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Case study

Induced Modification of Flexural Toughness of Natural Hydraulic Lime Based Mortars by Addition of Giant Reed Fibers

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ABSTRACT

Nowadays, there is a growing need to reduce the environmental impact generated by the use of inorganic materials for building applications.

The aim of this work is to investigate the bio-lime based mortar flexural toughness improvement due to the addition of common reed fibers (*Arundo donax* L.) in order to evaluate their possible application as ductile eco-compatible prefabricated bricks or laying and joint mortars for masonry.

Different sets of specimens were tested by varying the fiber weight content and the fiber length. Moreover, chemical treatments with *Linseed Oil* and *Polyethylene glycol* (PEG) were performed to improve the physical and mechanical properties of the fibers as well as the fiber/matrix interfacial adhesion.

The Mechanical characterization of the neat and treated fibers was performed through *Single Fiber Pull-out Test* and *Single Fiber Tensile Test.* The quasi-static mechanical properties of the composites were evaluated through *Three-Point Bending* and *Compressive* tests. Finally, an analytical model proposed in the literature has been used to evaluate the parameters that influence the post-fracture behavior of the composites.

Overall, the findings of this study are valuable to understand the flexural behavior of new eco-compatible natural fibers reinforced mortars for masonry application providing scientific evidence of the effectiveness of giant reed fibers in the manufacturing of green building materials, as bricks or laying mortars.

1. Introduction

Nowadays, there is a growing interest in ecological and natural building materials and methods [1]. The use of natural fibers as reinforcement for cement or lime-based mortars is increasingly emerging due to the improvement of mechanical properties that encourages their application in green building [2,3].

Flexural toughness is crucial for building applications to withstand horizontal stresses such as earthquake shocks or wind. A significant advantage concerning fiber reinforcement of brittle materials is the composite behavior after cracking. Post-cracking toughness induced by natural fibers in cement materials may allow the large-scale construction use of such composites. The reinforcement is distributed into the composite leading to the effective capacity of sealing and bridging cracks under flexural or tensile stress [4].

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However, very short research has considered giant reed fiber as reinforcement of cementitious matrix, although its high potential as successful substitutes of inorganic and artificial fibers for green building due to the advantages of environmental efficiency, lightweight, low cost and good mechanical properties [5].

A considerable amount of research has investigated the influence of different types of fibers on the mechanical performance of concrete composites for building engineering [6–8]. Felekoğlu et al. [9] found that high strength concrete with high strength fibers provides the best performance in flexural strength and toughness. However, very few can be found in literature about the use of fibers in natural hydraulic limes (NHL) based mortars for masonry applications. Some research [10] has evidenced the crucial role of the reinforcement in improving their flexural toughness and post-cracking behavior, which are properties of fundamental importance especially for masonry structures located in areas of seismic activity where hydraulic lime are used in the repair of heritage buildings [11]. The use of different types of fibers in cementitious materials is also widespread for several reasons. Synthetic or metallic microfibers (e.g., PAN carbon, Pitch carbon, PVA, Steel microfibers) are commonly used for high-performance structural concrete for their ability to seal microcracks in concretes or mortars [12,13]. However, vegetable lignocellulosic fibers present several attractive advantages which are recently encouraging a wider use in building engineering [14,15]. Vegetable fiber cement composites exhibit improved toughness, ductility, flexural capacity and crack resistance compared with unreinforced cement-based materials. The primary benefit of fiber reinforcement is the behavior of the composite after cracking, as the fibers bridge the matrix cracks and transfer the loads [16]. Further advantages are their low real (1.3÷1.5 g/cm^3) and apparent density (0.4÷1.5 g/cm^3), high specific stiffness and strength, renewability, low processing energy, and their availability at low cost and in a variety of morphologies and dimensions [17,18]. It was also ascertained that the addition of natural fibers is useful in restraining plastic shrinkage of the cement matrix, promoting an active self-healing of plastic cracking [19]. Therefore, their use is effective to compensate for shrinkage brittleness and give higher toughness to the material [20]. Natural fibers also find several civil applications for their insulating properties that allow obtaining materials of better thermal resistance for construction of roofs or external insulating walls [21] coupling to seismic improvement help in convincing final users.

The ability to bear loads even after the first damage occurs also identifies their potential to absorb energy beyond the first rupture load [22]. The flexural properties it is well known to be strongly affected by fiber dosage [23], shape [24], geometry [25], distribution and orientation [26,27], fiber/matrix interfacial adhesion [28–32].

The use of a particular plant as a source of fiber for a given application depends on its availability and cost of extraction [33]. The choice of using the giant reed *Arundo donax* L. fiber as reinforcement for biolime mortars is justified by the characteristics of this type of plant, very available in nature and with high quantities of materials at the end of their service life cycle to building purposes. They also have good mechanical properties such as high stiffness and strength, which encourage a practical use as natural reinforcement for brittle mortars. Chemical and morphological characterization of the fibers used in this work was performed in previous studies [3,34].

In this paper, the flexural properties of reed fibers reinforced natural hydraulic lime mortars have been investigated in order to consider their application as ductile eco-compatible prefabricated bricks, laying and repairing mortars for green building masonry application.

2. Materials and methods

2.1. Raw Materials

2.1.1. Arundo donax L. fiber

Beams of dried common reed stems, previously separated from the leaves, were provided from a plantation in the area of Catania in the east of Sicily. The stems were approximately of equal inner and outer diameters to ensure similar physical and mechanical properties. After cutting the stems with a band saw, the outer skins were manually decorticated by mechanical separation with the aid of a mallet. The fibers were finally obtained by cutting the outer skins with the aid of a scalpel.

Firstly, the influence on the flexural properties of the composites in function of the weight content of short fiber (4 cm) was investigated. Secondly, three different aspect ratios of the fibers were obtained in order to evaluate the influence of the fiber length. The average thickness and width, which were evaluated by averaging three measures for each fiber on a sample of 20 fibers, were respectively equal to 0.35 ± 0.08 mm and 2.88 ± 0.69 mm. The nominal lengths investigated were 4 cm, 8 cm and 12 cm, the latter is the longest possible as it is the average distance between the culms of the *Arundo donax* L. stem, the smaller sizes have been chosen in order to investigate the modification of toughness by reducing the fiber length. Fig. 1 shows the manufacturing process of the *Arundo donax* L. fibers used in this work.

2.1.2. Biolime mortar

Biolime based mortars are recyclable as inert at the end of life, with reduced CO_2 emissions compared to cement ones.

The premixed mortar used in the experimentation, *Kerakoll Biocalce Pietra*, was an NHL 3.5 based mortar for building applications in the construction and grouting of masonry. The main properties are reported in Table 1, according to the technical datasheet of the mortar. It is constituted by 67% of recycled minerals and belongs to the M5 class, according to the standard BS EN 998-2 [35], it is mainly used for building laying masonry and plastering. The binder is a Natural Hydraulic Lime, classified as NHL 3.5, according to BS EN 459-1 [36] Italian Standard that includes mortars having a compressive strength between 3.5 and 10 MPa after 28 days of hardening. Fig. 2 shows the XRD pattern for the raw material used as

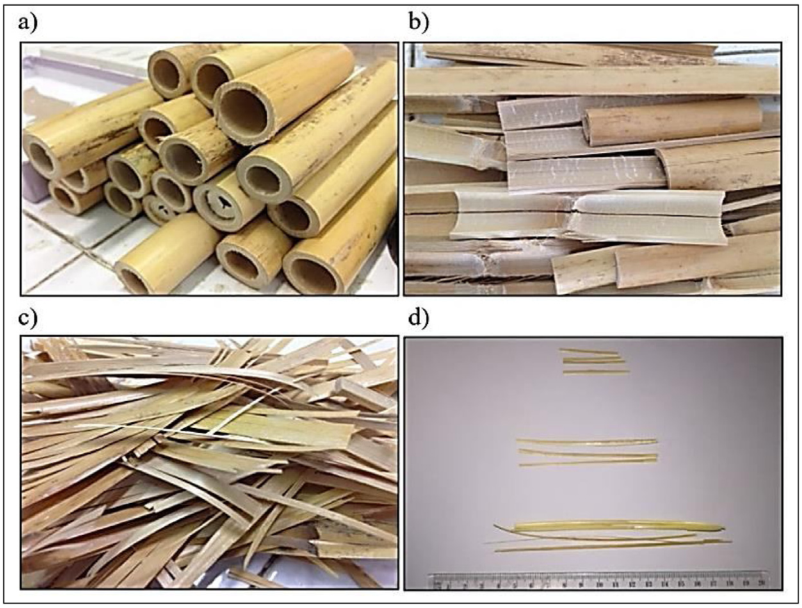

Fig. 1. Manufacturing process of the fibers: a) Cut stems; b) Broken stems; c) Decorticated skins; d) 4, 8, 12 cm long *Arundo donax* L. fibers.

