural strength, σ_F, a sort of fracture toughness in bending, G_F, can be attained. Both the values of A_F and G_F are given in Tab.3, whereas the average values of the main mechanical performances (i.e., P_{max}, A_F and G_F) of the three mortars are compared in the histograms depicted in Fig.7.

Due to the presence of wool fibers, the values of ductility (A_F in Fig.7b) and of fracture toughness (G_F in Fig.7c) increase more than the maximum applied load (P_{max} in Fig.7a). Such increments are more or less similar to those observed in the cement-based composites reinforced with steel or plastic fibers [Balaguru 1992]. In particular, the values of A_F calculated for L and LT mortars are, respectively, 110% and 115% higher than that of M mortar.

The ductility is a fundamental property shown by the specimens reinforced wool fibers. Indeed, the higher the fracture toughness, the higher the durability, and thus the sustainability, of cement-based composites [Reinhardt 2013]. In other words, the sustainability of the mortars reinforced with wool fibers can be ascribed to the reduction of the cement content, to the use of waste wool, and to the higher mechanical performances as well.

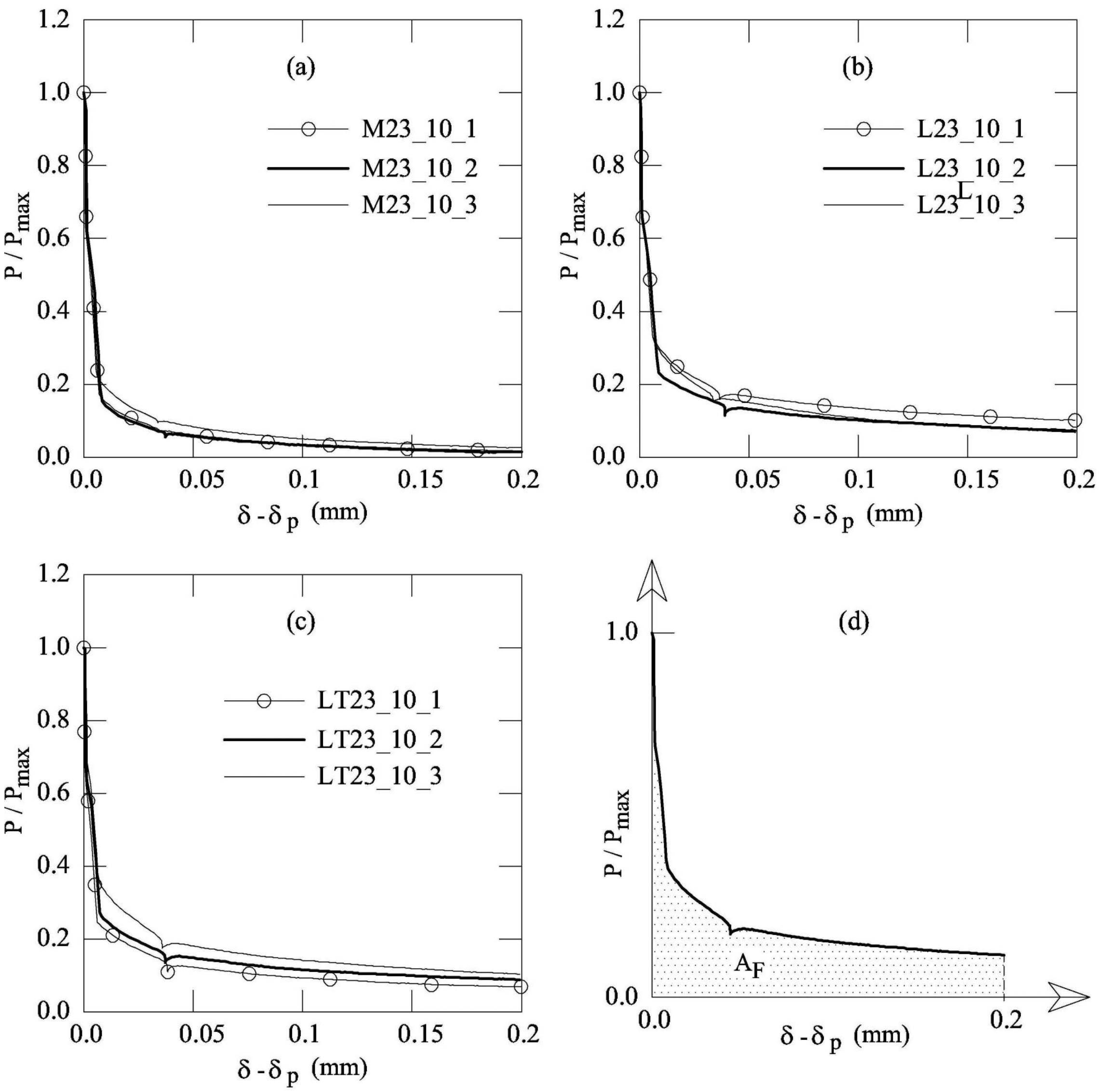

Fig. 6: The post-peak response of the mortars: (a) plain mortar - M; (b) mortar reinforced with ordinary wool – L; (c) mortar reinforced with wool treated with atmospheric plasma– LT; (d) definition of the ductility.

