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Concrete Blocks Reinforced with *Arundo donax* Natural Fibers with Different Aspect Ratios for Application in Bioarchitecture

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Abstract: In recent decades, the construction industry has advanced in its use of natural green resources, such as vegetable fibers (e.g., flax, hemp, jute, etc.) added in concrete mixtures, to create building materials that are both economically and environmentally sustainable. The pricing, low energy cost, and environmental sustainability of these natural fibers are driving this interest. The quantity of fibers and the ratio of fiber length to its transverse diameter (aspect ratio) are critical characteristics that have a decisive impact on concrete's mechanical qualities. The influence of the aspect ratio of *Arundo donax* fibers on the tensile characteristics of concrete blocks was specifically investigated in this study. These fibers were collected from the outer section of the stem of this plant, which grows commonly in Mediterranean locations, but that is also found all over the world. Experiments were carried out on cylindrical concrete blocks with a constant amount of fiber (1 percent by weight) and different aspect ratios: 30, 50, and 70 (mm/mm) respectively, to assess their tensile strength, even when compared with concrete blocks without any fiber addition. Tensile tests on *Arundo donax* fibers were also conducted, with the aim to contribute to the analysis of their interaction with cementitious matrices, and to assess differences between the various compositions. The results showed a direct impact of the aspect ratio on the final tensile strength of concrete blocks, with higher aspect ratios producing superior tensile properties.

Keywords: Bioarchitecture; concrete blocks; natural fibers; *Arundo donax*; aspect ratio; splitting tensile strength; Brazilian test

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1. Introduction

The use of natural fibers in construction—a technology used since ancient Egypt, with a history of more than 5000 years—is one of the most effective and promising solutions that may effectively increase in the sustainability of buildings in the modern era, hence contributing to the implementation of the concept of Bioarchitecture. Indeed, the analysis of natural elements that may be used as building components—a topic that is traditionally included in the scientific sector of Rural Buildings, i.e., one section of the widest field of Agricultural and Biosystems Engineering—may strongly contribute to the respect of the principles of sustainability, in the framework of a circular economy model aimed to improving the quality of life, by establishing a balanced relationship between nature and the built environment, satisfying the current needs without compromising the opportunities for future generations [1,2].

Concrete has traditionally been regarded as one of the most cost-effective building materials due to its low cost, availability, long durability, ease of shaping and sizing, capacity to withstand adverse weather conditions, and excellent compressive strength [3–5]. However, it has a variety of issues that raise significant concerns in the construction industry, such as poor tensile strength, which is about 1/10 of its compressive strength [3,4,6].

Many researchers have looked at the viability of employing natural fibers as reinforcement materials in concrete blocks, to offset this disadvantage, due to the fibers' unique qualities, low cost, and low environmental impact. At the same time, these applications may help to value residual biomass from the agricultural sector [7,8], resulting in positive benefits on the agricultural production chain [9] and rural landscape [10–12]. Material reinforced with natural fibers is the oldest form of composite material which, indeed, has always been obtained, at low cost, from materials present in nature, using local labor and technology and with reduced energy consumption. Due to these characteristics, the use of natural fibers as a form of concrete reinforcement is of particular interest for less-developed regions, where building materials have high costs and require the use of skilled labor.

Among the natural fibers most studied and investigated by many researchers, flax fiber [13–17] has very significant mechanical properties that are superior to glass fiber [18–21] or hemp fiber [22–27], which are widely used in multiple building applications [28] due to their excellent mechanical strength and stiffness [29]. Remarkable mechanical and thermal properties, by comparison, were shown by Staiger and Ticker [30] in 2008 in jute fiber, which is also used in the development of a low-cost construction material reinforcement for many applications [31–33], whereas sisal fiber [34] has shown high tensile strength and stiffness [35]. Other natural fibers have also been investigated as reinforcing material in composite materials, such as bagasse fiber [36] or kenaf fiber [37,38] which showed mechanical and workability properties of reinforced concrete comparable to normal concrete [39].