Table 1
Main fresh and hardened properties of the biolime mortar.

Technical data according to standard		
Type of mortar	Premixed masonry mortar for external use in elements subject to structural requirements	EN 998-2
Chemical nature of the binder	Natural Hydraulic Lime NHL 3.5	EN 459-1
Particle size range of the aggregate	0-1.4 mm	EN 1015-1
Apparent density of the powder	1.57 kg/dm^3	UEAtc
Consistence of the fresh mortar	165 mm	EN 1015-3
Apparent density of the fresh mortar	1.97 kg/dm^3	EN 1015-6
Apparent density of the hardened mortar	1.8 kg/dm^3	EN 1015-10
Compressive Strength	M5	EN 998-2
Coefficient of resistance to water vapor	$15 \leq \mu \leq 35$	EN 1015-19
Water absorption by capillary	0.4 kg/(m^2 · min$^{0.5}$)	EN 1015-18
Thermal conductivity ($\lambda_{10,}$ dry)	0,75 W/mK	EN 1745

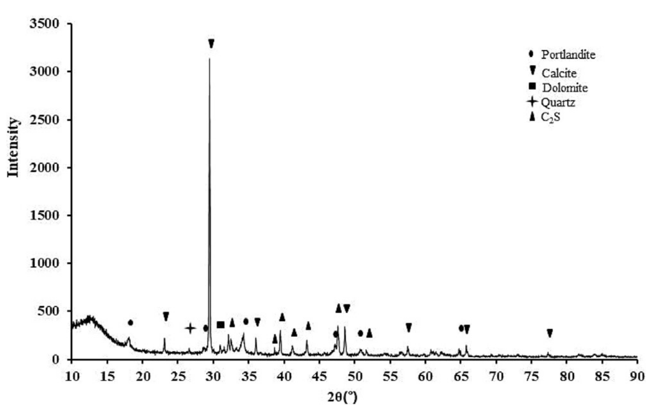

Fig. 2. XRD pattern for the premixed mortar used.

matrix. The diffractogram evidences the presence of portlandite, belite (C_2S), calcite, dolomite and quartz. The mineralogic composition of the mortar suggests that it is constituted by hydraulic lime, pozzolanic additives, silica sand, dolomitic and carbonate limestone.

2.2. Chemical treatments of the Arundo donax L. fiber

The effect of two different chemical treatments on the mechanical flexural properties of the composites was also investigated. The former, with Linseed Oil ($C_{18}H_{30}O_2$), was performed for three reasons. Firstly, it is supposed to improve the mechanical properties of the fibers giving them more stiffness and strength. Secondly, since its hydrophobic nature, it may reduce fiber water absorption from the mortar in the fresh state and hence ensure its correct designed water to binder ratio [22]. Finally, in hardened mortars, linseed oil will reduce the moisture absorption of the fibers from the air that could cause a reduction in stiffness and strength of the fibers [37,38]. Indeed, it is essential to preserve the cellulose fibers from water uptake, it can be achieved by less hydrophilic surfaces (either natural or after an adequate treatment), and without losing the quality of the fiber bridging that is responsible for the composite ductility [4]. The latter treatment, with *Polyethylene glycol* (PEG) ($C_{2n}H_{4n+2}O_{n+1}$), was performed since it is commonly used as chemical additive of wooden materials to limit swelling and distortion due to water absorption and consolidate archaeological woods found in marine or moist environments and soils [39]. The opinion of the authors is that PEG may reduce the swelling of the fibers due to water absorption from the mortar and therefore enhance the interfacial adhesion between fibers and mortar. Before the preparation of the mortars, single fiber pullout tests have been performed on fiber treated with PEG 600 and PEG 4000 to choose the most suitable one. Before both the chemical treatments, the fibers were dried using an *Isco Mod VO 90* oven at a temperature of 103 °C for 24 h to minimize the influence of the moisture content and hence stabilize their physical properties.

2.2.1. Linseed oil treatment

The treatment with Linseed Oil consisted of soaking the dried fibers in an aluminum container filled with the additive, and then mechanical stirring was carried out for about 5 min. The treatment time was determined from single fiber absorption oil tests on a sample of 5 fibers. The average weight increment due to linseed oil absorption was determined through the Eq. (1):

$$\Delta M_t[\%] = 100\ \frac{M_t - M_0}{M_0} \quad (1)$$

Where ΔM_t is the percentage weight increment in function of the treatment time, M_t is the weight at the time t and M_0 is the dried weight of the fibers. By observing the Fig. 3, it is possible noting that already after 1 min, the fibers can be considered saturated. We choose a longer time to avoid the risk of ununiformed absorption.

2.2.2. Polyethylene glycol treatment

The treatment with PEG consisted of soaking the dried fibers in a container with a solution of distilled water and PEG at 30% by weight, after that the containers were put in an *Isco Mod VO 90* oven at T = 35 °C until total evaporation of the solvent to allow the complete absorption of the PEG by the fibers (96 h). The fibers were then washed with distilled water to remove the polymer in excess and left drying at room temperature for 24 h before the manufacturing of the samples. The percentage of 30% by weight was considered a fair compromise between using enough PEG to modify the characteristic of the fibers and maintaining a low viscosity solution to ensure a good wettability of the fibers [40,41].

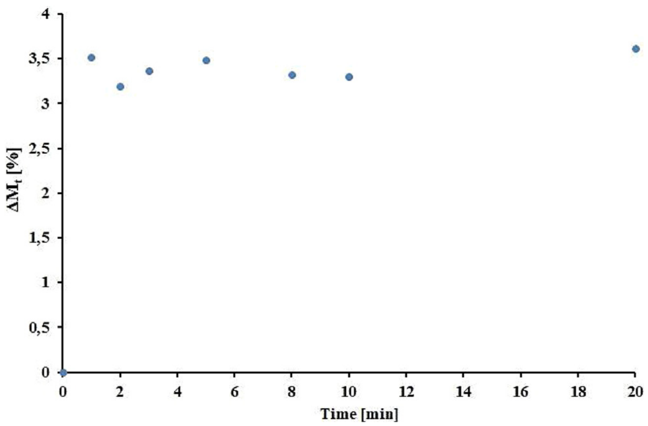

Fig. 3. Linseed Oil absorption of the *Arundo donax* L. fibers in function of the treatment time.

2.3. Physical and mechanical characterization of Arundo donax L. fiber

2.3.1. Water absorption test

Single fiber water absorption test at different times after linseed oil treatment was performed in order to evaluate the suitable reticulation time before the preparation of the mortars. The water absorption percentage ΔWA_t was calculated by the following Eq. (2):

$$\Delta WA_t[\%] = 100\ \frac{m_t - m_0}{m_0} \tag{2}$$

Where m_t is the weight at the time t and m_0 is the initial weight of the linseed oil treated fibers. Fig. 4 shows the water absorption curves of the untreated fibers (NT) and the linseed oil treated fibers at different times from treatment i.e., T_0 h, T_4 h and T_72 h. The water absorption after 10 minutes, which is approximately the time necessary for mixing and casting the mortars, was 16.5%, 12%, 9% and 3% respectively for NT, T_0 h, T_4 h and T_72 h fibers. On the basis of these results, the fibers were dried in laboratory-controlled conditions i.e., 25 °C and 60% RH, for three days, as also suggested by the literature [42], before the manufacturing of the samples in order to allow the proper reticulation of the oil on the surface of the fibers and hence reduce their water absorption capacity.

2.3.2. Single fiber pull-out test

Single fiber pull-out tests were performed on fiber treated with PEG 600 and PEG 4000 in order to choose the most suitable one for the preparation of the mortars. At least ten measures have been performed to estimate the quality of interfacial adhesion between fibers and mortars. It significantly influences the flexural properties of the mortars, especially regarding the post-fracture behavior. The tests were performed on 12 cm long fibers in displacement control in a *Zwick/Roell Z005* testing machine equipped with a 5 kN capacity load cell. The testing speed was set to 0.5 mm/min. The nominal embedment length of the fiber in the mortar was 25 mm [43], which is far lower than the critical bond length [44], allowing the evaluation of the *Maximum Pull-out Strength* τ_{max} for each specimen. The nominal width and thickness were respectively 3.50 mm and 0.5 mm. The *Maximum Pull-out Strength* τ_{max} was calculated by dividing the maximum pull-out force by the contact surface between fiber and matrix using the following Eq. (3)

$$\tau_{max} = \frac{F_{max}}{2l_i(w + t)} \tag{3}$$

where F_{max} is the maximum pull-out force, w and t are respectively the width and the thickness of the fiber calculated as the average of three measures within the embedment length, while l_i is the fiber-matrix embedment length. Fig. 5 shows the experimental setup for the *Single Fiber Pull-out* test.

