Experimental analysis on concrete blocks reinforced with *Arundo donax* fibres

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Abstract

Over the last decades, there has been growing attention in research and development on non-conventional building materials, such as vegetable fibres (*e.g.*, flax, hemp, jute, *etc.*), to be used as eco-friendly materials in a wide range of applications in civil construction. The main reasons for this interest are related to the specific properties, price, and sustainability of natural fibres, which can be considered 'green' building materials. In this article, the tensile strength of a new type of fibre extracted from the stem of the Giant Reed *Arundo donax* L. has been investigated. First, these fibres, which widely grow in Mediterranean areas but are diffused worldwide as well have been extracted from the outer part of the plant stem. Then, in order to have an initial idea of their influence on the mechanical properties of concrete, some experimental bricks have been prepared, with the addition of different weight percentages of this vegetal fibre. Compression and tensile tests on the whole block have been performed to assess the mechanical properties of these bricks. Hence, the differences between concrete bricks without fibre and those reinforced with different weight percentages of natural fibre have been analysed, assessing their potential applications in bio-architecture.

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Introduction

Over the last decades, growing attention on the use of less polluting materials and technologies (Millogo *et al*., 2014) and natural fibres instead of synthetic ones (*i.e.*, glass, carbon, or kevlar fibres) has been focused by both the academic and industrial world (Fiore *et al*., 2014). The main reasons for this interest are the specific properties, price, and low environmental impact of this kind of fibre. At the same time, these applications may also contribute to the valorisation of residual biomass coming from the agricultural sector (Picuno *et al*., 2019; Manniello *et al*., 2020a), hence producing positive impacts on the agricultural production chain (Statuto *et al*., 2013) and rural landscape (Statuto *et al*., 2019; Manniello *et al*., 2020b).

A great variety of natural fibres are currently available as reinforcements of construction materials. For example, some authors have investigated flax fibres' tensile properties, obtaining values higher than glass fibres (Baley, 2002). Rohi and Dixit (2016), instead, focused on the multiple properties of hemp fibre characterised, among others, by excellent mechanical strength and high values of Young's Modulus (stiffness), which makes it useful to strengthen concrete in many building applications (Sedan *et al*., 2008).

Jute fibre has shown good mechanical and thermal properties (Staiger and Ticker, 2008) exactly as sisal fibre which is characterised by high tensile strength and stiffness (Lobovikov *et al*., 2007). Balaji *et al*. (2014) investigated, instead, the behaviour of bagasse fibre as a natural renewable source for the manufacture of composite materials, while many other authors focused on coconut fibre (Sharma and Singh, 2017), which showed mechanical strength and stiffness higher than glass (Mohanty *et al*., 2005). Elsaid *et al*. (2011) performed several experimental types of research to study the mechanical properties of concrete reinforced with natural kenaf fibres, showing mechanical and workability properties comparable to those of standard concrete.

Wool (Coatanlem *et al*., 2006) and rice husk fibres (Sivaraja and Kandasamy, 2010) have also been studied as reinforcing materials in green building, while some recent scientific articles advance the feasibility of using less common natural fibres (Statuto *et al*., 2018; Parlato *et al*., 2021) such as artichoke (Fiore *et al*., 2011) or okra (Santulli *et al*., 2014). Some studies have also focused on the fibres of isora (Mathew *et al*., 2011), ferula (Seki *et al*., 2013), althaea (Sarikanat *et al*., 2014), piassava (Nascimento *et al*., 2012), sansevieria (Sathishkumar *et al*., 2013) and buriti (Demosthenes *et al*., 2020), demonstrating excellent mechanical properties in addition to numerous advantages related to their availability and environmental sustainability.

