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Natural Cellulosic Alfa Fiber (*Stipa Tenacissima L.*) Improved with Environment-Friendly Treatment Cementitious Composites with a Stable Flexural Strength

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Abstract Using natural fibers in structural applications is the subject of much research in the scientific world. Natural fibers are bio-sourced, biodegradable, have a low carbon footprint, and have interesting mechanical properties. The lightness, tensile strength, and elongation before break make natural fibers suitable candidates to replace synthetic fibers. Sometimes, natural fibers must undergo heavy chemical treatment for the extraction of microfiber. This is not the case in this paper, which presents a first attempt to use esparto fiber in its raw state without heavy treatment without soda and bleach. In this paper, the raw esparto stem cut into short fibers is treated, then prepared and used as reinforcement in mortar. The mechanical properties of the esparto stems were identified, analyzed, and improved. The mechanical tests showed a weak adhesion between the mortar and Alfa. Also, excessive absorption of water by the stem induced a delay in the mortar's setting. Even with unsaturated stems, this phenomenon is observable. An improvement was applied to the natural Alfa stem to improve its adhesion and reduce the absorption of spillage water. For the first time, as a major innovation in natural fibers used for cementitious composites, a method is presented in this paper allowing the use of Alfa (esparto) fiber in a mortar while keeping the mechanical strength properties of the mortar. Test specimens 4x4x16 cm were made and reinforced with short fibers of 2 and 3 cm with different volume concentrations: 1%, 2%, and 5%. The flexural strength and compressive strength were determined experimentally. The results show that for the 1% concentration of short fibers of 3cm, the compressive strength is 26 MPa, which is almost identical to the strength of the control specimen equal to 26.03 MPa. Flexural strength of the improved fibers concentrated at 1%, 2%, and 5% reach nearly 4.75 MPa very close to the flexural strength of the control specimen, which is 5.57 MPa. The flexural strength doesn't decrease with treated Alfa fiber concentration increase: this is a unique case in which flexural strength doesn't decrease compared to other natural fibers results in the literature. In conclusion, Alfa-treated short fibers can be used in secondary structural applications subject to compressive and light bending forces, for example, paving applications.

Keywords Cement-Based Composites, Fiber

Reinforced Concrete, Construction Materials, Natural Fiber, Mechanical Properties

1. Introduction

The Alfa plant is very widespread in North Africa and in the western south of Europe. It grows spontaneously in arid or semi-arid environments and covers an estimated area of 600 000 ha in Tunisia, 4 000000 ha in Algeria, 3186 000 ha in Morocco, 350,000 ha in Libya, and 300,000 ha in Spain [1]. This plant is of ecological and social-economic interest in Tunisia. On the one hand, it plays an essential role in the maintenance of the pastoral balance and, on the other hand, presents an income for the populations living close to these esparto fields. The uses of Alfa fiber are diverse. Historically, Alfa is used in handicrafts, for example, manufacturing ropes and high-quality paper production [2]. A significant amount of research has been carried out on the Alfa plant to find new outlets for this low-cost plant. Incorporating the plant in building materials produced a more environmental-friendly material with good thermal and mechanical properties [3], [4].

Natural fibers like Alfa are mostly studied in synthetic polymer matrices composites [5]–[10] and biopolymers matrices composites [11], [12]. Mechanical properties of short Alfa fiber-reinforced composites [13], [14], braided Alfa stems reinforced composites [15] and time dependency induced by the usage of polymers are studied, for Alfa fibers [16] and synthetic fibers [17]. The viscoelasticity can have a benefic effect on noise and vibration dumping [18]. Some researchers tried to study the tensile and compression performance of composite materials based on rubber particles and alpha fibers [19]. The reinforcement with Alfa fibers improves the rubber composite properties such as breaking strength and elongation at break. Applications of natural fibers composites have spread to automotive [20] and biomechanics [21] as well. However, the use of this plant in the construction field is recent [22], and many studies tried to better understand the behavior of this plant and natural fibers in general in cement mortars mixtures [23]. Experimental investigations on the impact resistance of cement mortar slabs reinforced with four natural fibers, coir, sisal, jute, hibiscus cannebinus, and subjected to impact loading showed a maximum absorbed value of 253.5 Joules for a 30x30x2 cm slab [24].