The *Stress-Slip* response is reported in Fig. 6 for three representative tests for each typology. Both for untreated and PEG treated fibers, at small slips the experimental curves show an elastic followed by a plastic bond stress versus slip response. At higher slips, the remarkable fluctuations can be ascribed to differences in the dimensions and shape of the cross-section of the fiber along the pull-out direction [43]. This induces multiple mechanical interlockings between fiber and mortar during the pull-out. The latter are responsible for the alternate loss and recovery of the shear strength that mostly is higher than the adhesive shear strength that determines the first separation between the fiber and the mortar.

The average results, shown in Fig. 7, highlight a slight increase, even if not clearly stated due to high value of standard deviation, of the pull-out strength in function of the molecular weight from 0.024 for untreated fibers to 0.032 MPa for PEG 4000 treated fibers with an increase of 33,3%, suggesting an improved fiber/matrix compatibility. According to this consideration, the treatment with PEG 4000 was chosen for the preparation of the mortars.

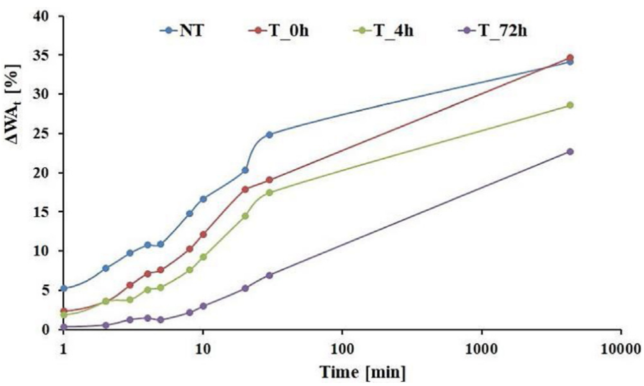

Fig. 4. Water absorption of the fibers after different times from linseed oil treatment. Legenda: NT: Untreated fibers; T: Treated fibers, where 0 h, 4 h and 72 h indicates the time elapsed between linseed oil impregnation and water absorption measurements.

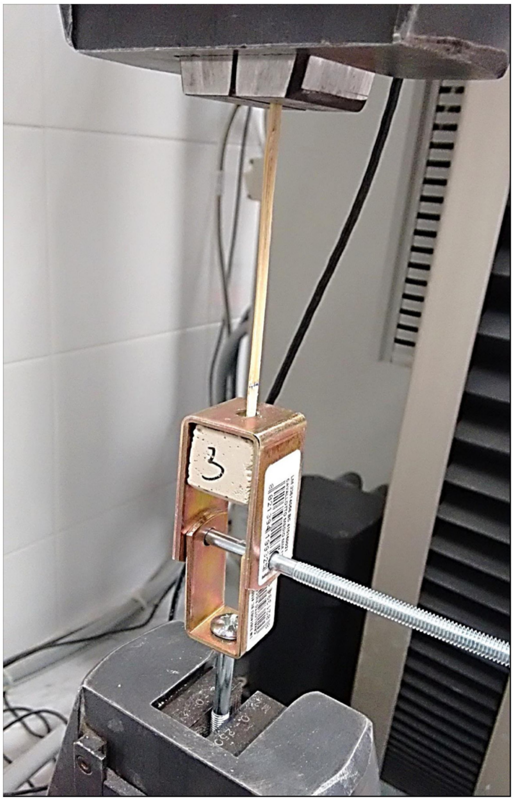

Fig. 5. Setup Single Fiber Pull-out Test.

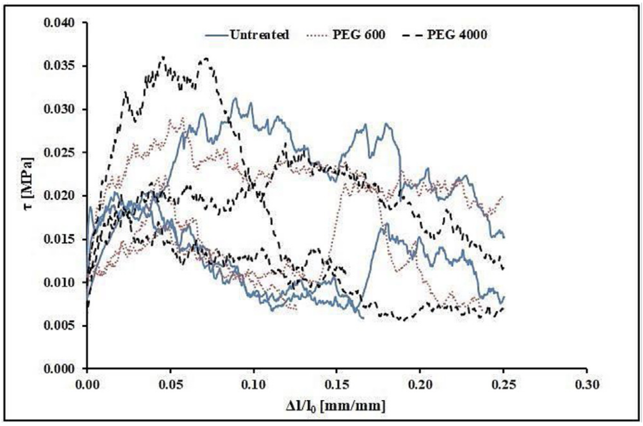

Fig. 6. Stress-Slip curves of the Single Fiber pull-out test.

2.3.3. Single fiber tensile test

Single fiber tensile tests were performed on at least 20 *Arundo donax* L. not treated and PEG 4000 treated fibers, as PEG can induce a reduction in both Young Modulus and Tensile Strength [45], in order to estimate the influence of the chemical treatment on their mechanical properties. The tests were performed in displacement control on 12 cm of nominal length fibers. It is the average distance between the culms of the plant and hence can be considered representative for tensile characterization. An Electromechanical Universal Testing Machine (WANCE UTM 502), *MP Strumenti* equipped with a load cell of 50 kN was used. The testing speed was set to 0.5 mm/min to obtain the rupture of the fibers within 1÷2 min. The distance between grips was set to 70 mm to allow a gripping length of at least 25 mm for each side adequate for transferring

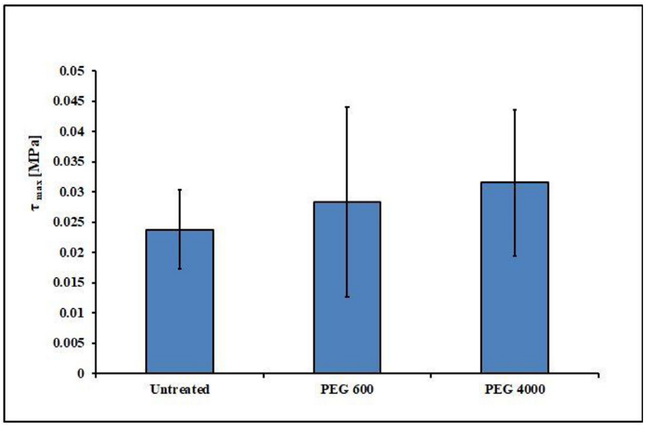

Fig. 7. Single Fiber pull-out test results.

the load without local damages of the fibers. The actual displacement of the specimens was evaluated using an NCS CISRI extensometer, having a fixed gauge length equal to 50 mm and capable of measuring displacements up to 10 mm. The average resistant cross-section of each fiber was evaluated by taking three measures of width and thickness along the longitudinal axis with a centesimal caliber. For each sample, *Tensile Strength* (the ratio between the Load of Rupture and the average resistant cross-section of the fiber) and *Young Modulus* (the slope of the initial linear behavior in the *Stress-Strain* curve) were calculated and the results recorded as mean value and standard deviation. The *Stress-Strain* curves of four representative tests, shown in Fig. 8, evidence a brittle behavior of both untreated and PEG treated fibers with an overall linear elastic trend until failure. Fig. 9 shows the results of the *Single Fiber Tensile Test*. The treatment with PEG 4000 leads to a slight increase in both the *Young Modulus* and the *Tensile Strength*, respectively by 3.2% and 2.2%.

2.4. Composites manufacturing

The first purpose of this experimental research was to evaluate the influence of short fiber (4 cm) content on the mechanical flexural behavior of bio-lime based mortar composites. The amount of fiber addiction is expressed in weight percentage instead of volume percentage, i.e., 1% means 1 g of fiber for 100 g of dry mortar. Weight percentage was preferred to ensure good repeatability of mixtures, as equal volumes of fibers can contain significantly different amounts of fibers due to compaction issues, especially for long fibers. The fiber content range was determined by preliminary tests aimed to evaluate the maximum fiber content that allowed a practical feasibility of the mortars. Weight content higher than 2% led to very difficult compaction and evident issues of fiber dispersion and homogeneity of the samples. For this reason, it was decided to investigate the fiber content range between 0 and 2% wt.

Hence, four different sets of specimens were prepared by varying the percentage of the fibers: 0%, 0.5%, 1%, 2% by weight.

The authors also investigated the modification of the flexural behavior of biolime based mortars in function of the fiber length. To this purpose 4, 8 and 12 cm long fibers were used as reinforcement at two different percentages: 1% and 2% wt.

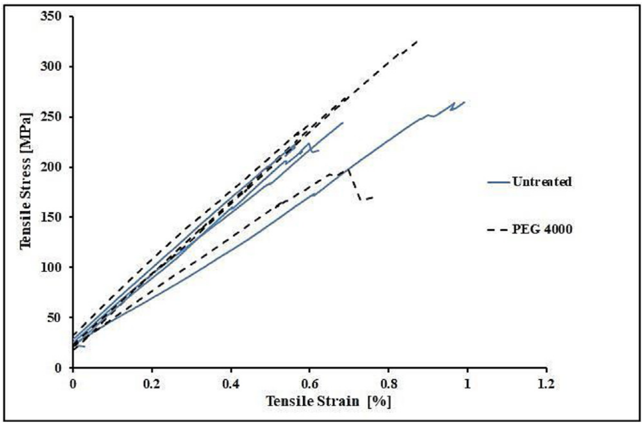

Fig. 8. Stress-Strain curves of the Single Fiber tensile test.