Some authors [40] studied the mechanical properties of coconut fiber-reinforced concrete [41], which showed mechanical strength and stiffness higher than that of glass fiber [42]. The effects of coconut fiber length and content on concrete properties were particularly analyzed by other authors [43], and the behavior of coconut fiber-reinforced building materials [44–49], for their use in a variety of applications, was also investigated [50–53]. Among the less common natural fibers used as reinforcement in building materials [54,55], we would definitely mention artichoke [56], okra [57], isora [58], ferula [59], althaea [60], piassava [61], sansevieria [62], and buriti [63].

Fiber content (the amount of fiber in the concrete block) and the fiber aspect ratio (the ratio of the length and the transversal diameter of the fiber, usually expressed as a single number greater than 1) are two critical characteristics that influence the strength development of fiber-reinforced blocks. Most studies on the use of natural fiber for enhancement of concrete blocks have focused on the fiber content, whereas few studies have investigated the correlation between the aspect ratio and the mechanical properties of concrete blocks [64–68].

Significance of Current Work

By itself, concrete represents a material with high compressive strength, but characterized by high fragility, low tensile strength, and low cracking resistance. For this reason, reinforcing materials using natural fibers represent the oldest form of composite materials; in fact, they have always been obtained, at low cost, from materials present in nature using local labor and technology and with reduced energy consumption. Due to these characteristics, the use of natural fibers as a form of concrete reinforcement is more widespread, mostly in less-developed regions, where high-cost construction materials are present and high-cost skilled labor is available.

The aim of this study was to examine a new type of fiber, extracted from the stem of *Arundo donax* L., as a potential reinforcement in concrete blocks. Specifically, the present study investigated the effect of the aspect ratio of *Arundo donax* fibers on the tensile properties of concrete blocks. In this regard, *Arundo donax* fibers of different aspect ratios (30, 50 and 90) and fixed content (1% by weight) were incorporated into concrete blocks to study their influence on tensile strength.

The *Arundo donax*—harvested annually, preferably during the winter period—produces a large quantity of biomass that can be used for thermal energy production or for the production of second-generation ethanol [69]. In addition, this natural fiber has a variety of applications, including as a supply of fiber for printing paper [70] and as a biomass source for energy production [56]. It has also been utilized in the manufacturing of alternatives to wood-based chipboard [71,72], insulating panels [73], or ecological starch-bonded panels [74], among other things, due to its non-woody qualities.

The stems of the *Arundo donax* are often used for the production of supports for horticultural plants and fishing rods, in the musical field for the creation of reeds for wind instruments, in phyto-purification plants, and in the interventions of stabilization of land at hydrogeological risk. The most significant studies on the mechanical properties of *Arundo donax* were conducted by Spatz et al. [75] in 1997, who focused on the variability of mechanical properties through bending, compression, and torsion tests at different points of the plant, highlighting that the central part of the culm presented the most homogeneous mechanical characteristics. Other experimental tests carried out more recently by Conte et al. [76], through three-point bending tests, concerned the influence of moisture content on the flexural elastic modulus of *Arundo donax*. Molari et al. [77] in 2021 studied the potential of this natural fiber as sustainable reinforcement in building materials. The results they obtained showed good mechanical properties, very similar to those of many bamboo species, which are already used in construction. Ortuno et al. [78] instead investigated the mechanical properties of *Arundo donax* to provide technical data in order to propose the use of this green material in sustainable construction. Fiore et al. [79] in 2014 studied the possibility of using *Arundo donax* natural fibers as reinforcement in polymer composites. Using tensile tests on single fibers and a mathematical model they investigated the relationship between the transverse size of the fibers and the mechanical properties. Other authors [80] have previously highlighted the high tensile strength of this natural fiber, especially when compared to other natural fibers such as Spanish broom [81].

