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INDUCED MODIFICATION OF FLEXURAL TOUGHNESS OF BIO-LIME BASED MORTARS BY ADDITION OF GIANT REED FIBERS

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Abstract

Fibers are often used as reinforcement of brittle materials, like mortars, in order to modify their mechanical behavior; particularly the modification in post-cracking toughness, induced by low elasticity modulus fibers in the artificial stone material, is the main goal in natural fibers mortar manufacturing.

In this work *Arundo donax* L. fibers are used to reinforce lime mortars according to the characteristics of this plant, very commonly available and with high mechanical properties, similar to bamboo, traditionally used in buildings in Spain.

Influence of fibers' length and weight ratio is studied. Particularly, three different fibers' lengths, 4, 8 and 12 centimeters, and three weight ratio, 0.5, 1 and 2% are used. The experimental characterization focused on bending and compression tests on mortars' samples as well as tensile and pull out tests on single fiber.

Overall, according to experimental results, mechanical flexural properties of the mortar are significantly improved by the addition of natural fibers at different weight contents and lengths, optimal fibers' weight ratio and length was individuated.

Keywords:

Arundo donax L.; Natural fibers; Flexural toughness; Fiber length; Percentage of fibers; Mechanical characterization

1 INTRODUCTION

Nowadays, the use of natural fibers as reinforcement for cement or lime based mortars is increasingly emerging due to the improvement of mechanical properties which allows the material to be more suitable for several practical applications [Agopyan 2005 and Fiore 2014]. A major advantage concerning fiber reinforcement of a brittle material is the behavior after cracking of the resulting composite. Post-cracking toughness induced by natural fibers in the cement material may allow the large-scale construction use of such composites. Distributed reinforcement into the composite offers effective capacity of sealing and bridging cracks under flexural or tensile stress [Santos 2015]. The toughening effect in brittle ceramic matrix is obtained by bridging and breaking of long reinforcements, frictional pullout and breaking of short reinforcements, and local matrix spalling [Zhai 2000]. The He-Hutchinson (HH) criterion is commonly used to describe the phenomenon governing the progress of the crack in a fiber reinforced ceramic composite. Better toughness behavior is obtained when the crack grows along the axis of the fiber rather than through the fiber, due to debonding and pull out at the interface. The former mechanism is promoted by using high stiff fibers as reinforcement for brittle ceramic matrix [Ahn 1998 and Kabel 2018]. A considerable amount of research has been carried out to investigate the influence of different types of fibers on the mechanical performance of concrete composites for building engineering [Kim 2008 and Lin 2014]. Felekoglu et al. found that high strength concrete with high strength fibres provides best performance in flexural strength and toughness [Felekoglu 2009]. However, very few can be found in literature about the use of fibers in natural hydraulic limes (NHL) based mortars for masonry applications. Some researches [Chan 2010 and Ferrara 2011] have evidenced the crucial role of the reinforcement in improving their flexural toughness and post-cracking behaviour, which are properties of fundamental importance especially for masonry structures located in areas of seismic activity. The use of different types of fibers in cementitious materials is also widespread for several reasons. Even though 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 [Brandt 2008], vegetable lignocellulosic fibers present several interesting advantages which are recently encouraging a wider use in building engineering. The main advantages are their low real ($1.3 \div 1.5 g/cm^3$) and apparent density ($0.4 \div 1.5 g/cm^3$), high specific stiffness ($1.1 \div 80.0$GPa) and strength ($0.1 \div 3.0$GPa), biodegradability, renewability, low processing energy, and their easy availability at low cost and in a variety of morphologies and dimensions [Jarabo 2012 and Satyanarayana 2017]. It was ascertained that addition of natural fibers is useful in restraining the plastic shrinkage of cement mortar matrices promoting an effective self-healing of plastic cracking [Filho 2005 and Onuaguluchi 2006]. Therefore, their use is effective to compensate the shrinkage brittleness and give greater toughness to the material [Di Bella 2014]. Natural fibers find also several civil applications for their insulating benefits that allow to obtain materials of better thermal resistance for the construction of roofs or external insulating walls [Belhadj 2014].