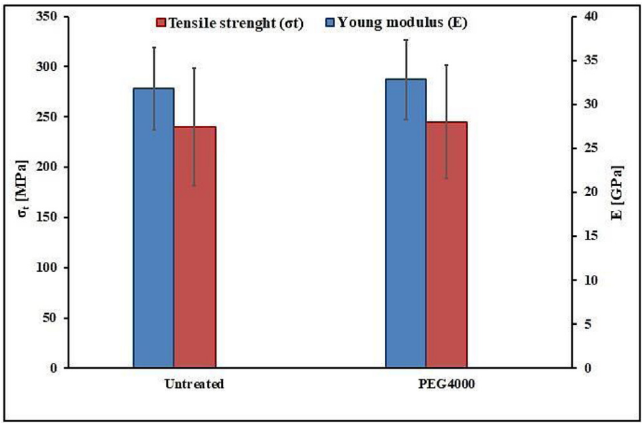

Fig. 9. Single Fiber tensile test results.

Firstly, the effect of Linseed Oil treatment was evaluated on shorter fibers (4 cm) reinforced samples in function of the weight content (0; 0.5%; 1%; 2%). Afterward, the experimental tests were performed to study the influence of the fiber length (4, 8, 12 cm) and the treatment with PEG at the percentages of 1% and 2%. The mix proportions of all the types of composites are reported in Table 2.

The water to mortar ratio, suggested by the technical datasheet of the biolime mortar, was equal to 0.18 in order to have the best performance in terms of fresh and hardened properties. Dry mortar and water were mixed manually in a damp container for 3 minutes until the mix became homogeneous and workable. Then, the fibers were added to the mortar and mixed for 2 minutes to obtain the homogeneity of the mixture. Six specimens for each formulation were obtained by casting the biolime mortar, mixed with randomly disposed fibers, in polystyrene foam molds (Fig. 10). The nominal dimensions of each specimen were 40×40 x 160 mm, which can be considered representative of main applications like prefabricated bricks and laying mortars, according to the standard BS EN 1015-11 [46]. The samples reinforced with longer fibers evidenced worse workability, especially at higher percentages, compared to those containing short fibers at lower percentages. It is in accordance to what evidenced by Savastano et al. [47] and Onuaguluchi and Banthia [15] who observed reduced workability of cement composites reinforced with natural fibers such as eucalyptus pulp, coir and eucalyptus pulp or sisal fibers in function of the aspect ratio and volume fraction in mixtures. At least five samples for each type of composite were prepared. The setting and hardening of the samples were carried out according to the standard BS EN 1015-11 [46]. Mortars stayed five days within molds at 20 ± 2 °C and 65 ± 5% RH to allow the complete setting and avoid damages of the samples during the demolding process. The hardening lasted 23 days at the same laboratory-controlled conditions (20 ± 2 °C and 65 ± 5% RH) to complete the hardening process of the mortars and ensure the achievement of high mechanical properties before the execution of the tests.

Table 2
Mix proportion of the composites, the quantities reported refer to the preparation of six specimens for each category according to the standard BS EN 1015-11 [46].

Type of composite	NHL 3.5 Mortar (g)	Fiber (g)	Water (g)	Fiber length (cm)	Fiber percentage (%)	Fiber treatment
Not Reinforced	3000	-	540	-	-	-
NT_4_0.5	3000	15	540	4	0.5	None
NT_4_1	3000	30	540	4	1	None
NT_4_2	3000	60	540	4	2	None
LO_4_0.5	3000	15	540	4	0.5	Linseed Oil
LO_4_1	3000	30	540	4	1	Linseed Oil
LO_4_2	3000	60	540	4	2	Linseed Oil
NT_8_1	3000	30	540	8	1	None
NT_8_2	3000	60	540	8	2	None
NT_12_1	3000	30	540	12	1	None
NT_12_2	3000	60	540	12	2	None
PEG4000_4_1	3000	30	540	4	1	PEG 4000
PEG4000_4_2	3000	60	540	4	2	PEG 4000
PEG4000_8_1	3000	30	540	8	1	PEG 4000
PEG4000_8_2	3000	60	540	8	2	PEG 4000
PEG4000_12_1	3000	30	540	12	1	PEG 4000
PEG4000_12_2	3000	60	540	12	2	PEG 4000

Notations: NT_4_0.5 stands for Untreated fibers of 4 cm length and 0.5% weight content; LO_4_2 stands for Linseed Oil treated fibers of 4 cm length and 2% weight content; PEG4000_8_1 stands for PEG 4000 treated fibers of 8 cm length and 1% weight content.

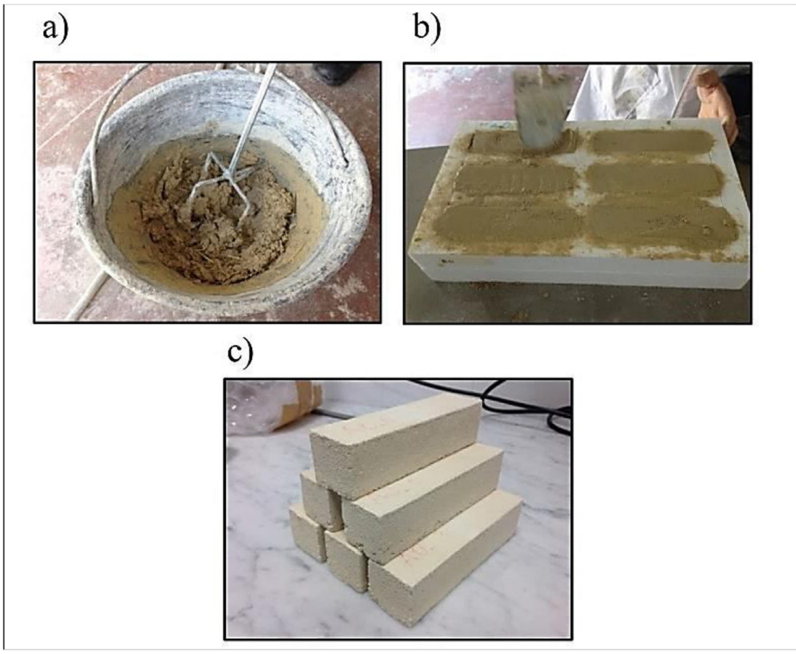

Fig. 10. Manufacturing process of the composites: a) Mortar and fibers mixing; b) Fiber reinforced mortar casting; c) Composites after 28 days of hardening.

2.5. Mechanical characterization of the composites

2.5.1. Three-point bending test (TPB)

At least five specimens for each type of composite under study were tested according to the standard BS EN 1015-11 [46] to estimate the flexural properties of mortar for masonry. Before testing, the actual dimensions (length, thickness and width) of each specimen were recorded with the aid of a centesimal caliper as the mean values of three different measures in order to consider dimensional changes due to mortar shrinkage. Three-point bending tests were performed in a *Zwick/Roell Z005* testing machine equipped with a 5 kN capacity load cell in displacement control mode. The crosshead speed was 0.5 mm/min in order to cause the first fracture of the specimens within 1÷2min and allow to evaluate the post-cracking behavior of the composites. The span length was set to 100 mm.

The nominal flexural stress (σ_f) at the outer surface of the test specimen at the midspan was obtained using the following Eq. (4)

$$\sigma_f = \frac{3P\ L}{2bh^2} \tag{4}$$

where P is the given load during the test, L is the span length, b and h are respectively the width and thickness of the specimen. The correspondent flexural strain (ε_f) was evaluated using the Eq. (5) according to the standard ASTM D790 [48].

$$\varepsilon_f = 100\frac{6\Delta lh}{L^2} \tag{5}$$

It is defined as the percentage change in the length of an element of the outer surface of the test specimen at the midspan with respect to the initial dimensions of the sample, while Δl was the displacement of the loading pin during the test measured by the testing machine.

From TPB test, the *First Fracture Flexural Strength* (*FFFS*), the *Post Fracture Flexural Toughness* (K_{ULT}) and the *Post Fracture Flexural Strength* (*PFFS*) were evaluated. The FFFS was calculated by the Eq. (4) when P reaches the load correspondent to the first crack propagation, which was detected as the load value corresponding to the initial deviation from the linear behavior in the *Stress vs Strain* curve. The K_{ULT} was calculated as the area below the *Stress vs Strain* curve. In particular, the post-fracture range considered for each specimen was between the flexural strain correspondent to the first crack propagation and the flexural strain of 8%. The PFFS is defined as the maximum value reached by the flexural stress in the post-fracture range.

