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STUDY ON NATURAL FIBER BASED COMPOSITES FOR STRENGTHENING OF MASONRY STRUCTURES

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Sommario

Nel presente lavoro sono riportati i primi risultati ottenuti da una vasta indagine sperimentale svolta su materiali compositi in fibre naturali, quali: lino, canapa, juta, sisal e cocco. In accordo con le normative vigenti, sono state svolte prove di trazione sui singoli fili e sui tessuti, allo scopo di definire una classifica in termini di resistenza, di questi materiali, nel loro stato naturale. I compositi prodotti e studiati sono stati caratterizzati da due differenti matrici: a base polimerica e a base di malta; ottenendo così compositi NFRP (Natural Fiber Reinforced Polymer) e NFRPG (Natural Fiber Reinforced Grout). Una nuova tecnologia di intreccio tra le fibre, la cosiddetta "braiding technology", è stata esaminata, allo scopo di aumentare le caratteristiche meccaniche dei materiali naturali non-impregnati. I risultati ottenuti sono stati comparati con i più comuni materiali compositi (CFRP e GFRP).

Abstract

In the present paper the first results obtained from a vast experimental investigation carried out on natural fiber composite materials (flax, hemp, jute, sisal and coir) are reported. Tensile tests on single yarns and fabrics have been carried out according to the current standards. Two types of matrices have been used: polymeric and mortar-based matrices. Therefore, the composites materials NFRP (Natural Fiber Reinforced Polymer) and NFRG (Natural Fiber Reinforced Grout) have been obtained. A new fiber placement technology has been studied, the so-called "braiding technology", in order to increase the mechanical properties of the natural non-impregnated materials. The results obtained, were compared with those of the most common composites systems (CFRP and GFRP).

Keywords: masonry, natural fibers strengthening, braided structures

1. INTRODUCTION

Historical masonry buildings show objective difficulties in relation to ordinary buildings when dealing with conservation issues, for their constructive and typological variety. The definition of a univocal and reliable modeling and analysis strategy is very difficult. Moreover, choosing strengthening techniques is equally complex. Attention has to be focused on limiting interventions to a minimum, avoiding unnecessary strengthening. This goal is clearly in agreement with the principles of sustainable development. Currently, the option for composite materials to strengthen cultural and historical heritage is frequent. This reinforcement technique represents the easiest and direct solution to face collapse mechanisms that typically characterize masonry structures [1], under static and seismic effects. Composite materials have numerous advantages when compared to traditional materials [2], but at the same time they present some disadvantages that cannot be avoided. In fact, these materials cause environmental pollution during their manufacture, but also a high use of energy, necessary for disposal at the end of their life cycle. When using natural fibers and bio-resins, natural fiber-reinforced composite materials are renewable, cheap, completely or partially recyclable, and biodegradable. [3]. Their availability, renewability, low density, and price as well as their mechanical properties make them an attractive alternative to glass, carbon and other man-made fibers used for the manufacturing of composites. Natural fiber-containing composites are more environmental friendly, and used in many fields like transportation (automobiles, railway coaches, aerospace), building and construction industries (ceiling paneling, partition boards) [3]. In this paper, a wide experimental investigation dealing with the use of natural fibers was carried out in the Civil Engineering Laboratory and Fibrous Materials Laboratory at University of Minho. The experimental investigation has been organized in two parts: the tensile tests and single-lap shear bond tests on reinforced bricks. This paper shows the results of the first part of the research.

2. EXPERIMENTAL PROGRAM

The natural materials used in the experimental plan are constituted by bidirectional fabrics of flax, hemp, sisal, jute and coir fibers (Figure 1). Tensile tests have been organized in two specific groups: tensile tests on single yarns (Figure 2b) and tensile tests on fabrics (Figure 2c). The tensile tests on fabrics were carried out considering both non-impregnation and impregnation of the fibers. The matrices used to produce composites with impregnated system were: polymeric matrices (epoxy and polyester) and mortar-based matrices. The polymer matrices used are the epoxy resin and the polyester resin in order to produce Natural Fiber Reinforced Polymer (NFRP). Finally it was used mortar-based matrices in order to produce Natural Fiber Reinforced Grout (NFRG).