In this work is investigated the influence of addition of common reed (*Arundo donax* L.) natural fibers on the mechanical properties of a biolime mortar, especially in terms of flexural behaviour after cracking, for practical use in masonry fields as ductile ecocompatible prefabricated bricks or laying mortars. It is well known that flexural strength is a crucial feature for building applications to withstand horizontal stresses such as earthquake shocks or wind. The capacity of the material to bear loads even after the first damage occurs identifies also their ability to absorb energy beyond the first rupture load [Sellami 2013]. Flexural properties are strongly affected by fiber dosage [Lee 2017], shape [Yoo 2017], geometry [Li 1996], distribution and orientation [Ferrara 2011], fiber/matrix interfacial adhesion [Simoes 2017, Ferreira 2018, Deeb 2014 Vincent 2013, Zerbino 2012, Sanal 2013].

2 MATERIALS AND METHODS

2.1 Raw materials

Arundo donax L. fiber

Arundo donax L. is widespread all over the world, and sometimes causes issues related to its invasivity, according to these considerations the use of its fibers as reinforcement for biolime mortars is justified. Moreover, giant reed fibers have good mechanical properties, i.e. 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 experimentation have been performed in a previous work [Fiore 2014].

Beams of dried common reed stems, previously separated from the leaves, have been provided from a plantation in the area of Catania in east Sicily. The stems were approximately of the same inner and outer diameters to ensure similar physical and mechanical properties. After cutting the stems with a band saw, the outer skin was manually decorticated from the stems 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.

All the fibers are characterized by more or less the same thickness, i.e. 0.38mm, and width, i.e. 3.21mm, while they have been cut in three different lengths, i.e. 4, 8 and 12cm, in order to study the influence of fibers aspect ratio on flexural mechanical properties of the composites.

Fig. 51 shows the manufacturing process of the *Arundo donax* L. fibers used in this experimentation.

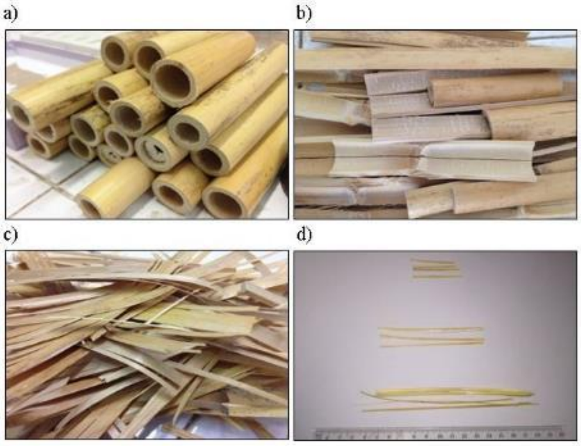

*Fig. 51: Manufacturing process of the fibers: a) Cut stems; b) Broken stems; c) Decorticated skins; d) 4, 8, 12*cm *long Arundo donax L. fibers.*

Biolime mortars

Biolime based mortars are recyclable as inert at end of life and with reduced CO_2 emissions with respect to cement based ones.

The premixed mortar used in the experimentation was an NHL 3.5 for building applications in the construction and grouting of masonry. NHL 3.5 indicates a Natural Hydraulic Lime having a compression strength between 3.5 and 10 MPa after 28 days of curing. *Fig. 52* shows the XRD pattern for the raw material used as matrix. It is constituted mainly by calcite, portlandite, dicalcium silicate (C_2S) dolomite and quartz.

This mortar belongs to M5 class, according to the standard EN 998-2, and is mainly used for building laying masonry and plastering.

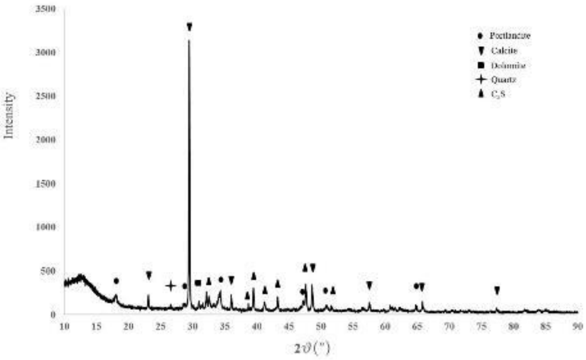

Fig. 52: XRD pattern for the premixed mortar used.