2. Materials and Methods

2.1. *Arundo donax* Fibers

Arundo donax was present in the Mediterranean basin in ancient times. Most probably it originated in East Asia, then spread to the rest of Asia, North Africa, Middle East, and Southern Europe, where it has been cultivated for thousands of years [82,83]. Other hypotheses state that the species was introduced into North America in the early 1800s, from southern California, to counter erosion phenomena. In Italy, its spread originates from the central regions, where it soon developed a strong invasiveness, whereas in the north the presence of *Arundo donax* is more reduced [84].

This plant prefers river environments, artificial canals, countryside, and soils difficult to access by man or left in a state of abandonment (Figure 1). The presence of *Arundo donax* is increasingly rare as the altitude increases; the plant is completely absent at altitudes higher than 700 m [82].

It is a species present in all countries [85] and, due to its adaptability and speed of growth, can represent a natural resource of high economic interest.

The material used in the laboratory tests of the present research was culms of *Arundo donax*, collected along the "*Bradano*" river basin, in the Basilicata region (Southern Italy). They were carefully cut in order to obtain homogeneous fibers and then dried in an oven at 105° until a relative moisture content of less than 10% was reached (Figure 2). The average culms' height was 3 m and the average culms' diameter was 2 cm.

Figure 1. Culms of *Arundo donax* used as reinforcement material in concrete blocks.

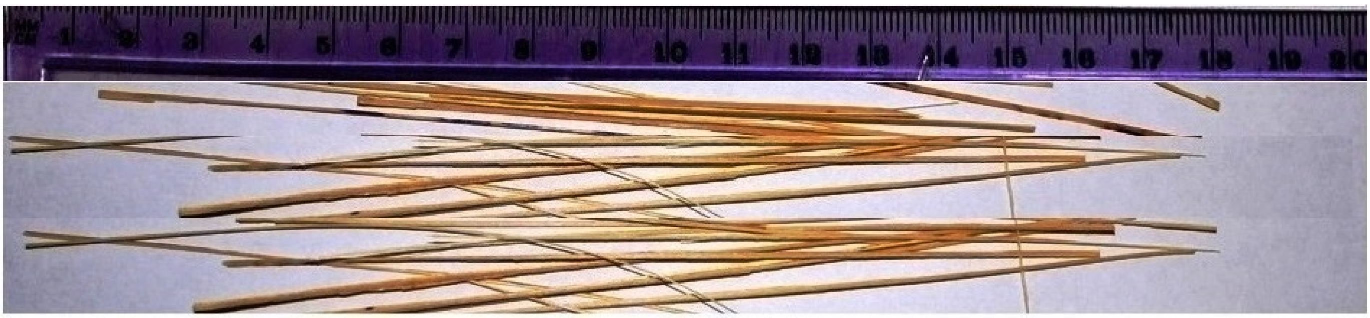

Figure 2. *Arundo donax* fibers.

2.2. Tensile Test on Arundo donax Fibers

The obtained fibers were first characterized from the point of view of their tensile strength at the Laboratories for Testing Materials of the SAFE School of the University of Basilicata (Potenza, Italy) using a Galdabini PMA10 universal testing machine. These tensile tests were carried out using a maximum load cell of 2.5 kN equipped with an internal optical reader that reads the displacement. While the lower head of the machine was fixed, the upper head extended along the axis of the fiber (Figure 3). The samples were blocked to the grips, the pressure of which was adjusted using a pressure gauge. The tests were performed under displacement control, with a loading rate of 2 mm/min. The tested samples were fixed to the grips of the machine. In addition, they were well aligned and straight within the grips, in order to avoid any misalignment and consequent errors in the measurement.

Figure 3. Tensile tests on *Arundo donax* fibers.

Ten specimens of *Arundo donax* fiber were tested, in order to calculate averaged values, and to limit the measurement errors related to the expected relatively high scatter of the mechanical response of the fibers. Indeed, natural fibers present a complex microstructure and wide heterogeneity, which is derived from their intrinsically irregular morphology.