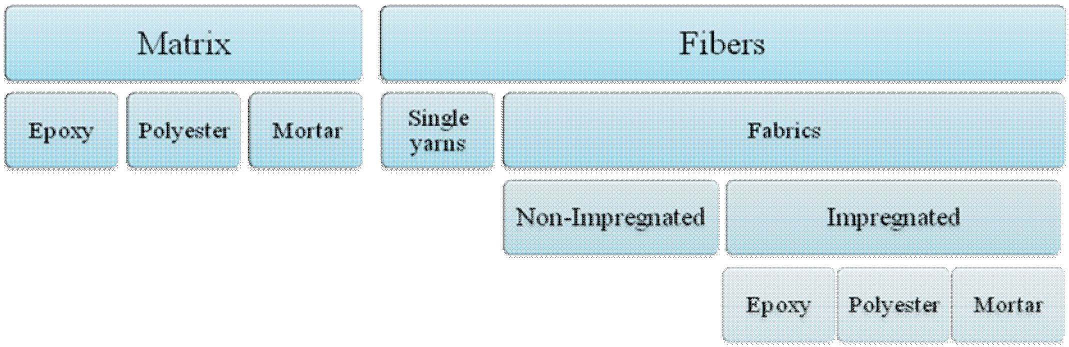
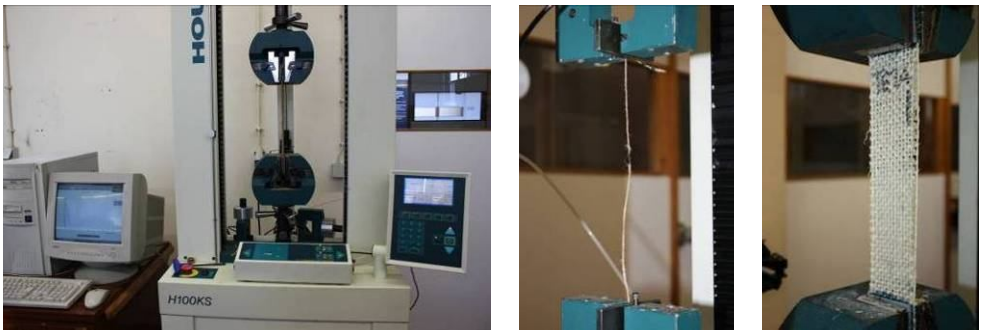


Figure 1: Scheduling of experimental working plan for tensile tests.



a) b) c)

Figure 2: Tensile tests: (a) Testing machine; (b) yarns; (c) fabrics (c).

2.1 Tensile tests on single yarns

The study on the natural fiber-based fabrics was preceded by tensile tests on single yarns. Each single yarn was measured and weighed in order to compute the linear density (Tex) and tenacity (N/tex) of the different materials and tests were done in accordance with [4]. Flax, hemp, jute, sisal and coir fibers were used and many specimens for each type of yarns, different in diameter and orientation in the fabrics, have been tested. Table 1 shows average values and coefficients of variation obtained for all fibers tested.

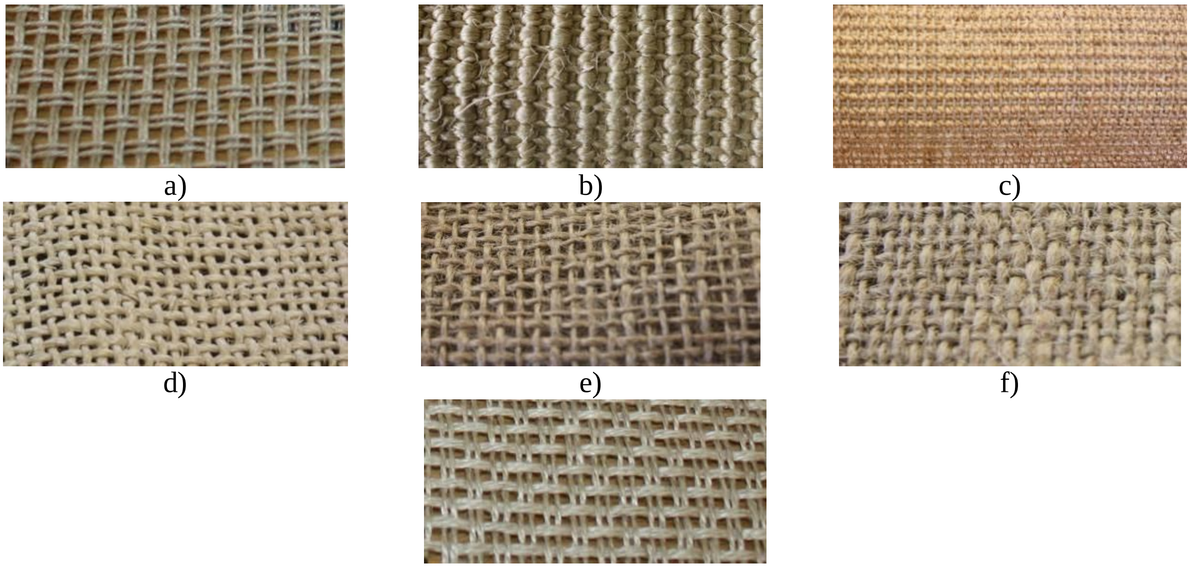
Table 1 : Average values obtained from tensile tests on single yarns