Composites manufacturing

The first purpose of this experimental research was to evaluate the influence of short fiber (4cm) content on the mechanical flexural behavior of bio-lime based mortar composites. Hence, four different sets of specimens have been prepared by varying the weight percentage of the fibers: 0%, 0.5%, 1%, 2% of the weight of the premixed mortar.

According to the results obtained with this preliminary characterization, the authors also investigated the influence of fiber length on mechanical behaviour of biolime based mortars by using 4, 8 and 12cm long fibers in mortars with 1% and 2% of fibers by weight.

The composites were obtained by mixing for five minutes the biolime mortar with randomly oriented fibers, and using a water to mortar weight ratio equal to 0.18 according to mortar's technical sheet. The so obtained fibers reinforced mortars (FRM) were casted in proper polystyrene foam molds, 40x40x160mm, according to the standard EN 1015-11. At least five samples for each type of composite were prepared. The setting and hardening of the samples, were carried out respectively for 5 days within molds, thereafter in air for the following 23 days at the same temperature controlled conditions (21 ± 2 °C and 50 ± 5% R.H.).

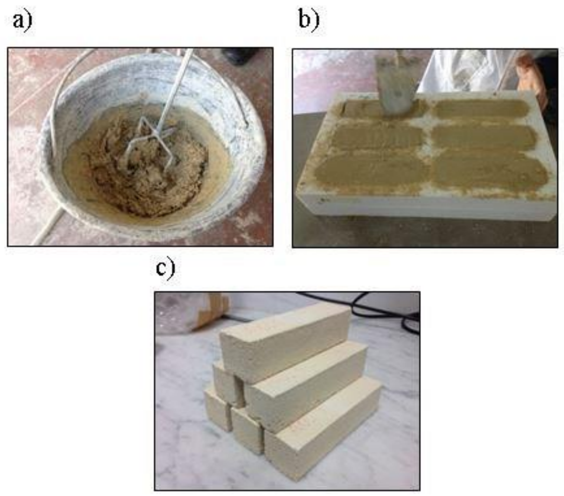

Fig. 53: Manufacturing process of the composites: a) Mortar and fibers mixing; b) Fiber reinforced mortar casting; c) Composites after 28 days of hardening.

2.2 Mechanical characterization

Single fiber tensile test

Single fiber tensile tests have been performed on at least 20 *Arundo donax L.* in order to estimate their mechanical properties (Tensile Strength and Young Modulus). The tests were performed in displacement control on 12cm long fibers as it is the average distance between the culms of the plant. An Electromechanical Universal Testing Machine (*WANCE UTM 502*), *MP Strumenti* equipped with a 50kN load cell was used. The testing speed was set to 0.5mm/min in order to obtain the rupture of the fibers between 1 and 2 minutes. The distance between grips was set to 70mm to allow a gripping length of at least 25mm for each side. The actual displacement of the specimens was evaluated using an *NCS CISRI* extensometer having a fixed gauge length equal to 50mm and capable of measuring displacements up to 10mm. 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 has been calculated: the Tensile Strength and, dividing it by density, the Specific Tensile Strength; the Young Modulus and the Specific Young Modulus as the ratio between the Young Modulus and the density, for every result we considered mean values and standard deviations.

Single fiber pull-out test

Single fiber pull-out test has been performed on at least 10 specimens in order to estimate the quality of interfacial adhesion between fibers and mortars.

This significantly influences the flexural properties of the mortars especially regarding to the post-fracture behavior. The tests were performed on 12cm long fibers in displacement control in a *Zwick/Roell Z005* testing machine equipped with a 5kN load cell. The testing speed was set to 0.5mm/min. The nominal embedment length of the fiber in the mortar was 20mm, which is far lower than the critical bond length [Teklala 2018], allowing the evaluation of the Maximum Pull-out Strength τ_{max} for each specimen. The nominal width and thickness were respectively 3.50mm and 0.5mm. The Maximum Pull-out Strength τ_{max} has been calculated by dividing the maximum pull-out force by the contact surface between fiber and matrix using the following Eq. 1.

$$\tau_{max} = \frac{F_{max}}{2l_i(w+t)} \quad (1)$$

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. The results were reported as mean values and standard deviations.