Mechanical characteristics of classical concrete lightened by natural and treated natural fibers to the concrete decrease the modulus of elasticity, the flexural strength and the compressive strength. Khelifa et al. [25] showed that the usage on untreated Alfa fibers the flexural strength and decrease the compressive. Same result about the decrease of mechanical properties when the natural fibers percentage increases is found in literature [26], [27]. The durability of concrete is reinforced with alfa fibers exposed to external sulfate attack and thermal stresses. The concrete with 1% alfa fibers is the one that behaves best in terms of resistance to thermal stress, and its loss of resistance is the lowest and the closest to that of polypropylene concrete, which is of the order of − 20 MPa [28]. Alfa/Epoxy composite randomly reinforced with short fibers shows better mechanical properties [29]. Alfa/Epoxy composite reinforced with unidirectional fibers can be used in structural beams to lighten structural elements [30].

The main objective of this work is to determine the length and the rate of addition of natural Alfa fibers to obtain a fibrous mortar with good mechanical properties. For this purpose, mortars formulations were elaborated with different lengths of fibers (20 and 30mm) for volume fractions of 1, 2, and 5%. After the elaboration of the different mortars, control specimens were taken. Characterizations in the fresh state, workability, and density, were carried out. Then, the mechanical behavior of the mortars was studied through bending and compression tests for natural and improved Alfa stems.

2. Materials and Methods

2.1. Alfa Stems

2.1.1. Properties and Preparation

The Alfa plant (Stipa tenacissima L) used was collected from the region of Kasserine located in the center of Tunisia. This plant has a height of up to 1 m. Diameter is measured from a collected sample and the measures show that stems have diameters about 0.7 mm to 1.3 mm (see Table 1).

Table 1. Diameters of Alfa stems collected from the region of Kasserine and used in this paper

Diameter (mm)	0,70	0,80	0,90	1,00	1,10	1,20	1,30
Number of fibers per diameter	3	6	4	16	14	6	1
%Of fibers per diameter	6%	12%	8%	32%	28%	12%	2%
Cumulative% of fibers per diameter	6%	18%	26%	58%	86%	98%	100%

The Alfa stems are temporarily constrained with an adhesive tape (see Fig. 1-b) and manually cut to produce short fibers (see Fig. 1-c). Short fibers lengths are 20 mm and 30 mm (see Fig. 1-d).

El-Abbassi et al. [31] observed by the microscope that Alfa has very fine porous. Alfa fibers consist mainly of 39.53% of cellulose, 27.63% of hemicelluloses, and 19.53% of lignin. That's why Alfa fibers are subjected to heavy treatment with soda and bleach to extract only cellulose. This is not the case for this paper. In this paper, to decrease this porous to avoid water of mixing suction and to improve the moisture resistance of the short Alfa fiber, improvement by reducing fibers permeability is applied [32].

a. Manual tools b. Adhesive tape constrained alfa stems

c. Cutting to 2cm and 3cm d. Obtained short fibers

Figure 1. Short fibers cutting from Alfa stems

Previously tensile test on Alfa/Epoxy composites showed a weak adhesion of the fiber with the matrix (see Fig. 2).

a. MTS Tensile Machine b. Alfa/EPOXY Sample c. Weak adhesion d. Zoom on weak adhesion zone

Figure 2. Weak adhesion between natural Alfa stem and Epoxy in tensile tests

a. Alfa stems improved

b. Natural Alfa stems

c. Short fibers of improved Alfa

Figure 3. Alfa stems and short fibers improved rough surface

Therefore, it appears necessary to improve the adhesion properties of Alfa fibers with cement mortar, the same conclusion got by Ajouguim et al. 2019 [33]. Surface treatments of Alfa fibers are considered before their incorporation into the cement matrix. The surface of Alfa stems is made rough (see Fig. 3-a) compared to natural Alfa stems (see Fig. 3-b). Alfa stems are then cut to 2 cm and 3 cm short fibers (see Fig. 3-c).