2.3. Cylindrical Concrete Samples

In order to perform splitting tensile strength (Brazilian) tests on concrete elements added with *Arundo donax* natural fibers, some cylindrical concrete samples (Figure 4) with 10 cm diameter and 15 cm height were prepared with the addition of 1% by weight of *Arundo donax* vegetal fiber (added as an initial reference following a random distribution), having a different aspect ratio (AR)—defined as the ratio between the length and equivalent diameter—as follows:

- 4 samples were reinforced with natural fiber having AR = 30: length equal to 90 mm and transversal equivalent diameter equal to 3 mm;
- 4 samples were reinforced with natural fiber having AR = 50: length equal to 150 mm and transversal equivalent diameter equal to 3 mm;
- 4 samples were reinforced with natural fiber having AR = 70: length equal to 210 mm and transversal equivalent diameter equal to 3 mm.

Figure 4. Cylindrical samples used during laboratory tests.

Moreover, in order to evaluate the practical results, one cylindrical sample of the same concrete but without any additive fiber was also prepared.

The concrete samples consisted of:

- Pozzolanic cement "CEM IV 325", according to UNI EN 197-1:2011 [86], in a percentage of 20% of the total volume, that constitutes the active component of concrete. Compared to Portland cement, it has a slower hardening process, thus improving workability and durability [87]. Today, industrial cement manufacturers are increasingly using materials such as pozzolan, fly ash, and volcanic ash, to replace part of Portland cement, in order to reduce CO2 emissions and the relative cost, and to improve the resistance to chemical attack by sulphates and sea water.
- sand particles, consisting of loose sedimentary rock with a grain size measuring less than 1.5 mm and a humidity content below 10%, in a percentage of 30% of the total volume;
- quarry gravel, crushed and rounded rock with granule size less than 30 mm, in a percentage of 40% of the total volume;
- water, which has the fundamental function of hydrating the cement and whose quantity greatly influences the strength characteristics of the hardened concrete, in a percentage of 10% of the total volume.

In the preparation of the mixture, the grain size of the aggregates was mixed between fine and coarse, in order to, as much as possible, fill the spaces between contiguous elements and reduce the volume of voids, which reduce the mechanical strength of hardened concrete. Finally, after vibrating the concrete mix, aimed at improving compactness and adherence of blocks to formworks, the samples were subjected to maturation for 28 days in a humid environment, with the aim of conferring compactness and mechanical resistance over time to the fluid mixture described above.

2.4. Splitting Tensile Strength Test on Cylindrical Samples (Brazilian Test)

The experimental splitting tensile strength (Brazilian) tests were executed at the Laboratories for Testing Materials of the SAFE School of the University of Basilicata (Potenza—Italy) using a Tecnotest K300-sv universal testing machine. The Brazilian test was performed on the cylindrical samples, according to UNI EN123-90-6 [88]: the two opposite generators of the sample undergo a compression that generates a traction on the diametrical plane that contains the load (Figure 5). The testing machine is equipped with a 100 kN load cell and an internal sensor that provides the displacement reading. The lower head of the machine is fixed, and the upper head is free to compress the two opposite generators of the sample. The sample is constrained in the grips, which exert a pressure that can be adjusted via a pressure gauge, in order to avoid the ovality of the anchor bolts and the subsequent ovality of the anchorage clamps.

Figure 5. Breakage of the sample at the end of the splitting tensile strength test (Brazilian test).

The tests were carried out in a displacement control, with a loading speed of 0.4 mm/min and a frame acquisition frequency of about 1/700–1/800 ms. The test was supervised by the optical technique of Digital Image Correlation (DIC), which controls the deformation and displacement of the cement blocks. This experimental test allowed indirect evaluation of the tensile strength of a concrete block and, consequently, its stiffness, by testing 4 samples for each different AR, in order to mediate the results according to the intrinsic anisotropy of the block. Figure 6 shows the failure of the generic sample along the transversal and longitudinal directions.

Figure 6. Breakage of the sample, after maximum applied load, along the transversal (**left**) and longitudinal (**right**) directions.