Three point bending test (TPB)

At least five specimens for each type of composite under study were tested according to the standard EN 1015-11 to estimate the flexural properties of mortars for masonry applications. Before testing, the actual dimensions (length, thickness and width) of each specimen have been recorded with the aid of a centesimal caliper; the reported measurement was the average of three different measures. Three point bending tests have been performed in a *Zwick/Roell Z005* testing machine equipped with a 5kN capacity load cell, in displacement control mode. The crosshead speed was 0.5mm/min in order to cause the first fracture of the specimens within 1÷2min and to evaluate the post-cracking behavior of the composites. The span length was set to 100mm. From TPB tests, the First Fracture Flexural Strength (σ_0), the Post Fracture Flexural Toughness (K_{ULT}) and the Post Fracture Flexural Strength (σ_{pc}) have been evaluated. The first fracture flexural strength was calculated using the following Eq. (2)

$$\sigma_0 = \frac{3P_0L}{2bh^2} \quad (2)$$

where P_0 is the load correspondent to the first crack propagation, which has been detected as the load value corresponding to the initial deviation from the linear behavior in the Load-Displacement curve, L is the span length, b and h are respectively the width and thickness of the specimen.

The Post Fracture Flexural Toughness was calculated by measuring the area below the Stress vs Strain curve. In particular, the post fracture range considered was between the strain correspondent to the first crack propagation and the 8% of the flexural strain.

Tab. 9: Experimental results of Single Fiber Tensile test and Single Fiber Pull-out test

Arundo donax L.	Tensile Strength	Young Modulus	Specific Tensile Strength	Specific Young Modulus	Maximum Pull-out Strength
	MPa	GPa	MPa/(g/cm^3)	GPa/(g/cm^3)	MPa
Average	240	31.8	235	30.8	$23*10^{-3}$
Standard deviation	58.6	4.7	67.6	4.9	$6.5*10^{-3}$

The latter was evaluated using the following Eq. (3)

$$\epsilon_f = \frac{6\Delta lh}{b^2} \quad (3)$$

where $\boldsymbol{\varepsilon}_f$ was the flexural strain, while Δl was the displacement of the loading pin during the test. The maximum value of the flexural stress in the post fracture range is the Post Fracture Flexural Strength.

Compression test

For each mortar mix, five specimens were tested and the results reported as average and standard deviation of the maximum compression strength obtained from valid tests (at least 3 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 200N/s in order to obtain the break for all the specimens between 30s and 90s according to the standard EN 1015-11. A compression jig assembly was used in order to compensate any lack of parallelism between the loaded surfaces of the specimen during compression tests. The tensile stress values for each sample were obtained by dividing the maximum load by the resistant cross section of the specimen (40x40mm^2).

3 RESULTS AND DISCUSSIONS

In *Tab. 9* the results of the Single Fiber Tensile test and Single Fiber Pull-out test are reported. The high value of standard deviation of every properties is due to the fact that *Arundo donax L.* are natural fibers, intrinsically inhomogeneous.

In *Fig. 54* are reported the characteristic three-point bending Stress-Strain curves of not reinforced mortars and reinforced with short fibers at three different percentages by weight (0.5%, 1%, 2%), that clearly shows the dramatic effect of fibers' percentage on post fracture resistance.

Fig. 57 shows that First Fracture Flexural Strength slightly decreases with fiber's percentage due to a greater defectiveness of the mortar which leads to higher fragility in the linear elastic range. By contrast, there is a marked increase in the Post-Fracture Flexural Toughness as a function of the fiber content, ***Fig. 58***. Some 2% fiber reinforced samples showed higher post fracture flexural strength than correspondent σ_0 due to the greater interface between matrix and fibers that act as obstacles to the propagation of the fracture and bridges between the fractured matrix. The prevalent unstable response in the Stress-Strain curves after the first crack occurred may be inferred to the bridging effect induced by the fibers that obstacle cracks propagation. When more energy needs to be spent 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.