Mortar specimens reinforced with non-improved Alfa short fibers are fabricated to study the adhesion properties of Alfa fibers with the cement mortar. Results are shown in the results section.

2.1.2. Moisture Content

Moisture is one of the important properties of building materials. It is the actual water content of a material in the pores. The moisture is noted W and is expressed in percentage (%). A sample of the esparto fibers was weighed and then placed inside the oven for 24 hours at a temperature of 105°C. After drying, fibers are covered with aluminum foil to prevent ambient humidity absorption. Once the samples cooled, a second weighing is carried out with a precision balance (0.001 g). The initial sample weight was 100 g, after processing the wet weight became 90 g. The result got confirm that Alfa fibers contain an average moisture content of about 10%. Improved Alfa fibers showed no moisture content. The sample of 100g kept the same weight after processing.

2.1.3. Water Absorption Capacity

The water absorption by immersion is the difference between the mass of a sample saturated in water and its mass in a dry state. The results got confirm that this fiber contains an average moisture content of about 10%. The absorption capacity of the natural fiber is about 79.77%. Improved Alfa fibers showed no water absorption, no decrease in water level was observed.

2.1.4. Density

Before moving on to composites, it is important to know the mechanical properties of the fiber. However, these properties are easily influenced by several factors, among others, the origin of the plant, the variety, growing, and harvesting conditions, thus explaining the difference between the values found in the literature. Reference [4] shows that the density of Alfa is equal to 1.4 g/cm^3, Belhassen et al. [11] found the density of Alfa is equal to 1.3 g/cm^3 and Bessadok et al. [32] show a value of 0.89 g/cm^3.

To determine the density of a sample, it is necessary to know 2 quantities: its mass and its volume. The density of a substance is the ratio of its mass to its volume. For samples used in this paper, the density of non-improved alfa fibers varies between 0,81 g/cm^3 and 1 g/cm^3, and the density of improved alfa fibers varies from 0,88 g/cm^3 to 1 g/cm^3.

2.2. Sand

The sand used in this study is 0/4 mm and comes from Borj Hfaiedh quarry located in Bou Argoup Nabeul in the northeast of Tunisia. The granulometric curve of the sand is presented in Fig. 4.