In the present paper, the tensile strength of a new type of fibre extracted from the stem of the Giant Reed *Arundo donax* L., has been investigated. The Giant Reed is a perennial rhizomatous grass that grows plenty and naturally in all the temperate areas of Europe (mainly in the countries of the Mediterranean area) and can be easily adapted to different climatic conditions. However, thanks to its high growth rate, it represents an invasive and aggressive species in some environmental conditions, so its disposal is difficult (Fiore *et al*., 2014). In Italy, this allochthonous species is invasive in some territorial contexts, and in others, it is almost completely naturalised. Its field of application is vast, ranging from the production of reeds in musical woodwind instruments for at least 5000 years to the use as a source of fibres for printing paper (Ververis *et al*., 2004). *A. donax* L. is also used as a diuretic and biomass source for chemical feedstocks and energy production. Furthermore, this non-wood plant has been recently considered in the manufacturing of chipboard panels as an alternative to the wood-based ones (Flores *et al*., 2011; Fernandez-Garcia *et al*., 2019). The stem of the giant reed is often used to make fences, trellises, stakes for plants, windbreaks, sun shelters (Pilu *et al*., 2012). Due to their specific mechanical properties (*e.g*., strength-density ratio), the stems of the giant reed are also employed in agricultural buildings and relevant construction activities.

Materials and methods

Some experimental concrete bricks (Figure 1) - *i.e*., cubic samples with 15 cm side and cylindrical samples with 10 cm diameter and 15 cm height - have been prepared in relevant moulds, with the addition of different weight percentages of *A. donax* vegetal fibre (0.0, 0.2, 0.6 and 1% by weight, respectively).

The concrete samples consist of Pozzolanic cement 'CEM IV 325', according to UNI EN 197-1:2011, in a percentage of 20% of the total volume, sand particles, measuring less than 1.5 mm with a humidity content below 10%, in a percentage of 30% of the total volume; quarry gravel, with a characteristic grain size of less than 30 mm, in a percentage of 40% of the total volume; and water, in a percentage of 10% of the total volume. Regarding fibres, the material used was the culms of Giant Reed (Figure 2).

They have been collected along the 'Bradano' river basin in the Basilicata region (Southern Italy) and dried in an oven at 105°C until a relative moisture content of less than 10% was reached. The average culm height was 3 m, and the average culm diameter was 2 cm. In order to get the most homogenous fibres, samples with different lengths have been cut from culms, avoiding nodes.

Finally, after vibrating the concrete mix, aimed at improving compactness and adherence of blocks to formworks, the samples have been left for 28 days in a humid environment to promote their curing and hardening.

To assess the mechanical properties of these bricks, tensile tests on single fibre have been performed, and compression and tensile tests on the whole block. These mechanical tests have been performed at the Laboratories for Testing Materials of the SAFE School of the University of Basilicata (Potenza, Italy) using a Galdabini PMA10 universal testing machine.

Tensile test on *Arundo donax* fibres

In the present experimental tests, fibres obtained from the trunk of the plant - cut and treated to obtain homogeneous shape and size, preferentially between 3-8 cm long - have been examined by tensile test (Figure 3). Only fibres from internodes have been tested.

The preparation of the fibres to be subjected to tensile tests has been performed according to ISO 22157:2019, respecting the relevant requirements: the cross-section of the samples is almost rectangular, with a width (3 mm) equal to around half the thickness (6 mm); the span between the anchors is between 50 mm and 100 mm; the anchorage has prevented the samples sliding and crushing.

The tensile tests have been carried out using a maximum 2.5 kN load cell equipped with an internal optical drive that reads the displacement. While the lower head of the machine was fixed, the upper head was stretching along the axis of the fibre (Figure 3).

The sample has been fixed to the grips, which exercised a pressure that could be adjusted using a pressure gauge. The tests have been carried out in displacement control, with a loading speed of 2 mm/min (which has been estimated as the right compromise according to the stiffness and size of the sample) and a frame acquisition frequency of approximately 1/700-1/800 ms. The 10 tested samples - having a variable free length of 3-8 cm each - have been fixed to the grips of the machine. The slack has been removed

Figure 1. Cubic and cylindrical samples for the laboratory tests.

Figure 2. Culms of Giant Reed used in laboratory tests.

without stretching the sample and making sure it was well aligned and straight within the grips and in the line along the load applied to the fibre, since any misalignment could produce a transverse/torsion movement of the grips, hence introducing errors in the measurement of elongation and contributing to the premature failure of the fibre.

During the tensile tests, failures occurred at the anchorages in some samples. This means that the samples are not subject to a perfectly centred normal deformation, but a specific bending moment component was present anyway. This is essentially due to the low load of these samples and, therefore, to a lack of sensitivity of the machine to low loads. On the other hand, most of the samples have showed a perfectly centred normal deformation with failure in the centre or at least away from the anchorages (Figure 4), so only these samples have been taken into consideration for the experimental analysis.