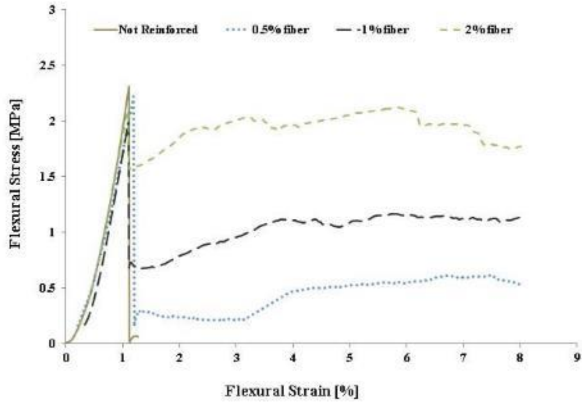

Fig. 54: Typical Flexural Behaviour of short fiber (4cm) reinforced mortars at different weight contents.

Fig. 55: TPB test of a characteristic short fiber 2 % reinforced specimen.

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. This is explainable since the greater interface between fiber and matrix requires more energy to cause their complete separation.

Fig. 56 shows the characteristic Stress-Strain curves of not reinforced mortars, and reinforced by adding fibers at 1 % by weight for three different lengths (4cm, 8cm, 12cm). 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 longer defects that lead to greater brittleness of the mortar in the linear elastic range.

By contrast, there is a noticeable increase in the post-fracture stress with the increase of the fiber length, due to the greater amount of fibers crossing the mid-section where the composite fracture is triggered. Particularly, the use of 12cm fibers leads to a post fracture flexural strength higher than first fracture stress.

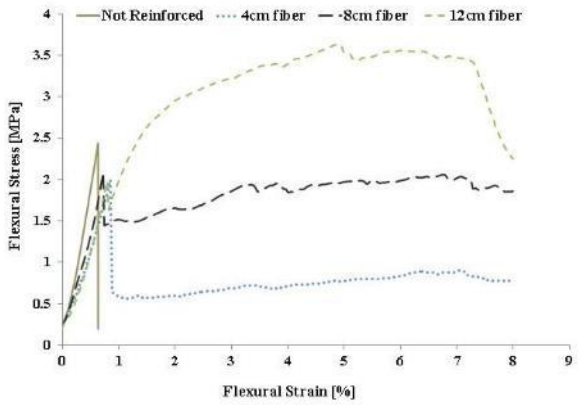

Fig. 56: Typical Flexural behavior of the mortars for 1 % wt reinforced composites in function of the fiber length.

The value of First Fracture Flexural Strength decreases depending on the length of the fibers probably due to the longer corresponding defects in the areas of scarce interface between fibers and mortar (*Fig. 57*).

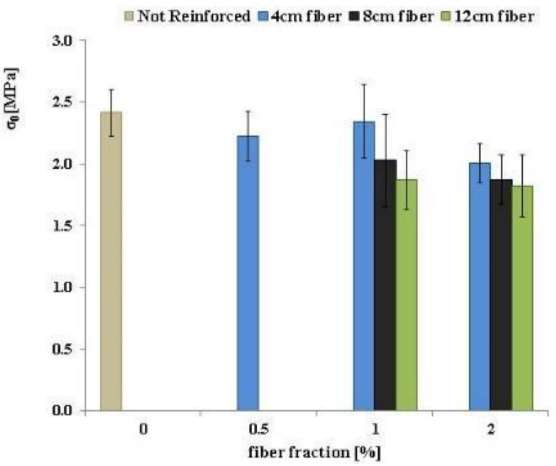

Fig. 57: First Fracture Flexural Strength in function of fiber fraction for different fiber lengths.

On the other hand, from *Fig. 58* 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 more energy needed 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 greater influence of the fiber distribution on the mechanical properties.

For composites with the addition of short fibers (4cm), the upward trend of the Post Fracture Flexural Toughness in function of the fiber percentage is attributed to the greater presence of the fibers at the middle section subjected to the bending stress.

Moreover, the fall of the Post Fracture Flexural Toughness of the composites with the addition of 2% of long fibers (12cm) compared to those at 1% is due to the excessive fiber content.