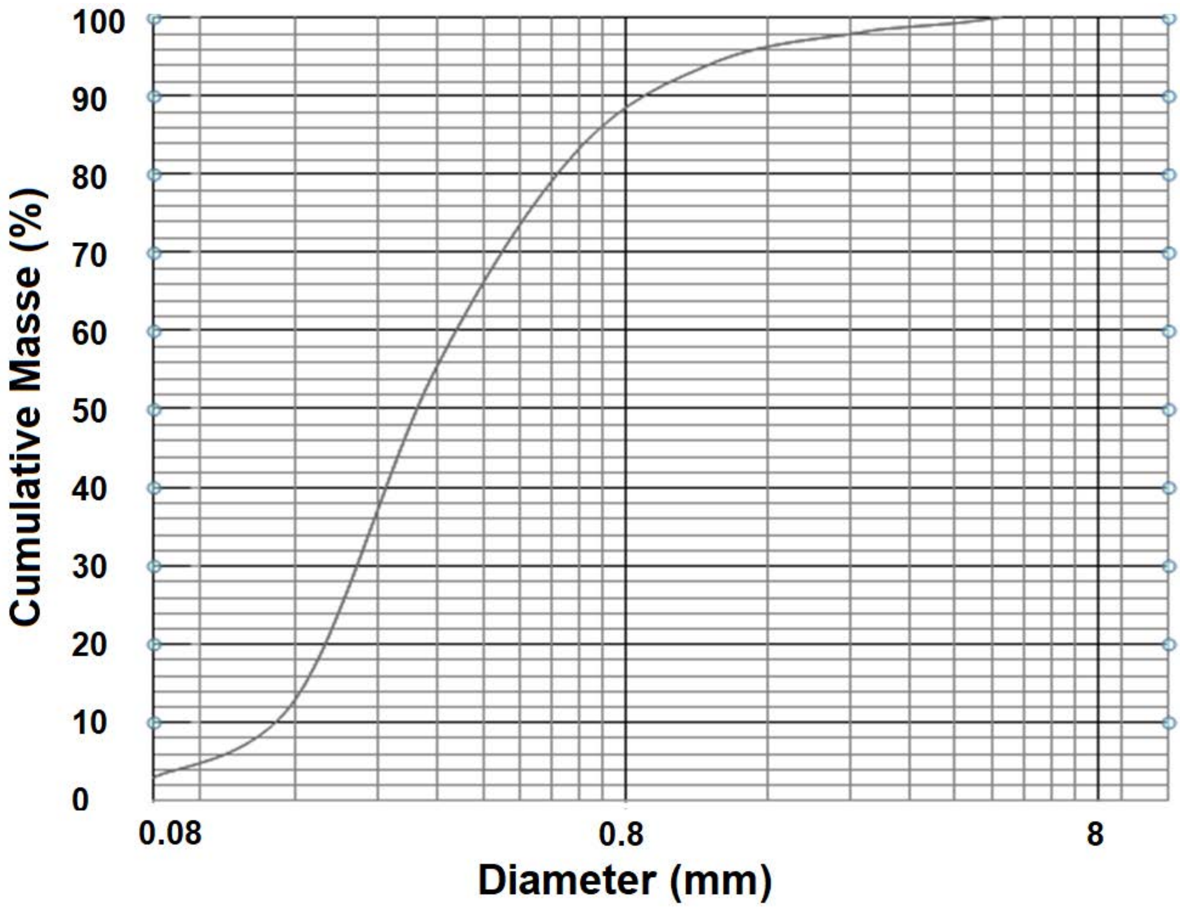


Figure 4. Sand granulometric curve

Table 2. Cement CEM I 42.5 N Properties

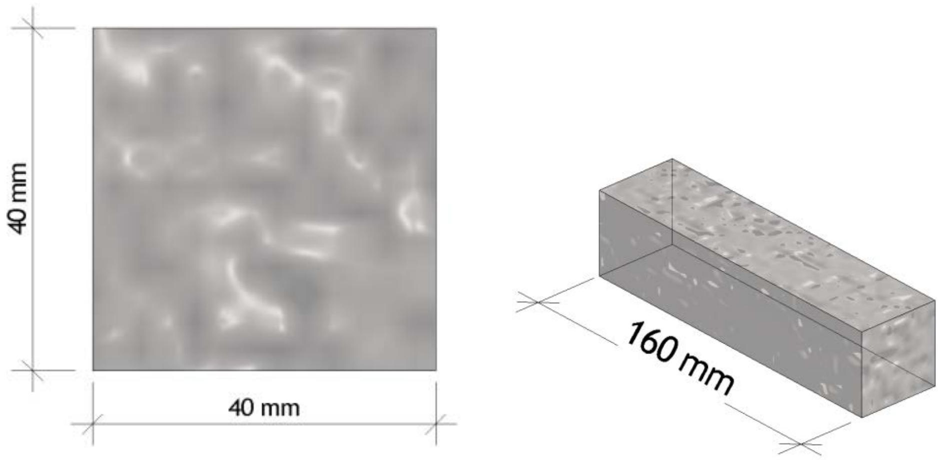
Chemical Properties	Physical Properties	Mechanical Properties
Loss on ignition ≤ 5.0% Sulfate (SO3) ≤ 3.5% Insoluble residue ≤ 5.0% Chloride ≤ 0.10%	Time to set ≥ 60 min Stability (expansion) ≤ 10 mm	Short term strength (2 days) ≥ 10.0 MPa Current strength (28 days) ≥ 42.5 MPa and ≤ 62.5 MPa