2.5.2. Compressive test

For each mortar mix, five specimens were tested according to the standard BS EN 1015-11 [46] and the results reported as mean values and standard deviation of the maximum compressive strength obtained from valid tests (at least three specimens for each type). The tests were carried out in force control on the halves of the samples previously tested in bending, in a universal electromechanical machine *MP Strumenti Tools WANCE UTM 502*, at the loading speed equal to 200 N/s in order to obtain the break for all the specimens between 30 and 60 s according to the standard. On the opposite surfaces of the specimen, a compression jig assembly was used to compensate for the lack of parallelism between the surfaces of the specimens. The compressive strength for each sample were obtained by dividing the maximum load by the resistant cross-section of the specimen ($40 \times 40\,mm^2$).

2.6. Water Absorption by Capillary Test

Water absorption tests were conducted on at least 3 specimens for each type of mortar investigated on the halves of the samples, previously tested in bending, according to the standard BS EN 1015-1018 [49]. Before performing the water absorption test, the samples were dried in an oven at 60 °C until the constant mass was reached. The samples were then placed in a container with the fracture surface of the prism downward on suitable supports to maximize the contact between the water and the surfaces of the samples. The water level in the container was maintained between 5 and 10 mm throughout the test, which was performed in laboratory condition 22 ± 2 °C and $65 \pm 5\%$ RH. The mass of each sample was recorded at 0, 10, 90 min after the immersion and the Absorption Coefficient was evaluated by the following Eq. (6):

$$C = 0.1(M_2 - M_1) \tag{6}$$

where: C is the Absorption Coefficient, M_1 is the mass of the sample after 10 min of immersion and M_2 is the mass of the sample after 90 min of immersion.

3. Results and Discussions

Fig. 11 shows the typical *Stress-Strain* curves of non-reinforced mortars and reinforced with short fibers at three different percentages by weight (0.5%, 1%, 2%). A slight decrease of the *First Fracture Flexural Strength* can be observed in function of the percentage due to a greater defectiveness of the mortar that leads to higher fragility in the linear elastic range. By contrast, there is a marked increase in the *Post Fracture Flexural Strength* in function of the fiber content. In fact, for some 2% fiber reinforced samples, it is even higher than the corresponding FFFS value due to the higher interface between matrix and fibers that hampers the advancement of the fracture and bridges the fractured matrix. The unstable response in the *Stress-Strain* curves after the first crack occurred can be due to the bridging effect induced by the fibers that hinder the cracks propagation due to pull-out leading to subsequent load recovery [50]. When more energy is required to create new crack surfaces, the stress increases. As soon as the stored energy is enough to create new crack surfaces, a drop in the stress of the material occurs. The bridging effect induced by the addition of the giant reed fibers during the TPB test is shown in Fig. 12 for a NT_4_2 specimen.

The average *First Fracture Flexural Strength* (Fig. 13) of the mortars with short fibers (4 cm) up to 1% wt were not significantly different compared to the not reinforced one. For 2%, instead, it was recorded a fall of approximately 17%.

This can be attributed to exceeding fiber content which causes a worse quality of the composites due to the presence of agglomerates and higher void content. The area below the *Stress-Strain* curves represents the toughness of the material in bending. The toughness significantly increases as the percentage of short fibers increases. It is explainable since the greater interface between fiber and matrix requires more energy to cause their complete separation.

The treatment with Linseed Oil caused a worsening of the adhesion between fiber and matrix and consequently, a decay of the values of *First Fracture Flexural Strength*, *Post Fracture Flexural Strength* and *Post Fracture Flexural Toughness*, as shown in Fig. 13. It may be due to the hydrophobic nature of linseed oil that led to worse compatibility between fiber and matrix and

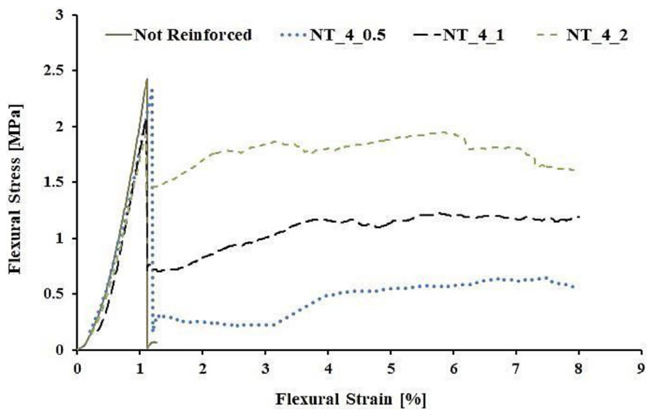

Fig. 11. Typical Flexural Behavior of the mortars for different short fiber content.

Fig. 12. TPB test of a characteristic NT_4_2 specimen.

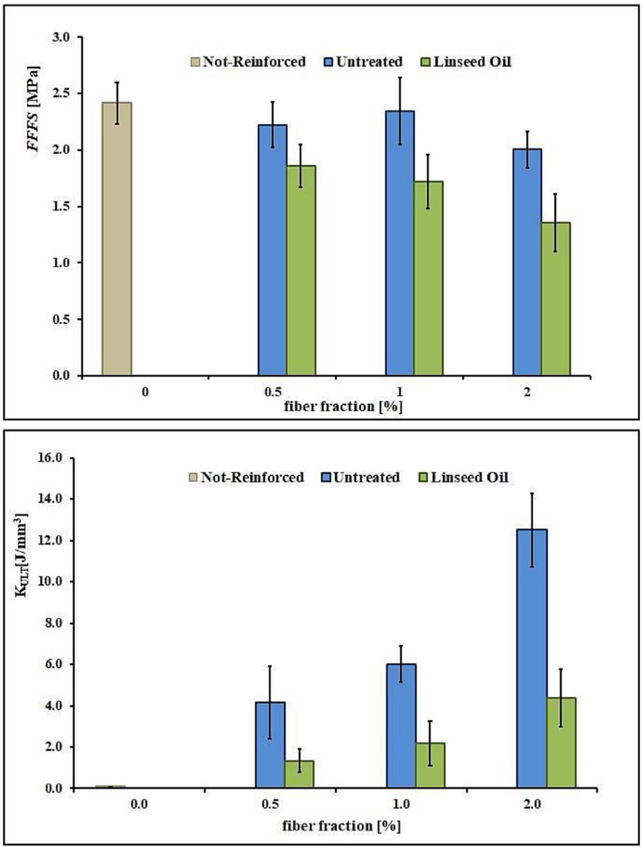

Fig. 13. First Fracture Flexural Strength (above) and Post Fracture Flexural Toughness (below) of the composites in function of the weight content of untreated and linseed oil treated fibers.

scarce interface adhesion between mortar and reinforcement. According to these considerations, the treatment with linseed oil was abandoned.

As mortars with 0,5% of fiber content did not show a significant increase in toughness, the influence of the fiber length was evaluated on 1 and 2% reinforced mortars.

Fig. 14 shows the typical *Stress-Strain* curves of not reinforced mortar, and 1% wt fiber-reinforced composites at three different lengths (4 cm, 8 cm, 12 cm). It can be noted that as a function of the length, there is a slight decrease of the *First Fracture Flexural Strength* due to the presence of more extended defects that lead to higher brittleness of the mortar in the linear elastic range. By contrast, there is a noticeable increase in the post-fracture stress with the rise of the fiber length, due to the higher amount of fibers crossing the midsection where the composite fracture is triggered. In particular, for 12 cm fiber reinforced mortars, a hardening behavior was observed. Similar results were obtained by Kim et al. [6], who evidenced a deflection-hardening FRCC behavior for low volume fractions of high strength steel fibers and high molecular weight polyethylene spectra fibers. The presence of a more extensive interface between matrix and reinforcement is supposed to hinder the advancement of the fracture.

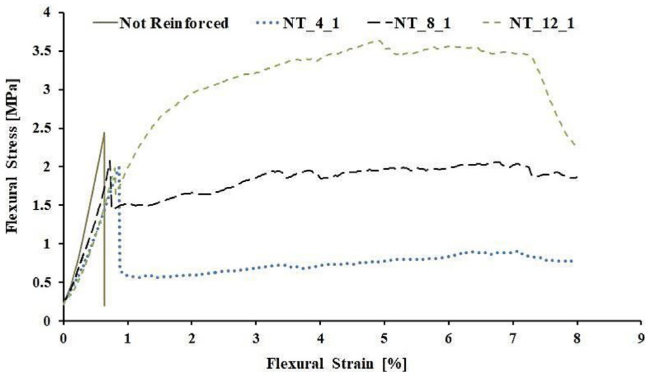

Fig. 14. Typical Flexural behavior of the mortars for 1% wt reinforced composites in function of the fiber length.