3. Results and Discussions

In Table 1, the tensile properties of *Arundo donax* fibers are reported in terms of the average value for the 10 specimens, with the corresponding 95% confidence interval according to ISO 22157:2019 [89], where as Figure 7 shows the relationship between the applied load and the resulting fiber elongation. From the analyses carried out, it was found that these natural fibers have a remarkably high tensile strength before their yield point, especially if we consider that for an ordinary steel used for construction, the reference value is about 400–700 N mm^{-2}. Moreover, as highlighted by other authors [76], this resistance value is also higher than that of other different natural fibers, such as Spanish broom, which showed lower tensile strength and deformation properties, specifically 41.53 N mm^{-2} (natural sprig) and 36.62 N mm^{-2} (rope). Indeed, this difference would depend on several factors, such as the origin of the fiber, the manufacturing process, the environment of origin, and the part of the fiber considered.

Moreover, the value obtained here for *Arundo donax* is in line with the value obtained by Spatz et al. [75], who carried out tensile tests on parts of the 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 detected during our experimental tests (2.53 GPa—considering a length of 15 cm—see Table 1).

In Table 2, the results of the Brazilian tests on the different types of cylindrical concrete sample are reported for each AR, and for the cylindrical concrete sample without any additive fiber. These results are presented in terms of maximum applied load, consequent deformation, and tensile strength. Each of these characteristics is reported as its average value and corresponding 95% confidence interval. In order to give a possible comparison, the tensile strength values by Italian law are also reported in Table 2.

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

Maximum Tensile Strength [MPa]	Elongation at Yield Point [mm]	Yield Point [MPa]	Young Modules [GPa]
133.9 ± 0.33	7.9 ± 0.045	131.8 ± 0.45	2.5 ± 0.0072