2.3. Cement

The used cement for the development of the concrete is the Portland cement CEM I 42.5 N produced by CAT-COLACEM Jebel Djelloud factory according to Tunisian Standard NT 47-01 (2017). Properties of the cement are presented in Table 2.

2.4. Elaboration of the Cement-Based Composite Specimens

The specimen geometry and section are presented in Figure 5. The width and the depth of the specimen are equal to 4 cm. The beam is 16 cm long and the distance between supports is equal to 10 cm.



a. Section b. 3D view

Figure 5. Specimen geometry

Table 3. Composition of cement-based composites for natural Alfa fibers

	Cement (g)	Sand (g)	Water (ml)	Alfa fiber (g)
Control sample (C0)	450	1350	225	-
NAR20MM_ 1%	450	1343.7	225	6.3
NAR20MM_ 2%	450	1337	225	13
NAR20MM_ 5%	450	1319	225	31
NAR30MM_ 1%	450	1342.32	225	7.68
NAR30MM_ 2%	450	1335	225	15
NAR30MM_ 5%	450	1312	225	38

Table 4. Composition of cement-based composites for improved Alfa fibers

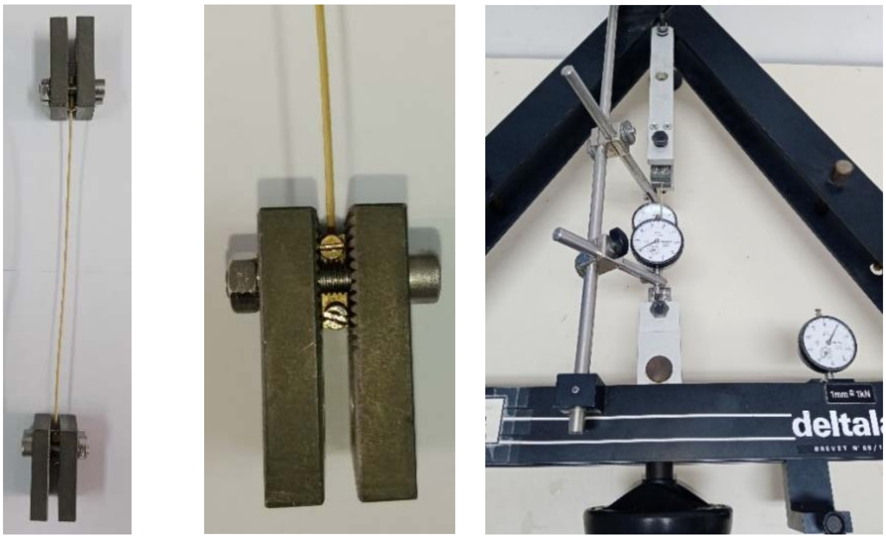
	Cement (g)	Sand (g)	Water (ml)	Alfa fiber (g)
Control sample (C0)	450	1350	225	-
NAR20MM_ 1%	450	1342.32	225	7.68
NAR20MM_ 2%	450	1335	225	15
NAR20MM_ 5%	450	1312	225	38
NAR30MM_ 1%	450	1342.32	225	7.68
NAR30MM_ 2%	450	1335	225	15
NAR30MM_ 5%	450	1312	225	38

The mortar elaborated, the cement-based composite, is a mixture containing cement, sand, and Alfa short fibers. The weight of Alfa for different concentrations is presented in Table 3 for natural no-improved Alfa fibers and in Table 4 for improved Alfa fibers. The name chosen for the prepared specimens is NARXmm_Y%: natural fiber Alfa reinforced mortar incorporating Y% Alfa Fibers of length X mm. The specimens were prepared with a water-cement ratio W/C equal to 0.5 and a sand cement ratio S/C equal to 0.3. These ratios are derived from an experimental campaign before this work.