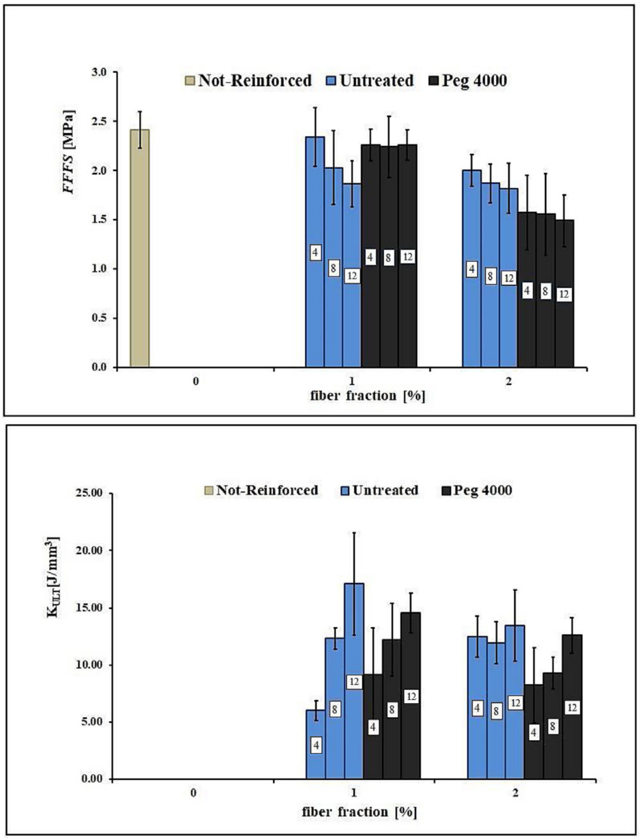

Fig. 15. First Fracture Flexural Strength and Post Fracture Flexural Toughness in function of fiber fraction for different fiber lengths, without or with PEG treatment.

The value of *First Fracture Flexural Strength* also decreases depending on the length of the fibers, probably due to the more extended defects in the areas of poor interface between fibers and mortar.

On the other hand, from Fig. 15, it is worth noting that for composites with 1% fiber addition *Post Fracture Flexural Toughness* increases as a function of the fiber length. This is due to the higher energy necessary to extract them from the matrix because of the higher interface between the fibers crossing the middle section of the specimen, where the first crack occurs, and the mortar. The increase of the standard deviation in function of the fiber length is due to the more significant influence of the fiber distribution on the mechanical properties. For composites with the addition of short fibers (4 cm), the upward trend of the *Post Fracture Flexural Toughness* in function of the fiber percentage is attributed to the higher presence of the fibers at the middle section subjected to the bending stress. Moreover, the fall of the *Post Fracture Flexural Toughness* with the addition of 2% wt of long fibers (12 cm) compared to those at 1% is due to the excessive fiber content. Agglomerates of

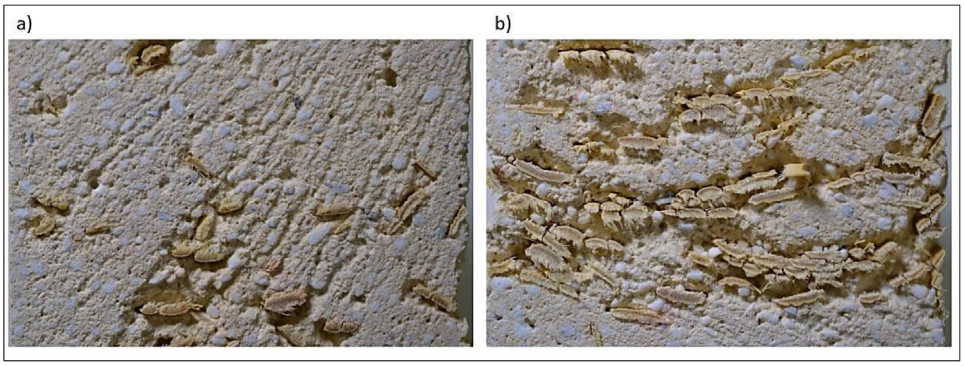

Fig. 16. Comparison morphologies: a) NT_12_1 specimen; b) NT_12_2 specimen.

fibers and hence more extended fiber/fiber interface rather than fiber/matrix interface lead to a higher content of defects in the matrix (Fig. 16). The composites reinforced with medium length fibers (8 cm) exhibit an intermediate behavior since the higher content of fibers crossing the crack surface of the specimen is compensated by the higher percentage of defects. Thus, the values of *Post Fracture Flexural Toughness* at 1 and 2% are very similar.

Nevertheless, the composites obtained with PEG 4000 treated fibers did not show an increase in mechanical properties compared to untreated fiber ones. In particular, not significant differences are highlighted in the *First Fracture Flexural Strength* at lower percentages, while a slight worsening is noted at higher contents (Fig. 15). This is due to the presence of higher fiber/fiber rather than fiber/matrix interface probably because of the slight increase of the stiffness of the fibers, as observed by the *Single Fiber Tensile* test that caused issues of compaction during the preparation of the mortars. This result is in accordance with what assessed by Coutts [51], who evidenced better fiber/cement matrix interaction for finer and less stiff fibers after mechanical refining treatment. It can be confirmed paying attention to the K_{ULT} variation with PEG treated fibers: PEG treatment has a positive effect on low percentage and short fiber length while it is ineffective as either the length or the percentage of the fiber increases. As can be observed from Fig. 17, the average compressive strength of the mortars slightly decreases by the addition of untreated fibers up to 2%, while the standard deviation increases significantly with fiber content. All the composites, however, showed values of strength higher than 5 MPa, which is the lower limit prescribed for M5 category mortars (EN 998-2, 2016). These results confirmed the capacity of the fibers to induce toughness to brittle mortars without harmfully affecting the *Compressive Strength*, which is their main mechanical property. It is possible noting that PEG treatment does not cause significant disadvantages in compressive strength at 1% of fiber content and implies just a small reduction at higher percentages.

What assessed so far finds evidence by observing the Fig. 18 that shows the results of the Water Absorption Test of the mortars. The values of the Coefficient *C* are in accordance with those obtained by the Flexural and Compressive tests. The absorption coefficient slightly increases in function of the fiber length and for PEG 4000 mortars due to the presence of higher amounts of defects and voids that imply further capillarity to the mortars.

Table 3 reports the overall results of this study to facilitate their comparison and evidence the relationship between the physical and the mechanical properties. It is evident that the inclusion of fibers increases the toughness and the reinforcement of composites, but also increases the porosity because of the dispersion deficiency of the fibers in the

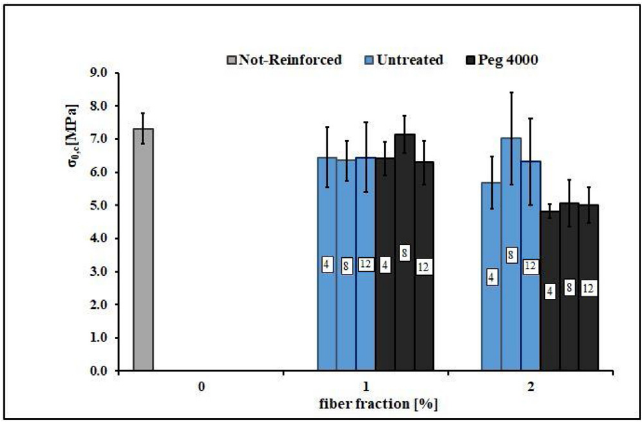

Fig. 17. Compressive Strength in function of the fiber fraction for not-reinforced mortars, untreated and PEG 4000 treated fibers reinforced mortars.

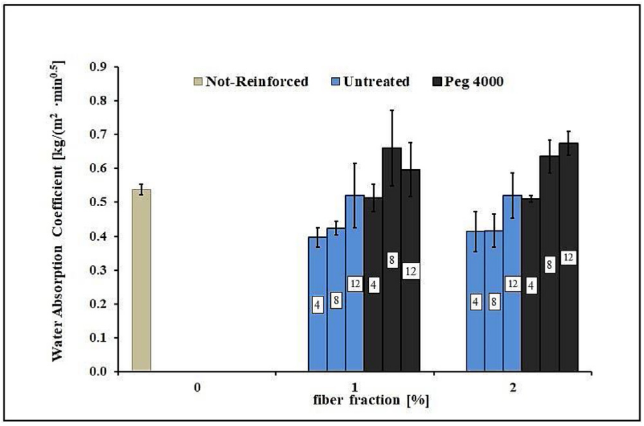

Fig. 18. Water absorption coefficient in function of the fiber fraction for not-reinforced mortars, untreated and PEG 4000 treated fibers reinforced mortars.

Table 3
Comprehensive experimental results.