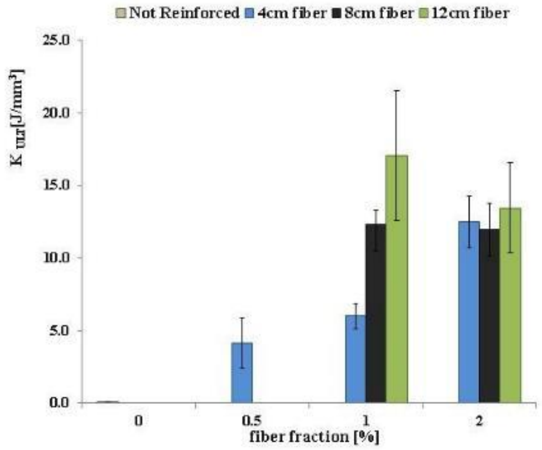

Fig. 58: Post Fracture Flexural Toughness in function of the fiber fraction for different fiber lengths.

In fact, the former are characterized by clusters of fibers and hence greater fiber-fiber interface rather than fiber-matrix interface leading to a higher content of defects in the matrix (*Fig. 59*). The composites added with medium length fibers (8cm) exhibit an intermediate behavior since the higher content of fibers that cross the crack surface of the spacemen is compensated by the higher percentage of defects, and thus the values of Post Fracture Flexural Toughness at 1 and 2% are very similar.

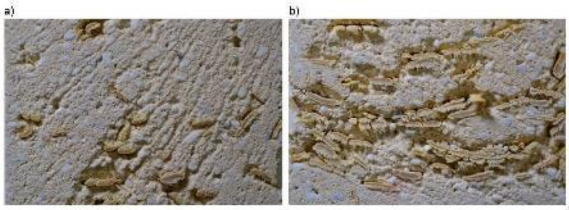

Fig. 59: Comparison of morphologies: a)12cm long fibers reinforced specimen at 1% by weight; b)12cm long fibers reinforced specimen at 2% by weight.

As can be observed from *Fig. 60*, the Compression Strength of the mortars was not significantly reduced by the addition of fibers up to 2%. All the composites, showed values of strength higher than 5MPa, which is the lower limit prescribed for M5 category mortars (EN 998-2). These results confirmed the capacity of the fibers to induce toughness to brittle mortars without harmfully affecting the Compression Strength, which is their main mechanical property.

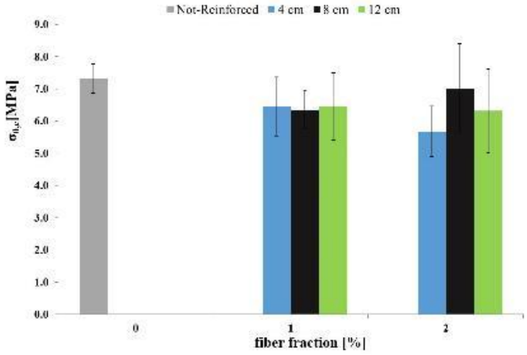

Fig. 60: Compression Strength in function of the fiber fraction for different fiber lengths.

4 SUMMARY

In the present work the influence of addition of *Arundo donax L.* fibers on the flexural properties of a biolime mortar has been investigated.

The results of the experimental characterization have confirmed that modification of biolime based mortar by addition of common reed fibers can have practical purposes for manufacturing ductile ecocompatible prefabricated bricks or laying mortars.

In particular, the First Fracture Flexural Strength remains almost steady for short fibers reinforced composites up to 1% wt. By contrast, as the fiber length increases, the values of this property decrease due to the more defectiveness of the material.

On the other hand, the Post Fracture Flexural Toughness significantly increases both in function of the fiber percentage and the fiber length up to 1 % wt. As the fiber length increases, the Post Fracture Flexural Strength and the Post Fracture Flexural Toughness increase due to the higher capacity of the fibers to control larger cracks. Overall, 1% wt of 12cm long fibers reinforced mortars provide the best flexural performances.

These results suggest that *Arundo donax L*. fibers can be effectively used in the formulation of sustainable biobased mortars, a further investigation can be performed to study the influence of fibers in thermal properties of mortars. The poor results showed in single fiber pull out tests suggest to investigate surface modification of fibers in order to increase adhesion to the inorganic binder.

5 ACKNOWLEDGMENTS

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