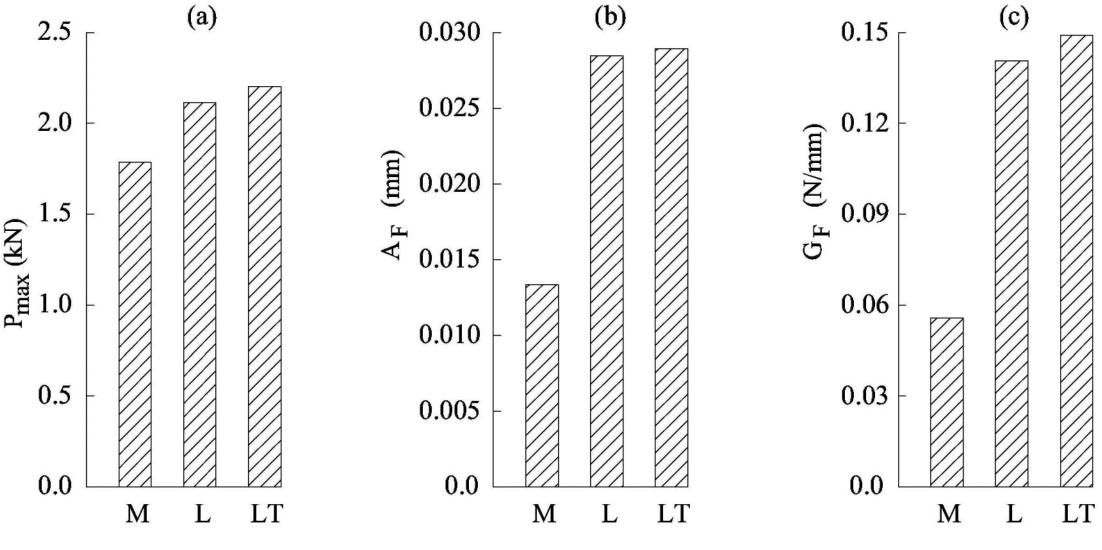

Fig.7. The average values of the main mechanical parameters measured in the three point bending tests: (a) the maximum load P_{max}; (b) the ductility A_F; (c) the fracture toughness G_F.

4 CONCLUSIONS

From the results of the experimental investigations previously described, and conducted for the first time on mortars reinforced with wool fibers, the following conclusions can be drawn:

- The addition of wool fibers, treated or not with the atmospheric plasma, can improve the performance of cementitious mortar and increase the sustainability of such building material.
- If 10 grams (1% in volume) of ordinary wool substitute an equivalent mass of cement in plain mortar, the flexural strength and the fracture toughness in bending increase of 18% and 110%, respectively.
- If 10 grams (1% in volume) of wool treated with atmospheric plasma substitute an equivalent mass of cement in plain mortar, the flexural strength and the fracture toughness in bending increase of 23% and 115%, respectively

Finally, further experimental campaigns need to be performed to optimize the tailoring procedure (e.g., reduce the cement and increase the fiber content, without compromising the workability and the mechanical performances) and to analyse the chemical damage of wool in alkaline environments.

5 ACKNOWLEDGMENTS

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