Compression test on cubic samples

After the setting and hardening period (28 days), for each typology of the cubic sample, the mechanical behaviour of the bricks has been measured by placing them between the rigid steel plates of the testing machine and testing them to unconfined compression strength through displacement-controlled uniaxial tests (Figure 5).

This testing machine consists of two columns high stiffness frame, with maximum vertical daylight between platens equal to 185 mm, horizontal daylight between columns of 175 mm, platens diameter equal to 153 mm, ram travel of approximately 45 mm, and 2 pressure transducers. The upper frame is fixed, while the lower frame is free to move and compresses the sample.

The frames are equipped with a safety device that interrupts the test after breaking the sample to prevent damage to the accessories used during the tests. Furthermore, a uniform load has been progressively applied without shock, and it has been continuously increased until failure, with the moving head of the testing machine travelling at a rate of 1 mm/min (UNI EN 123-90 - 3: 2019).

Figure 3. Tensile tests on *Arundo donax* fibres: front view (left) and side view (right).

Split tensile test on cylindrical samples (Brazilian proof)

A split tensile test - also known as the '*Brazilian*' test - has been carried out with the testing machine as well, then involving longitudinal compression along two diametrically opposed generating lines of the cylindrical sample, in accordance with UNI EN123-90-6 (Figure 6).

In this case, in the diametrical plane containing the load line, a tension representative of the tensile strength of concrete is gener-

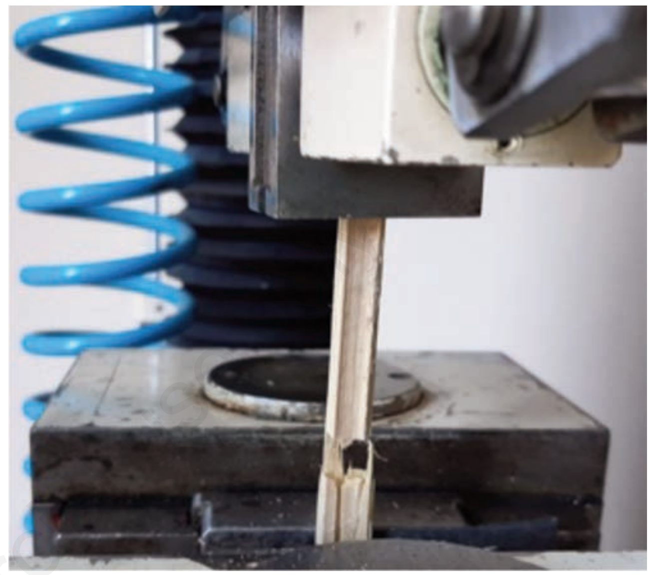

Figure 4. Tensile test on *Arundo donax* fibres: fibre breaks in the centre.

Figure 5. Compression test on a concrete brick reinforced with natural fibres.

ated in the orthogonal direction. The test has been performed on a cylindrical concrete brick by placing the sample with the horizontal axis between plates of a press and compressing them according to two opposite generators, in compliance with UNI EN 123-90-6.

Results and discussion

Tensile test on *Arundo donax* fibre

In Table 1, the tensile properties of *A. donax* fibres are reported in terms of average value, with the corresponding 95% confidence interval (ISO 22157:2019).

In Figure 7, the diagram elongation/load for the *A. donax* fibre is reported in terms of the average value obtained from laboratory tests. The mechanical behaviour of *A. donax* fibres appears to be very interesting, especially because its tensile strength is considerably high before the yield point. Just as a reference, the corresponding value for ordinary steel used for building is around 400-700 N mm^{-2}.

This tensile strength value is more important even if compared with other different natural fibres, which have showed, indeed, lower tensile strength and deformation properties, as was observed in the case of Spanish broom (Picuno, 2016). In this last case, from the laboratory tests, an experimental mean value of the tensile strength equal to about 41.53 N mm^{-2} (Natural sprig) and 36.62 N mm^{-2} (rope) has been detected, with a high standard deviation depending on the natural variability of the fibres. Indeed, this value difference depends on several factors, such as the fibre origin, the production process, the environment of origin, the part of the fibre considered, *etc*.