3. Results

3.1. Alfa Fiber Mechanical Properties

To determine the Young modulus, the elongation at failure, and the failure stress, Alfa fibers were subject to tensile tests. Alfa stem is placed between two clamps (see Fig. 6-a and Fig. 6-b). The clamps are attached to the triangular tensile bench (see Fig. 6-c) and applied load and displacement can be measured.



a. Alfa stem fixation   b. Clamp   c. Triangular tensile bench

Figure 6. Alfa stem tensile test

Table 5. Composition of cement-based composites for improved Alfa fibers

Natural Alfa Stem		Improved Alfa Stem	
Strain (mm/mm)	**Stress (MPa)**	**Strain (mm/mm)**	**Stress (MPa)**
0,00%	0	0,00%	0
0,12%	13,08	0,08%	8,84
0,27%	25,46	0,19%	17,68
0,46%	38,2	0,33%	26,53
0,57%	50,93	0,45%	35,37
0,73%	63,66	0,61%	44,21
0,87%	76,39	0,56%	53,05

Figure 7. Mortar workability test

Tensile test results are stated in Table 5 for natural alfa stem and improved alfa stem. From Table 5, directional young modulus E can be calculated. Initial young's modulus for natural Alfa fiber stem is equal to 11.12 MPa and young's modulus for improved Alfa fiber stem is equal to 11.59 MPa. Tensile failure stress for natural Alfa stem is calculated based on 10 failure tests. The values vary from 60.27 MPa to 181.89 MPa. The mean value of failure stress is equal to 122.08 MPa. Tensile failure stress for improved Alfa stem is equal to 88.42 MPa.

3.2. Fiber-Reinforced Mortar Workability

The workability of the different formulations was measured by the shaking table according to the standard EN-1015-3. The test comprises measuring the spreading diameter of the mortar with the help of a truncated cone placed on the table (see Fig. 7), then; the mixture is subjected to 15 shakes.

The spreading diameter is the average value of two measurements taken in two perpendicular directions. The measured diameters are given in Table 6.

Table 6. Spreading test results

Sample	CM	NAR20MM_			NAR30MM_		
Addition rate (vol.%)	0	1%	2%	5%	1%	2%	5%
Spread (cm)	17.10	16.75	16.65	16.45	16.85	16.65	13.10

Table 7. Mortar fresh density

Sample	CM	NAR20MM_			NAR30MM_		
Addition rate (vol.%)	0	1%	2%	5%	1%	2%	5%
Density (g/cm^3)	2.24	2.23	2.23	2.22	2.24	2.24	2.22

a. 3 points bending bench

b. specimens' sections after bending test

c. control specimen brittle failure

d. weak adhesion of Alfa fibers

Figure 8. Flexural strength test for 40x40x160 mm specimens

The analysis of the values shows that introducing the 20 mm long Alfa fibers slightly decreases the mortar NAR20MM_ spread compared to the Control Mortar (CM), which has a spread of 17.10 cm (see Table 6). For the 30mm long fibers, the spread considerably decreases for the NAR30MM_ 5% specimen to a value of 13.10 cm.

3.3. Fiber-Reinforced Mortar Density

The results of the fresh density of the different mortars are presented in Table 7. The densities of the fibrous mortars are between 2.22 g/cm^3 and 2.24 g/cm^3, i.e., values relatively close to those of the control mortar CM, which is about 2.24 g/cm^3. Introducing Alfa fibers in the mixtures does not lead to significant changes in the density of the fibrous mortars.