Type of composite	Apparent Density [g/cm^3]	Water Absorption Coefficient [kg/(m^2·min$^{0.5}$)]	Compressive Strength [MPa]	FFFS [MPa]	PFFS [MPa]	K_{ult} [J/mm^3]
Not Reinforced	1.835 ± 0.008	0.537 ± 0.015	7.318 ± 0.460	2.415 ± 0.188	0.132 ± 0.052	0.012 ± 0.008
NT_4_1	1.816 ± 0.012	0.397 ± 0.029	6.450 ± 0.908	2.344 ± 0.299	0.945 ± 0.681	6.014 ± 0.876
NT_4_2	1.790 ± 0.015	0.413 ± 0.059	5.675 ± 0.784	2.003 ± 0.159	1.696 ± 0.579	12.499 ± 1.794
NT_8_1	1.824 ± 0.014	0.423 ± 0.021	6.344 ± 0.595	2.027 ± 0.376	2.035 ± 0.217	12.312 ± 0.949
NT_8_2	1.793 ± 0.016	0.417 ± 0.049	7.015 ± 1.382	1.870 ± 0.200	1.950 ± 0.371	11.950 ± 1.827
NT_12_1	1.832 ± 0.016	0.520 ± 0.095	6.445 ± 1.050	1.867 ± 0.235	2.965 ± 0.836	17.086 ± 4.464
NT_12_2	1.793 ± 0.019	0.520 ± 0.066	6.318 ± 1.300	1.821 ± 0.253	2.308 ± 0.495	13.449 ± 3.116
PEG4000_4_1	1.875 ± 0.011	0.513 ± 0.040	6.409 ± 0.509	2.257 ± 0.162	1.619 ± 1.002	9.154 ± 4.068
PEG4000_4_2	1.828 ± 0.017	0.510 ± 0.010	4.819 ± 0.206	1.571 ± 0.380	1.502 ± 0.469	8.219 ± 3.281
PEG4000_8_1	1.840 ± 0.013	0.660 ± 0.111	7.151 ± 0.560	2.241 ± 0.311	2.201 ± 0.521	12.212 ± 3.169
PEG4000_8_2	1.797 ± 0.015	0.635 ± 0.050	5.065 ± 0.700	1.555 ± 0.416	1.653 ± 0.205	9.286 ± 1.414
PEG4000_12_1	1.816 ± 0.014	0.570 ± 0.080	6.292 ± 0.656	2.260 ± 0.150	2.538 ± 0.424	14.540 ± 1.723
PEG4000_12_2	1.788 ± 0.021	0.675 ± 0.035	5.011 ± 0.539	1.493 ± 0.263	1.960 ± 0.226	12.582 ± 1.560

cementitious matrix and, consequently, generating lack of stress transfer between the fibers and matrix according to Teixeira et al. [52]. Finally, in Table 4 are summarized some results reported in the literature over the past 2 decades regarding the mechanical properties of natural fibers reinforced cementitious matrix (NFRCM) with special focus on the flexural strength and toughness in function of the type of reinforcement, fiber content and length and the effect of the fiber treatment on the fiber/matrix interfacial adhesion. Overall, the results reported in the literature are in good accordance with our experimental results evidencing that vegetable fiber cement composites exhibit improved toughness, ductility, flexural capacity and crack resistance compared with unreinforced cement-based materials.

4. Analytical Model

The typical *Stress-Strain* response for FRCM is characterized by two fundamental mechanical properties that are the *First Fracture Flexural Strength* (*FFFS*) and the *Post Fracture Flexural Strength* (*PFFS*). It is well known that these properties are strongly influenced by a number of variables such as fiber percentages, distribution, orientation, interfacial adhesion, [28–31]. Recent studies have dealt with the formulation of different analytical models capable of adequately predicting the actual behavior of steel or synthetic fiber-reinforced cement mortars [27,69–73]. In this work the analytical model proposed by Naaman [69] have been used to evaluate the parameters which influence the post-fracture behavior of the *Arundo donax* L. fiber reinforced NHL based mortars by a best fitting procedure of the experimental results. The main assumptions of the model are: i) the matrix is brittle and characterized by a linear *Stress-Strain* curve until failure; ii) the fibers are either brittle or ductile with an initial elastic response; iii) the strain at failure of the matrix is smaller than that of the fibers; iv) the properties of the interface are assumed characterized by an equivalent elastic perfectly plastic bond stress versus slip response at small slips. The value of bond strength selected is assumed to represent an average value over a reasonable range of slip between the fibers and the matrix [69]. In our experimental study the first assumption finds validation since the NHL based mortars evidenced a brittle behavior with a linear *Stress-Strain* curve until failure as can be observed in Fig. 7 and Fig. 14. The second assumption is confirmed by observing the *Stress-Strain* response of the Single Fiber Tensile test shown in Fig. 8. The third assumption can be considered satisfied since the flexural strain at failure of the NHL mortars was in the range

Table 4
Summary of experimental results from literature over the past 2 decades.

Type of fiber	Type of matrix	Experimental investigations	Main Results	Reference
Sisal, caraua and jute fibers	Cement mortar	Single fiber pull-out test	Morphological, chemical, physical and mechanical characterizationof the natural fibers were correlated with the resulting bond properties with the matrix	[32]
Hemp, flax, sisal, jute and coir fibers	Cement-free mortar made with pozzolana lime and natural siliceous aggregates	Static compressive and bending tests	They produced composites with the fibres having good performance and from the experimental analysis the natural fibres potentials regarding strengthening can be easily understood.	[53]
Sisal fiber	Cement mortar free of calcium hydroxide	Fiber surface treatments by hornification, alkaly treatment, polymer impregnation, hybrid hornification and polymer impregnation, single fiber pull-out test	Significant improvements in the fiber–matrix interface were verified through the pullout test for the several used treatments. The hornification treatment increased the elastic and frictional bond, whereas the polymer and hybrid treatment resulted in a fiber slip-hardening behavior.	[43]
Polypropylene, sisal and kenaf fibers	Lime mortar	Static compressive and bending tests	It was demonstrated that natural fibers can be a valid alternative to the polypropylene for reinforcing lime mortars. Sisal fiber reinforced mortars showed lower compressive strength compared to the other fiber reinforced mortars	[20]
Sisal fiber	Cement mortar	Fiber surface treatment by wet and dry cycles, single fiber pull-out and bending tests	The pull-out resistance of the fibers submitted to ten cycles of wetting and drying was increased by about 40% to 50%. The higher fiber-matrix bond strength contributed to an increase in the ductility and post-cracking behaviour of the composite	[54]
Hemp fabrics	Geo-polymer	Fabric surface treatment by NaOH, three-point bending and impact test	NaOH treatment of hemp fabrics before the fabrication of the cement composites was an effective technique to improve the fabric/cement matrix interfacial bond since the treatment introduced the fabric fibre rough surfaces which facilitated the mechanical interlocking between the fabrics and the cement	[55]
Softwood kraft pulp between 0 and 10% wt	Cement mortar	Three-point bending test	The maximum strength decreased with the increase of the fiber content up to 4% wt. For higher contents, the flexural strength remained steady at the 50% of the maximum. The toughness of the mortars increased in function of the fiber content	[56]
Basalt and glass fibers	Hydraulic lime mortar	Static compressive and bending tests	Was observed an improvement in postcracking behavior and toughness for the reinforced mortars and a better resistance in freeze-thaw cycles	[57]
Kraft pulp	Cement mortar	Three-point bending test	The optimum fiber percentage for reinforcing cement was 8%wt. By increasing the amount of kraft fibers the ductility increased	[58]
Coconut fibers	Concrete	Static and dynamic mechanical tests	The best properties were observed with fiber length of 5 cm and a fiber content of 5%wt	[59]
Pulp fibers from waste paper and packaging	Cement mortar	Static compressive and bending tests	The compressive strength decreased with the fiber content. The flexural strength increased between 0 and 4% wt by 17% and decreased progressively afterwards	[60]
Agricultural waste fibers of bagasse, wheat and eucalyptus at 2 and 4%wt	Ordinary Portland Cement (OPC)	Three-point bending test	2% wt fiber content led to little change in the flexural behavior while a considerable increase was observed at 4% wt. The best performance was found for bagasse fiber	[61]

Table 4 (*Continued*)

Type of fiber	Type of matrix	Experimental investigations	Main Results	Reference
Hemp fiber	Natural Hydraulic Lime (NHL5)	Fiber surface treatment with NaOH and EDTA, three-point bending test	It was found that the chemical treatments with NaOH, EDTA induced the modification on fibres which played a significant role regarding the strength aspect of lime/ fibre interface	[62]
Nonwood plant fiber bundles of ramie, pineapple, sansevieria, kenaf, abaca, sisal, and coconut	None	Morphological, pysical and mechanical characterization of the natural fibers	According to the mechanical properties of the fibers, ramie bast, pineapple leaf, and sansevieria leaf showed great potential for use in high-performance plant fiber composites.	[63]
Recycled, softwood and hardwood pulps at 5, 10 and 15% wt	Cement mortar	Three-point bending test	By increasing softwood fiber content from 5% to 15%wt the toughness increased and the flexural strength increased slightly as fiber content increased from 5 to 10% wt and then decreased.	[64]
2% by volume of coir fibers (3 ± 1 cm long)	Ground granulated blast furnace slag (GBFS) activated with 10% of gypsum and 2% of lime	Static compressive and bending tests, impact test	The static mechanical strength and toughness similar to unreinforced matrix; the impact strength doubled that of the matrix	[2]
Coir, sisal, jute and hibiscus cannabinus at 0.5, 1, 1.5 and 2.5% wt of cement (20, 30 and 40 mm)	Cement mortar	Impact test	Increase of the impact strength by 3-18 times than the reference mortar. Of the four fibers, coir fiber reinforced mortars have shown the best performance.	[65]
Pinus and sisal pulps	Ground iron blast furnace slag (BFS) and Ordinary Portland Cement (OPC)	Three-point bending test	The mechanical properties of the BFS and OPC matrix were enhanced in a like manner by 4 and 8% wt of reinforcement for pinus and sisal pulps respectively. The highest flexural strength was recorded for BFS composites reinforced with pinus pulp at fiber loadings between 8 and 12% wt. The fracture toughness values of sisal pulp were lower than those corresponding to pinus pulp	[66] and [67]
Pinus caribaea residues from pencil manufacture	Ordinary Portland Cement (OPC)	Static compressive and bending tests	The toughness of tiles produced with the composite material was up to 124% higher than the reference mortar	[68]