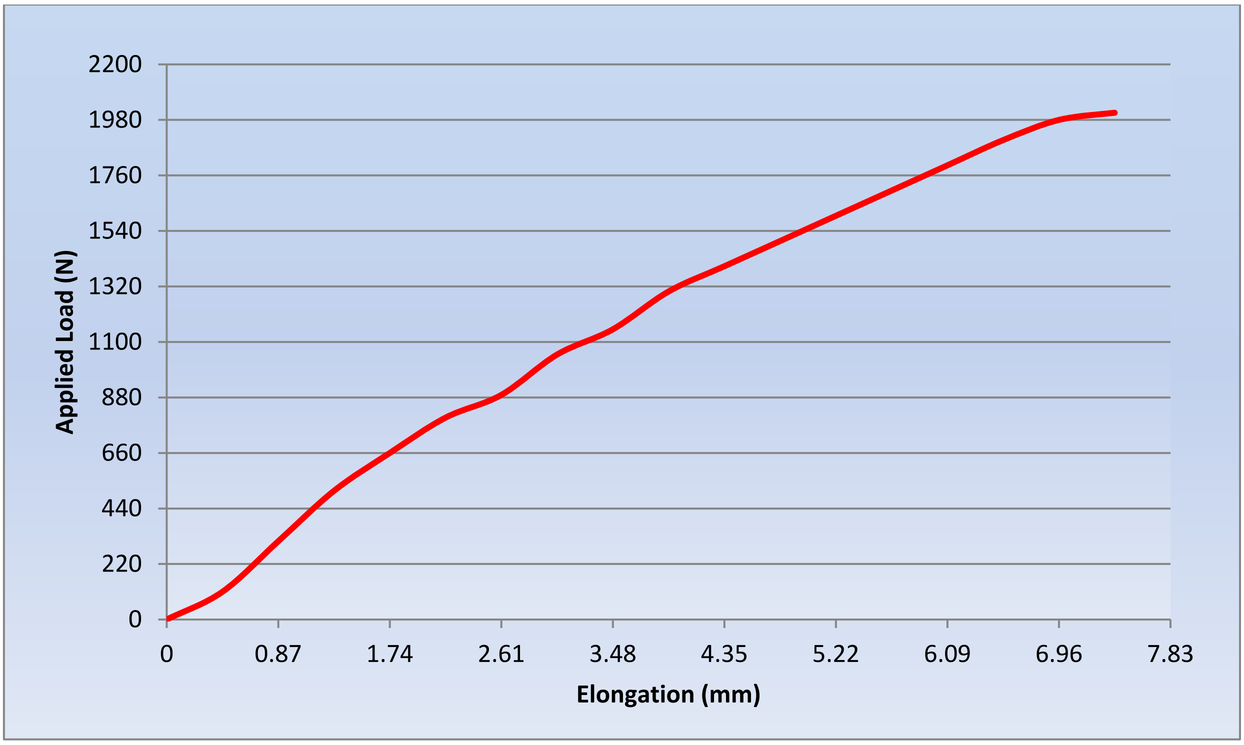

Figure 7. Elongation/applied load diagram for the tensile test on *Arundo donax* fiber.

Table 2. Tensile strength of the different cylindrical samples experimentally tested.

Comparison Sample without Fiber	Maximum Applied Load (N)	Deformation (mm)	Tensile Strength (MPa)	Tensile Strength by Law (MPa)
	37,100	**0.71**	**1.6**	**1.58**
AR	**Average Value (N)**	**Average Value (mm)**	**Average Value (MPa)**	**Average Value (MPa)**
30	54,525	1.3 ± 0.01	2.2 ± 0.005	2.3 ± 0.01
50	72,700	1.6 ± 0.013	2.6 ± 0.01	3.1 ± 0.01
70	95,800	2.4 ± 0.006	3.4 ± 0.007	4.1 ± 0.005

Table 2 and Figure 8 show that there is a direct proportionality between the AR of the *Arundo donax* fibers and the corresponding tensile strength of the reinforced concrete blocks: it increases from a value of 2.2 MPa to 3.4 MPa, corresponding to an increase in the AR from 30 to 70. This increase appears very significant when compared to the small dimensions of our blocks, and especially when compared to the values of the sample without natural fiber (1.6 MPa). It indicates that a proportional increase in the maximum load was tolerated before breaking, and hence a consequent improvement in the deformability characteristics of the composite material.

The tensile strength values are in line with the values provided by the Italian Technical Standards for Construction (also reported in the table), in which the strength of the generic sample is calculated as follows:

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

where "*F*" is the break load, "*L*" is the sample length, "*d*" is the diameter of the cylindrical sample.