			Linear Density [Tex]	Tenacity (N/Tex)	ε_{peak} [%]	f_t [MPa]	E [MPa]
JUTE	**JUTE^{BIG}**	*Average*	5060,98	0,05	0,38	14,69	46,20
		CoV	12%	27%	13%	39%	31%
	JUTE^{12}	*Average*	281,80	0,11	0,03	74,84	2769,70
		CoV	17%	15%	15%	20%	24%
	JUTE^{7}	*Average*	267,44	0,12	0,03	101,66	4460,12
		CoV	10%	14%	32%	46%	42%
	JUTE^{sisal}	*Average*	2068,79	0,21	0,07	224,51	3702,47
		CoV	24%	12%	20%	36%	43%
HEMP	**HEMP-BI**	*Average*	327,26	0,20	2,94	124,14	4236,98
		CoV	4%	11%	12%	19%	16%
	HEMP-UNI	*Average*	330,14	0,29	3,58	163,98	4578,41
		CoV	8%	4%	5%	13%	11%
	HEMP-MESH	*Average*	381,42	0,25	5,36	166,60	3104,87
		CoV	7%	7%	7%	23%	21%
SISAL	**SISAL^{2g}**	*Average*	3927,26	0,08	0,39	31,53	85,19
		CoV	18%	17%	26%	16%	18%
	SISAL^{1p}	*Average*	1439,31	0,18	0,08	144,18	1792,17
		CoV	17%	7%	3%	46%	43%
	SISAL^{coir}	*Average*	2905,37	0,22	0,06	144,93	2814,27
		CoV	23%	11%	10%	24%	32%
COIR	**COIR^{sisal}**	*Average*	2887,37	0,14	0,19	51,83	322,07
		CoV	3%	9%	16%	19%	16%
FLAX	**FLAX**	*Average*	322,90	0,29	3,22	198,10	5913,59
		CoV	3%	8%	7%	14%	18%

Analyzing the first results on the single yarns, it can be observed that flax and hemp are those that present higher values in terms of tensile strength, followed by sisal and jute. Concerning the failure mode of the yarns, it was observed non homogeneous; this is due to the fact that the specimens are characterized by non-uniform diameters and above all they are natural materials. Consequently, in order to obtain 5 good results, with a failure mode in the middle of the specimens, a number between 10-15 specimens, for each type of material, were tested.

2.2 Tensile tests on non-impregnated fabrics

Tensile tests on specimens taken from non-impregnated fabrics were carried out (Figure 3), in accordance with [5], using 200x50mm specimens. Aerial mass was measured for each sample (table 2). Specimens cut at 0º (weft direction) and 90º (warp direction) were prepared, with an equal number of yarns in the direction of load application. Steel plates were placed in the two specimens edges (figure 4a), in order to guarantee a uniform distribution of the load between the fibers and to avoid slipping of the specimen during the test. Table 4 shows the average of five results obtained in the warp direction.



a) b) c) d) e) f) g)

Figure 3: Different types of non-impregnated fabrics : Hemp (a); Sisal[yellow] (b); Sisal/Coir (c); Jute[sisal] (d); Juta[7] (e); Juta[12] (f); Flax (g)

Table 2: Specific weight

	JUTE[7]	JUTE[12]	JUTE[sisal]	SISAL[yellow]	SISAL/COIR	HEMP	FLAX
GSM	254,9	398,2	1099,1	1767,6	1375,4	454,5	388,4
[g/m^2]	2%	3%	4%	4%	2%	2%	1%