3.4. Flexural Strength of Fiber-Reinforced Concrete

To determine the flexural and compression strength of the cement-based composites reinforced with alfa short fibers, 40x40x160 mm specimens were manufactured and stored for 07 and 28 days in a humid chamber (T = 20±2°C, relative humidity >90%). They were subjected to flexural strength test and then to compression test according to the EN-1015-11 standard (see Fig. 8-a).

Fig. 8-b shows the failure mode of the mortar specimens after the bending tests. The control mortar shows a brittle failure (see Fig. 8-c). In addition, a slippage (see Fig. 8-d) of the natural non-improved fibers in the cement matrix was observed on the specimens after failure, which shows a poor adhesion at the interface between the Alfa fibers and the matrix.

Table 8. Flexural strength of fiber-reinforced concrete

Tests at 28 days	**Control Mortar**	**Natural Alfa Stem Reinforcement**						**Improved Alfa Stem Reinforcement**					
Sample	**CM**	**NAR20MM_**			**NAR30MM_**			**NAR20MM_**			**NAR30MM_**		
Addition rate (vol.%)	0	1%	2%	5%	1%	2%	5%	1%	2%	5%	1%	2%	5%
Effort at Break (N) Sample 1	2533,3	2474,5	2131,5	1794,3	2328,1	2191,8	1860,1	2136,1	1929,5	1893,8	2117,9	1974,0	2115,4
Effort at Break (N) Sample 2	2481,1	2414,9	2083,7	1763,7	2275,9	2162,4	1831,7	2099,7	1903,5	1867,0	2087,5	1947,4	2081,6
Effort at Break (N) Sample 3	2115,1	1997,1	1749,7	1549,2	1911,1	1956,3	1632,9	1844,3	1722,1	1679,1	1874,7	1761,8	1844,7
Effort at Break (N) Mean Value	2376,5	2295,5	1988,3	1702,4	2171,7	2103,5	1774,9	2026,7	1851,7	1813,3	2026,7	1894,4	2013,9
Flexural strength (MPa) Sample 1	5,94	5,80	5,00	4,21	5,46	5,14	4,36	5,01	4,52	4,44	4,96	4,94	4,96
Flexural strength (MPa) Sample 2	5,82	5,66	4,88	4,13	5,33	5,07	4,29	4,92	4,46	4,38	4,89	4,87	4,88
Flexural strength (MPa) Sample 3	4,96	4,68	4,10	3,63	4,48	4,58	3,83	4,32	4,04	3,94	4,39	4,41	4,32
Flexural strength (MPa) Mean Value	5,57	5,38	4,66	3,99	5,09	4,93	4,16	4,75	4,34	4,25	**4,75**	**4,74**	**4,72**
% Difference compared to control specimen	0,00%	3,4%	16,3%	28,3%	8,6%	11,4%	25,3%	14,7%	22,1%	23,7%	14,7%	14,9%	15,2%

Table 8 shows the measured stress values as a function of fiber length, concentration, and improvement, for the different studied mortars. At 28 days, the average value of the control mortar is 5.57 MPa.

Compressive strength of fiber-reinforced concrete

The compressive strength remains always one of the most important characteristics of concrete and mortars. The compressive strength is measured through a compression machine (see Fig. 9-a) at 07 and 28 days, only 28 day's results are presented in this paper. The failure of the fiber-reinforced specimen is not brittle (see Fig. 9-b).