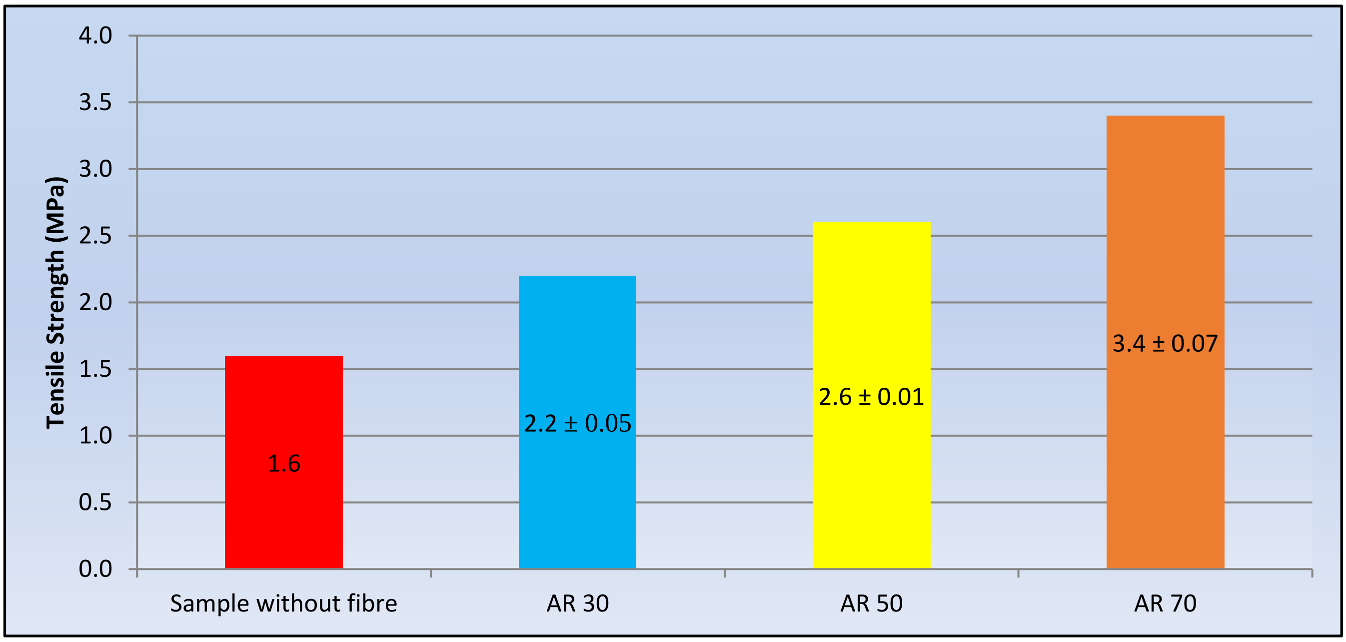

Figure 8. Increase in tensile strength for each AR considered and comparison with sample without any additive fiber.

Finally, Figure 9 reports a tensile strength/load applied for each AR considered, with the correspondent trend line, and shows the direct proportionality between the two parameters (elastic phase) before the sample breaks.

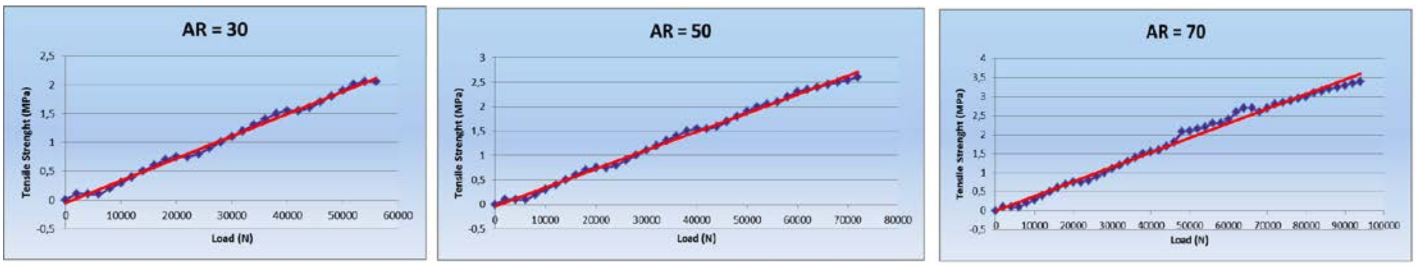

Figure 9. Tensile strength/load applied diagram for each AR considered.

From this figure, it is possible to notice that the higher the AR, the higher the load applied to the sample, and the higher the strength of the sample before reaching the final failure. Thus, the obtained results seem to confirm a direct proportionality between the AR of *Arundo donax* fiber and the tensile strength of concrete blocks; as also highlighted by many authors [90], the greater this ratio, the greater the fiber length and then—as a direct consequence—the greater the counter-resistance force that the fiber produces within the concrete.

The results obtained in this work suggest therefore that natural fibers have a reinforcing function within the cylindrical concrete blocks considered. In fact, the comparison with a block without natural fiber showed an increase in the maximum applied load and in the consequent deformation before sample break. As a consequence, the tensile strength also increased, always in line with the values reported in the reference law. On the other hand, comparing between them the values obtained for concrete blocks with different ARs of natural fiber, the direct proportionality between this parameter and the tensile strength of the concrete blocks themselves was highlighted: an increase in the AR of *Arundo donax* fibers generates an increase in the tensile strength of concrete blocks, which will be greater as the size of the considered blocks increases. As reported in the relevant scientific literature that has tackled this scientific issue regarding the mathematical modeling or empirical equation [91], this is probably a result of the variability in the bond-slip law throughout the fiber, which is expected to be higher for longer fiber.