Moreover, the value here obtained for *Arundo donax* is in line with the value obtained by Spatz *et al*. (1997), who carried out tensile tests on parts of internode of length equal to 150 cm. They calculated the average elastic modulus of the epidermis for internodes extracted in the central part, and at the base of the culm of about 10 GPa, *i.e.*, a value of the same magnitude as that one detected during our experimental tests (2.53 GPa - considering a length of 15 cm - see Table 1).

Compression strength on cubic concrete samples

In Table 2, the results of compression tests on the four different types of cubic concrete sample, one for each fibre percentage are reported, while Figure 8 reports the corresponding compressive

Figure 6. Tensile test on a cylindrical concrete brick reinforced with natural fibres.

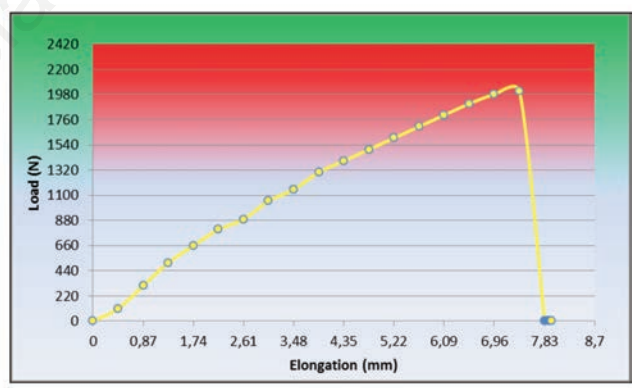

Figure 7. Elongation/load diagram for the tensile test on *Arundo donax* fibre.

Table 1. Tensile strength of the *Arundo donax* fibres experimentally tested.

Maximum load (N)	Maximum tension [N mm^{-2}]	Elongation at yield point [mm]	Yield point [N mm^{-2}]	Young modules [GPa]
2008	133.89±0.33	7.94±0.045	131.76±0.45	2.53±0.0072

Table 2. The maximum compressive strength of the different concrete bricks experimentally tested.

Vegetal fibres	0 (%)	0.2 (%)	0.6 (%)	1 (%)
Maximum applied load (N)	554,000	389,000	386,000	369,000
Deformation (mm)	1.87	1.83	2.2	2.85
Maximum compressive strength (Mpa)	24.62	17.29	17.16	16.4
Elastic modulus E (Mpa)	13.17	9.45	7.8	5.75

strength/deformation diagram for the four types of samples experimentally tested.

From the analysis of the results (Table 2), it can be deduced that the value of the compressive strength of the sample with concrete only reflects the literature values (typically, 25-60 MPa). As we imagined, adding different amounts of fibres (samples 2, 3, and 4) has led the compressive strength value to decrease, worsening this resistance value.

Directly proportional to the tension is the 'modulus of elasticity' (or Young's modulus), which represents the material's stiffness. The lower its value, the lower the stiffness of the sample, then indicating that the material can deform easily.

From Figure 8, indeed, it can be noticed that the behaviour of this material is almost elastic in the first phase, followed by a very limited plastic phase that quickly precedes the definitive failure of the cubic sample. From the results obtained through the present experimental tests, it can be concluded that further analysis should be performed, aiming to define the optimal percentage of natural fibres, also taking into account the length-to-thickness ratio. Indeed, natural fibres, even due to their increased aspect ratio (length/diameter) compared to non-fibrous filler, usually improve the mechanical properties of composite materials (Sharma *et al*., 2015). In fact, several studies (Danso *et al*., 2015) have emphasised the correlation between this factor and the mechanical properties of concrete blocks. It represents the ratio between the length of the fibre and its transverse diameter and is usually expressed as a single number greater than 1. The greater this ratio, the greater the fibre length, the greater the blocking force that the fibre produces within the concrete, thus the greater its compressive strength. In general, two fundamental parameters contribute to the development of the mechanical properties of blocks reinforced with natural fibres: the fibre content (percentage of fibres in the initial matrix) and the fibre Aspect ratio. Most studies have focused more on the first parameter, while much less attention has been paid to the Aspect ratio (Gaw and Zamora, 2011). Thus, there is a need to determine the fibre Aspect ratio that will produce the optimum strength when used to stabilize concrete blocks. There is a strong linear relationship between the mechanical properties of natural fibre reinforced concrete blocks and each Aspect ratio. This implies that researchers need to determine the optimal aspect ratio of fibres to be used as reinforcement and the optimal fibre content to produce blocks that will provide maximum strength.