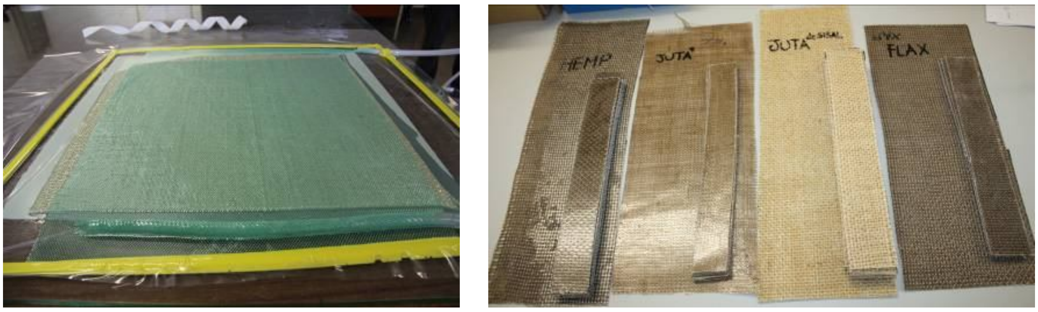
2.3 Tensile tests on NFRP

In the second phase of the experimental investigation, impregnated natural fiber composites were prepared. Two types of matrices were used: epoxy resin and polyester resin, consequently two natural fiber polymer composites were produced. As for the non-impregnated fabrics, also specimens in the weft and warp directions have been prepared and tested. Steel plates were applied in the external part of the specimens (figure 4b). The tests were conducted after 15 days from the preparation of test samples, in order to ensure proper curing of the polymer matrix.

a) b)

Figure 4 : Preparation of the specimens with the steel plates: (a) non-impregnated fabrics; (b) impregnated fabrics.

In previous tests done by the authors, it was observed that the fabrics have a higher strength at 90º, rather than at 0º. In this way, tensile tests on the fabrics with polyester resin have been carried out for fabrics in the warp direction only. In this case, the so called Resin Infusion Vacuum technique has been used to produce NFRP composites (Figure 5). In fact, thanks to this technique it is obtained a constant thickness of the specimens in contrast to that obtained with the epoxy resin, so it has a more reliability in the results.



a) b)

Figure 5: Vacuum Infusion technique: (a) preparation of the specimens; (b) specimens.

In this case, only four materials were examined (jute, sisal, hemp and flax) due to their better performance in previous tests. In fact, the other materials are characterized by yarns with high diameter and consequently the fabrics are very dense (figure 3-b/c). The results obtained are shown in Table 4.

2.4 Tensile tests on NFRG

Finally, Natural Fiber Reinforced Grout (NFRG) composites were prepared. A particular formwork was used in order to obtain a total thickness of the specimen of 5 mm, 2 layers of mortar of 2mm each were built (figure 6). Finally, even in this case steel plates in both extremities of the specimen have been glued.

a) b) c) d)

Figure 6: Preparation of NFRG: (a) first layer of mortar; (b) positioning of the fabric; (c) second layer of mortar; (d) specimen with and without steel plates.

3. RESULTS

All tensile tests were conducted in a normal atmosphere on specimens previously acclimatized, by means of a high precision universal testing machine, and conducted under displacement control of the crossbar. Before each test, a pre-load of 10N (NFRP) and 1,5N (NFRG) were applied and a crosshead speed equal to 100mm/min (NFRP) and 25mm/min (NFRG) were used. The results obtained for the tensile tests of the fabrics are shown in Table 3. It's possible to note that flax is the material with higher mechanical properties, followed by jute and sisal. Impregnated fabrics with epoxy resin (NFRP) present tensile strength greater than the polyester resin, so consequently it can be stated that the epoxy resin is most suitable as a matrix of natural fiber composite materials. Concerning the fabrics with the cement-based matrix further studies are still needed, especially regarding the thickness of the mortar to be applied to the specimen. The following image shows the different levels of strength of the natural fiber composite examined with the different matrices used (figure 7).