Table 9 shows the compressive strength of the control specimen CM is equal to 26.03 MPa on 28 days.

a. Compression machine b. Non-brittle failure

Figure 9. Compressive strength test

Table 9. Compressive strength of fiber-reinforced concrete

Tests at 28 days	**Control Mortar**	**Natural Alfa Stem Reinforcement**						**Improved Alfa Stem Reinforcement**					
Sample	**CM**	**NAR20MM_**			**NAR30MM_**			**NAR20MM_**			**NAR30MM_**		
Addition rate (vol.%)	0	1%	2%	5%	1%	2%	5%	1%	2%	5%	1%	2%	5%
Compressive strength (MPa) Sample 1	28,76	25,75	20,00	13,41	22,28	19,19	9,39	24,06	23,07	18,35	27,37	23,62	17,86
Compressive strength (MPa) Sample 2	27,94	25,42	19,79	13,04	21,82	18,76	9,27	23,78	22,79	18,05	26,96	23,20	17,63
Compressive strength (MPa) Sample 3	26,85	24,97	19,50	12,56	21,20	18,18	9,11	23,41	22,42	17,65	26,41	22,65	17,32
Compressive strength (MPa) Sample 4	20,56	22,42	17,86	9,75	17,62	14,83	8,18	21,28	20,28	15,35	23,27	19,45	15,55
Compressive strength (MPa) Mean value	26,03	24,64	19,29	12,19	20,73	17,74	8,99	23,13	22,14	17,35	**26,00**	**22,23**	**17,09**
% Difference compared to control specimen	0,0%	5,7%	26,2%	53,3%	20,7%	32,1%	65,6%	11,5%	15,3%	33,6%	0,5%	14,9%	34,6%

4. Discussion

Based on the results in Table 6, for high values of Alfa short fiber concentration 5% and longer fibers, more than 20mm, the workability of the mixture is reduced. This can be explained because fibers retain the mixture against spreading. This is a common result found for all natural fibers.

Regarding the density of the mixture, based on results in Table 7, introducing treated Alfa fibers in the mixtures does not lead to significant changes in the density of the fibrous mortars. The reason for that is the low concentration of fibers. The maximal concentration is 5% which is not significant. Further investigations for higher values of concentrations must be done in future works.

Based on Table 8, introducing Alfa fibers in the mortar reduces the flexural resistances. For non-improved alfa short fibers, the specimen NAR20MM_1% shows a decrease in the flexural strength by 3.4%, the NAR20MM_2% shows a decrease in the flexural strength by 16.3%, and the NAR20MM_5% shows a decrease in the flexural strength by 28.33%. It can be concluded that the increase in the volume fraction of Alfa fibers in the mix leads to a decrease in flexural strengths. This result is found in literature for natural fibers.

For treated Alfa fibers, for the two lengths, the specimen NAR30MM_1% shows a decrease in the flexural strength by 14.7%, the NAR30MM_2% shows a decrease in the flexural strength by 14.9% and the NAR30MM_5% shows a decrease in the flexural strength by 15.2%. Improved fibers show more stable results and better results for higher concentrations of fibers. This is the major discovery and innovation for this paper. The relative stability of the flexural strength values for the improved fibers is observed even with a 5% concentration, but the compressive strength drops for the natural fibers remarkably for high concentrations (see Table 9).

For the compressive strength, the results show that if the concentration of fibers increases, the flexural strength decreases, but for the 1% concentration of short fibers of 3cm, the flexural strength is 26 MPa which is almost identical to the strength of the control specimen equal to 26.03 MPa. This leads us to conclude that, with the improvement of the roughness and impermeability of the fibers, lighter concretes and more resistance to compression can be produced. Another finding from the results test is that the increase in the length of natural fibers decreases the compressive strength, while for improved fibers, the increase in fiber length keeps the compressive strength value superior to 17.09 MPa.

5. Conclusions

In this paper, the raw Alfa (esparto) stem cut into short fibers is prepared and used as reinforcement in mortar. The results show that with the improvement of the roughness and impermeability of the fibers, lighter mortars with the same compressive strength can be produced. For the 1% concentration of improved short fibers of 3 cm length, the compressive strength is 26 MPa, which is almost identical to the strength of the control specimen equal to 26.03 MPa. For flexural strength, improved fibers show more stable results and better results for higher concentrations of fibers compared to all previously studied natural fibers in literature.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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