The AR directly influences another aspect: the adhesion between the cement matrix and the reinforcing fiber. With the same composition and dosage, the higher the value of the AR, the greater the adhesion between the two materials, since the contact surface between them increases, and subsequently the performance of the fiber reinforcement improves, because the fibers stressed by traction tend to be more difficult to extract. This highlights the importance of this parameter for researchers and practitioners in the determination of the optimum AR of fibers to be used to reinforce concrete blocks, which can provide maximum strength when used in constructions.

Future analysis to identify the bond-slip laws would therefore enable a full assessment of the performance of *Arundo donax* natural fibers dispersed in concrete matrixes. Bond-slip laws capable of describing the relationships between natural fibers and cementitious matrices may be necessary to understand this interaction, since fibers promote a "bridging effect" across the opening cracks, which is controlled by several relevant parameters—such as fiber geometry, shape, dosage, orientation and distribution within the matrix, mechanical properties of fibers, and bond interaction between the fiber and cementitious matrix. It leads to an enhanced response in the post-peak branch of stress–strain relationships [91].

Our results, while verifying similar conclusions already reported in the scientific literature, also confirmed that *Arundo donax* natural fibers can be considered to be an interesting alternative to other structural material, for contributing to enhance the tensile characteristics of concrete. The use of this natural fiber could therefore be properly considered in structural elements, in which limited tensile strengths are needed, and substituted for the use of non-natural materials, such as steel, whose use in combination with concrete may also present different weak points (e.g., oxidation).

4. Conclusions

The use of fibers as a dispersed reinforcement in cement-based materials is a common solution for enhancing the mechanical properties of the cementitious matrices. However, the use of natural fibers in construction materials is a relatively new trend, motivated by the lower cost of these fibers with respect to "ordinary" industrial fibers, which are either made of steel or plastic materials. Although natural fibers present a complex microstructure and wide heterogeneity, several studies have demonstrated their potential [91].

The aim of this article was to contribute to a better understanding of the mechanical properties of *Arundo donax* natural fibers, and especially of their function within building materials, because they represent a low-cost and environmentally sustainable solution compared to industrial solutions. The results of tensile tests on the single natural fiber of *Arundo donax* showed that the tensile properties of these natural fibers are comparable to those of other industrial fibers, such as steel, or even superior to other natural fibers such as Spanish broom. Furthermore, the values obtained for the longitudinal modulus of elasticity are in line with the literature values. Moreover, these natural fibers with different ARs and fixed weights were inserted inside cylindrical concrete blocks to study the fibers' mechanical properties. Laboratory tests showed that the higher the aspect ratio of these natural fibers, the higher the tensile strength of the concrete blocks. This proportionality can become increasingly significant as the size of the concrete blocks increases.

Therefore, as a preliminary study, we can conclude that the use of *Arundo donax* fiber as reinforcement for concrete blocks is an innovative and sustainable solution from both an economical and an environmental point of view, due to its qualities related to elasticity, lightness, and strength, which allow a variety of uses in construction. These natural fibers, due to their high tensile strength and ability to mix with and adhere to the concrete matrix, increase the toughness and tensile strength of the composite material, while improving its deformation characteristics. The present study can be extended in the future by taking into account other important parameters and scenarios, including: the relationship between different weight % of *Arundo donax* natural fiber and different ARs; the consequent comparison with other types of natural fibers present in nature or other configurations [92]; the chemical and physical properties of *Arundo donax* fibers and their distribution in concrete blocks; the role of rheological properties and porosity of composite mortars, to understand their influence on mechanical properties; crack morphology of samples with different ARs; and mathematical modelling/empirical solutions, even based on different laboratory tests on compressive or flexural properties [93].

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