Table 3 : Average values obtained from tensile tests

Matrix\Fiber	Non-impregnated		NFRP-Epoxy		NFRP-Polyester		NFRG	
	ft [MPa]	E [MPa]	ft [MPa]	E [MPa]	ft [MPa]	E [MPa]	ft [MPa]	E [MPa]
JUTE[7]	32,9 14%	691,5 11%	87,3 31%	1382,2 17%	80,3 10%	4135,3 20%	25,9 7%	531,3 10%
JUTE[12]	31,4 5%	364,7 5%	77,6 10%	1430,1 11%	- -	- -	- -	- -
JUTE sisal	55,2 17%	863,3 15%	73,5 15%	748,1 20%	64,3 21%	1431,5 18%	35,6 8%	345,5 13%
SISAL yellow	17,7 11%	402,0 9%	35,2 25%	1272,9 29%	- -	- -	- -	- -
SISAL/COIR	9,9 6%	239,2 10%	27,6 6%	2235,8 16%	- -	- -	- -	- -
HEMP	46,7 8%	618,7 7%	63,1 12%	1674,7 9%	58,2 13%	1535,0 9%	33,1 8%	268,2 5%
FLAX	68,8 7%	1746,9 10%	117,4 17%	1866,6 20%	109,8 17%	4393,3 9%	57,2 3%	774,2 7%

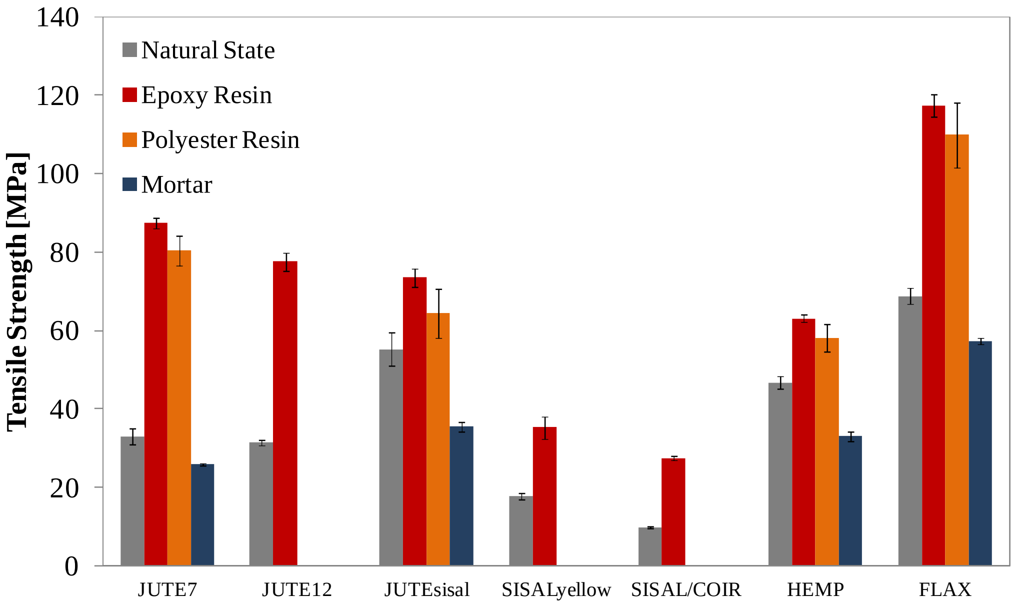
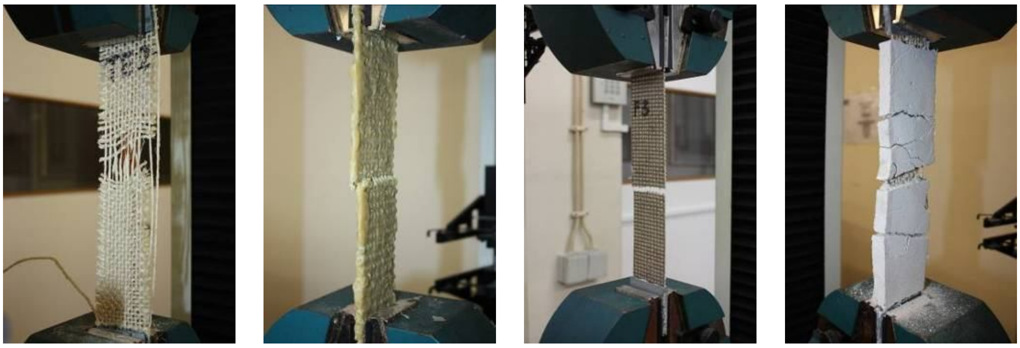