0.6÷1,1% (Fig. 11 and Fig. 14), the same as for the tensile strain at failure of the *Arundo donax* L. fibers (Fig. 8), but it would have been significantly lower if the mechanical tests had been performed in tensile rather than in bending. The last assumption is also valid due to the elastic-plastic behavior in the *Stress-Slip* response at small slips evidenced by the Single Fiber pull-out tests (Fig. 6). On the basis of these considerations, the Eq. (7) was used to evaluate the PFFS of the giant reed fibers reinforced NHL mortars [69]:

$$PFFS = 2g\tau_{max}\ FIER\ V_f\ \alpha \tag{7}$$

where:

• *g* is the *snubbing value* that amplifies the fibers effect since they interact with the mortar and allow the matrix to bear part of the load even after the first crack occurs. It can be calculated with the following Eq. (8) [69,73]:

$$g = \frac{f e^{f\pi\ 2} + 1}{1 + f^2} \tag{8}$$

the snubbing factor *f* depends on the material of reinforcement. For example, it is equal to 0.994 for nylon fibers, 0.702 for polypropylene. When the snubbing effect is negligible, it tends to zero.

• τ_{max} is the *Maximum Pull-out Strength* between fiber and mortar that can be experimentally evaluated through the Eq. (3). It gives information about the quality of the interfacial adhesion between matrix and reinforcement.

• *Fiber Intrinsic Efficiency Ratio* (*FIER*) was chosen to describe the main geometrical characteristics of the tested fibres. It has been defined as the ratio of bonded lateral surface area of fibre, to its cross sectional area. In this study FIER was calculated for the total length L of a given fiber by the Eq. (9) ([69,74]):

$$FIER = \frac{PL}{A} \tag{9}$$

Table 5
Analytical model parameters for untreated fiber composites.

Fiber Percentage by weight		1%			2%	
Nominal length (L) [mm]	40	80	120	40	80	120
Average thickness (t) [mm]	0.38	0.38	0.38	0.38	0.38	0.38
Average width (w) [mm]	3.21	3.21	3.21	3.21	3.21	3.21
Average Perimeter (P) [mm]	7.18	7.18	7.18	7.18	7.18	7.18
Average cross-section (A) [mm^2]	1.22	1.22	1.22	1.22	1.22	1.22
FIER	235.45	470.90	706.35	235.45	470.90	706.35
Fraction of fiber by volume (V_f)	0.018	0.018	0.018	0.036	0.036	0.036
Snubbing factor (f)	3.1	3.1	3.1	3.1	3.1	3.1
Snubbing value (g)	37.5	37.5	37.5	37.5	37.5	37.5
Maximum Pull-out Strength (τ_{max}) [MPa]	0.024	0.024	0.024	0.024	0.024	0.024
α_1	0.25	0.25	0.25	0.25	0.25	0.25
α_2	0.80	0.85	0.87	0.80	0.85	0.87
α_3	0.77	0.74	0.69	0.70	0.36	0.27
α_4	0.80	0.85	0.87	0.80	0.85	0.87
*PFFS*analytical [MPa]	0.937	2.036	2.989	1.686	1.966	2.316
PFFS experimental [MPa]	0.949	2.035	2.965	1.696	1.950	2.308

Table 6
Analytical model parameters for PEG 4000 treated fiber composites.

Fiber Percentage by weight		1%			2%	
Nominal length (L) [mm]	40	80	120	40	80	120
Average thickness (t) [mm]	0.38	0.38	0.38	0.38	0.38	0.38
Average width (w) [mm]	3.21	3.21	3.21	3.21	3.21	3.21
Average Perimeter (P) [mm]	7.18	7.18	7.18	7.18	7.18	7.18
Average cross-section (A) [mm^2]	1.22	1.22	1.22	1.22	1.22	1.22
FIER	235.45	470.90	706.35	235.45	470.90	706.35
Fraction of fiber by volume (V_f)	0.018	0.018	0.018	0.036	0.036	0.036
Snubbing factor (f)	3.1	3.1	3.1	3.1	3.1	3.1
Snubbing value (g)	37.5	37.5	37.5	37.5	37.5	37.5
Maximum Pull-out Strength (τ_{max}) [MPa]	0.032	0.032	0.032	0.032	0.032	0.032
α_1	0.25	0.25	0.25	0.25	0.25	0.25
α_2	0.80	0.85	0.87	0.80	0.85	0.87
α_3	0.99	0.61	0.45	0.46	0.23	0.17
α_4	0.80	0.85	0.87	0.80	0.85	0.87
PFFS analytical [MPa]	1.611	2.241	2.598	1.497	1.690	1.963
*PFFS*experimental [MPa]	1.619	2.201	2.538	1.502	1.653	1.960

where *P* is the cross-section perimeter of the fibers, *L* and *A* their length and cross-section area, respectively.

- V_f is the volumetric fiber fraction [69,72].
- α is obtained by multiplying four coefficients α_1,α_2,α_3,α_4 where:

−α_1 is the average or expected value of the ratio of fiber shorter embedded distance from a forming crack to the length of the fiber. Its value is approximated to 0.25 from statistical considerations [69,70].

−α_2 is the efficiency factor of fiber orientation; it is equal to 1 for unidirectional fibers; $2/\pi$ for fiber randomly oriented in planes; 0.5 for fiber randomly oriented in space. This factor directly influences the number of fibers intersecting a unit area of composite ([75,69,70]).

−α_3 is a coefficient of adhesion reduction to simulate the fact that the more is the fiber content, the more are empty spaces and fibers in contact with each other, leading the adhesion between fibers and matrix to be much worse [69,70]. It can be strongly influenced by the manufacturing process.

−α_4 is another coefficient of reduction concerning that fibers oriented more than 60° respect to the longitudinal axis have low effect on the post-peak strength during their pull-out [27,69,71].

By a procedure of best fitting with the experimental results, the parameters that affect the post-fracture behavior of the giant reed fibers reinforced mortars have been calculated in order to provide to the scientific community firsts useful data which can be used as reference for further studies in this scope of research.

The experimental and analytical values of *Post Fracture Flexural Strength* (*PFFS*) and the parameters of the model estimated by the comparison with the experimental flexural results are finally reported in Table 5 and Table 6.

5. Conclusions

In the present work the influence of addition of *Arundo donax* L. fibers on the flexural properties of a Natural Hydraulic Lime mortar has been investigated in order to propose more ductile eco-compatible prefabricated bricks or laying mortars for application in the green building sector. The most significant outcomes are following summarized:

- The use of giant reed fibers led to a significant increase of the *Post Fracture Flexural Toughness* (K_{ULT}) with respect to unreinforced mortars.
- The *First Fracture Flexural Strength* (*FFFS*) of the composites slightly decreased in function of the percentage and length of the fibers due to the presence of more defects and voids.
- NT_12_1 mortars exhibited the highest value of K_{ULT} with an increase of about 200% compared to NT_4_1 mortars.
- The treatment with Linseed Oil led to worse flexural properties due to the worse fiber/matrix adhesion.
- Despite leading to slightly better fiber/matrix adhesion, the treatment with PEG 4000 entailed an increase in the flexural properties only for PEG4000_4_1 mortars.
- Overall, the composites NT_4_2 and NT_12_1 evidenced the most interesting properties by counterbalancing the pros of fiber reinforcement and cons of induced defectiveness.
- An analytical model has been used to calculate the parameters that affect the post-fracture behavior of the giant reed fibers reinforced NHL mortars by best fitting of the experimental results.

In conclusion, the findings of this study confirm that modification of Natural Hydraulic Lime based mortar by the addition of common reed fibers can be a possible solution for manufacturing ductile eco-compatible prefabricated bricks or laying mortars for the green building sector.

Declaration of Competing Interest

The authors report no declarations of interest.

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