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The use of wool as fiber-reinforcement in cement-based mortar

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HIGHLIGHTS

- Wool and hemp fibers are used herein to reinforce cement-based mortars.
- Tests are performed on these mortars in accordance with UNI EN 196-1-2006.
- Similarly to hemp, the fracture toughness increases in mortars reinforced with wool.
- Hence, by using wool the environmental impact of cement mortars reduces.

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ABSTRACT

Fiber-reinforced cementitious mortars are widely used in the construction industry. Indeed, 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. Also vegetal fibers, such as bamboo and hemp, have been used in the last decades to reinforce mortars. Besides, with the aim of introducing 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 small beams made, respectively, with plain mortar, and mortar reinforced with 1% in volume of wool. To compare the performances with mortars containing vegetal fibers, also beams reinforced with hemp have been tested. In some tests, wool and hemp are 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, treated or not, is added to cementitious mortars. Similarly to hemp, wool does improve the mechanical and ecological performances of the mortars, and creates a link between textile and construction markets.

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 [1], 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 [2].

To find a solution to the above-mentioned problems, the construction industry has adopted eco-friendly practices to reduce the environmental impact [3]. Through the substitution strategy, for instance, pozzolanic mineral admixtures, such as fly ashes and silica fumes, take the place of clinker. In the same way, traditional aggregates can be replaced by waste materials (e.g., recycled aggregate concrete, rubber from end of life tyres, etc.). Nevertheless, environmental-friendly concretes are also obtained with the so-called material performance strategy, which consists of improving the performances of concrete [4]. In particular, both the embodied energy and the released CO_2 reduce when strength and toughness of concrete increase [5]. Accordingly, more sustainable cement-based composites can be obtained by reinforcing the matrix with randomly dispersed short fibers. Among them, vegetal fibers, made with bamboo and hemp, have been used to reinforce some cement-based composites [6]. Indeed, these natural fibers

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are usually stronger and more environmental friendly than synthetic fibers (e.g., PVA or polypropylene), and can enhance the toughness of cementitious mortars [7].

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 construction [8]. 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 [9].

Wool and other keratinous fibers, such as human hair, have been largely investigated in last years. In some studies, mesoscopic models of the keratin filaments are also proposed [10]. The models are generally based on the macroscopic mechanical properties of the fibers, which are similar to those of some polymers. Indeed, the elastic modulus of the wool, comprised between 1 and 4 GPa, is comparable to that of plastic fibers used to reinforce cement-based composites [11]. In other studies, theoretical and experimental analyses have been conducted in order to modify the structure of the filaments. For instance, Ceria et al. [12] introduced an atmospheric plasma jet treatment to modify the properties of wool fabric. 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). Also Wu and Li [13] proved that plasma treatment can effectively modify the surface characteristics of polyethylene fibers that reinforce concretes. The resulting surface modifications can lead to significant improvement in the interfacial properties fiber-cementitious matrix.

Accordingly, a huge amount of waste, composed by wool, is similar to the plastic reinforcement used in some cement-based composites, and thus it can be effectively used as a construction material, rather than landfilled. Nevertheless, experimental investigations on the use of wool as fiber-reinforcement in cement-based composites cannot be found in the technical literature. The authors believe that the tests performed on cementitious mortars reinforced with wool fibers, as described for the first time in the following sections, can be very useful to create an additional and more sustainable market for a valuable resource.

2. Experimental procedure

Three point bending tests have been performed at Politecnico di Torino (Italy) on specimens made with plain and fiber-reinforced cement-based mortars. The procedure used in the present experimental campaign is in accordance with the European guidelines EN 196-1 [14].

2.1. Materials and mixtures

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 Table 1 [14].

To the traditional mixture suggested by EN 196-1 [14], a suitable amount of non-treated (Fig. 1a) and plasma treated (Fig. 1b) wool fibers is added. In the case of the treated wool, the SEM image illustrated in Fig. 1b reveals that fiber surface is slightly modified, even if the original flakes are not damaged. The plasma treatment of the wool fabric is performed in the special pilot unit produced by Grinp s.r.l., within a research project named PLAFI and 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 per hour.

Both the non-treated fibers (hereafter named L) and the treated fibers (hereafter named LT) have different diameters (Fig. 2a for L, and Fig. 2c for LT) and lengths (Fig. 2b for L, and Fig. 2d for LT). The diameter is 19 μm in average (about a quarter that of the human hair [10]), whereas the average length of the two types of fibers is about 16 mm.

To measure the strength of the wool filaments, uniaxial tensile tests have been performed by controlling the stoke movement (displacement rate = 0.05 mm/s) of a MTS testing machine equipped with a loading cell of 10 N. Tensile strengths of 240 MPa and of 290 MPa are obtained from the stress-strain diagrams reported in Fig. 3a (for L fiber) and Fig. 3b (LT fiber), respectively. Such strength is almost identical to that measured by Chou et al. [10] in human hairs, whereas it is 30% lower than that of the polypropylene fibers used by Banthia and Nandakumar [11]. The elastic modulus (E_f in Fig. 3), comprised between 2 and 3 GPa, is comparable with those of human hair [10] and plastic fibers [11]. Finally, the density of both non-treated and treated wool is 1.32 g/cm^3 (at 17% of humidity).

To compare the performances of wool-reinforced mortars with those containing other natural fibers, which have been deeply investigated in past studies [7], also non-treated hemp and plasma treated hemp are used. With all the above-mentioned 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 [14].
- L = fiber-reinforced mortar, containing non-treated wool (Fig. 1a). 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 [7].
- 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. 1b).
- C = fiber-reinforced mortar, containing non-treated hemp. The composition of this mortar is similar to that of mortar L.
- CT = treated fiber-reinforced mortar. This mortar, similar to mortar LT, is reinforced with hemp fibers previously subjected to the plasma treatment.

As shown in Table 2, which reports the composition of all the mortars, the L and LT mortars are reinforced with 10 g (1% in

Table 1
Particle size distribution of the sand [14].

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

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