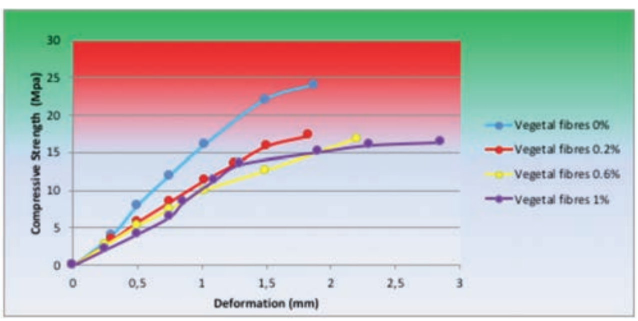

Figure 8. Compressive strength/deformation diagram for the compression test on cubic samples considered.

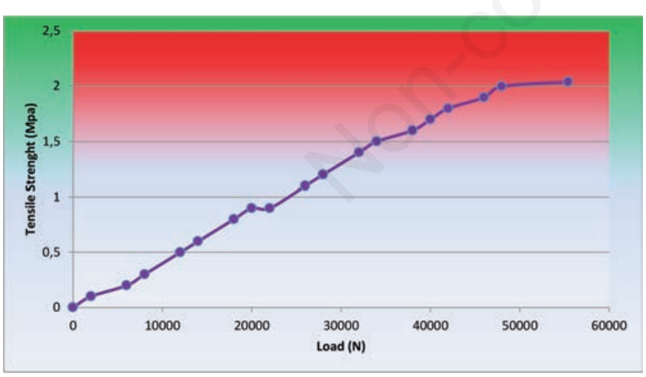

Figure 9. Tensile strength/load applied diagram for the cylindrical sample number 4.

Split tensile test on cylindrical samples (Brazilian proof)

In Table 3, the results of split tensile tests on the four different types of cylindrical concrete sample, one for each fibre percentage are reported. The tensile strength values are in line with the values provided by the Technical Standards for Construction, in which the strength of the generic sample is calculated as follows (Eq. 1):

$$\text{Tensile Strength} = \frac{(2*F)}{(\pi*L*d)} \quad (1)$$

Where 'F' is the break load, 'L' is the sample length, 'd' is the diameter of the cylindrical sample.

Figure 9 reports a tensile strength/load applied for sample 4 (1% of *A. donax* fibres), which shows the direct proportionality between the two parameters (elastic phase) before the sample breaks.

The analysis of the results reported in Table 3 shows the limit from which an increase in tensile strength can be appreciated following the addition of natural fibres: up to a fibre percentage of 0.6% weight (sample 3), there is no improvement in tensile strength, whereas from 1% onwards (sample 4) the tensile strength also begins to increase interestingly, if we consider the narrow range of difference between the various fibre percentages.

Table 3. Tensile strength of the different cylindrical samples experimentally tested.

Vegetal fibres	0 (%)	0.2 (%)	0.6 (%)	1 (%)
Maximum applied load (N)	37,100	20,800	37,500	55,400
Deformation	0.71	0.2	0.69	1.07
Tensile strength (Mpa)	1.6	0.9	1.6	2.04

Conclusions

The experimental tests performed in the present work mainly focused on the tensile properties of *A. donax* fibre, have highlighted some interesting considerations. It has indeed a very high tensile strength, especially when compared to other natural fibres such as *Spanish broom*. Moreover, the longitudinal elasticity modulus is in line with literature values. Subsequently, in order to have a first idea, which will certainly be deepened in future studies, the compressive and indirect tensile behaviour of concrete blocks reinforced with this natural fibre has been observed. Laboratory tests performed, one repetition for each fibre percentage, have highlighted that the compressive strength of concrete does not benefit from the addition of fibre in any three cases. The indirect tensile tests (Brazilian test), instead, carried out on cylindrical samples of concrete, have showed an improvement in the tensile strength of the samples, which starts from a threshold value: from 0.6% in weight of added fibre, there is an increase in strength resistance, as well as Young's modulus increase. Much more tests are anyway needed in the future, with different samples and different percentages of added fibre and evaluating the correct length-to-diameter ratio to reach values comparable, at least as a scale, to the stiffness of steel, in order to allow the use of these fibres in construction as they are considered low-cost and low-polluting materials.

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