Figure 7: Tensile strength - Materials diagram

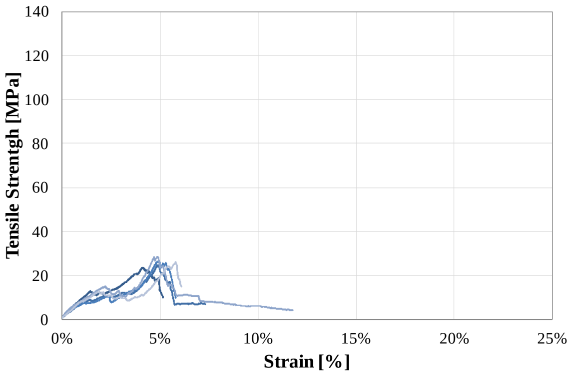
For the different strengthening systems used, it's of primary importance to discuss the failure modes of the specimens. In the case of non-impregnated specimens there is a reduction of area of the individual yarns that make up the fabric (figure 8a), while in the impregnated specimens with the polymer matrix, epoxy (figure 8b) and polyester (figure 8c), it's possible to notice a instantaneous and uniform break of the specimen. Finally, in the case of cement-based composite, the failure mode occurs slowly marked by the rupture of mortar at the beginning and follow the break/stretching of single yarns that make up the fabric (figure 8d). During the tests it was possible to observe a good bond between natural materials and the different types of matrixes.



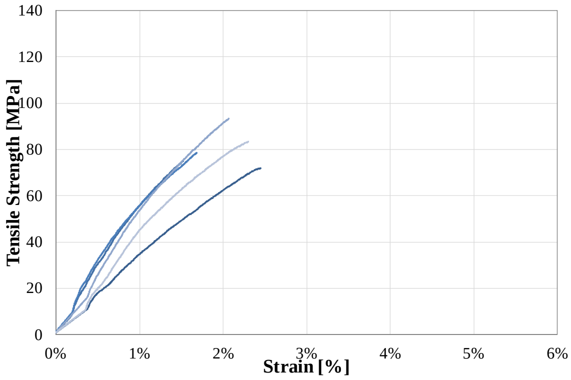
a) b) c) d)

Figure 8: Failure mode: Non-impregnated fabrics (a); NFRP with epoxy (b); NFRP with polyester (c); NFRG (d).

It's possible to observe failures the respective modes in Figure 9. Tensile strength of NFRP composites is almost twice of the NFRG composites and while in the first case the tensile strength-strain curve is characterized by a hardening portion, in the second case it is evident a softening portion.



a)



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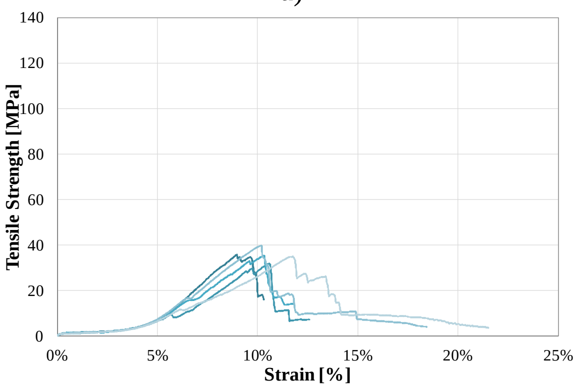

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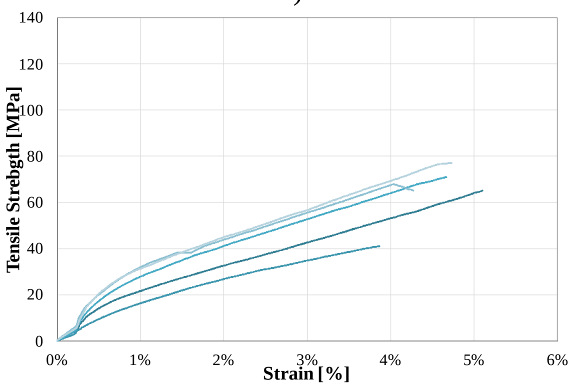
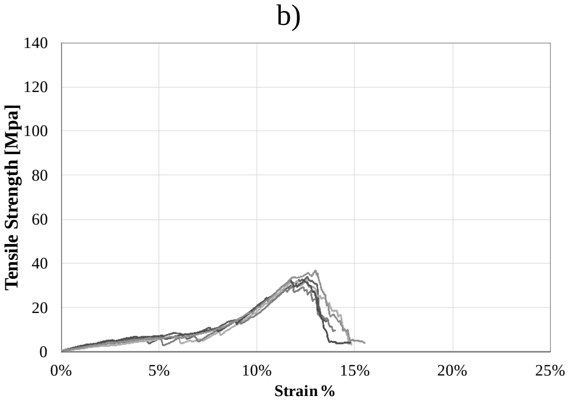
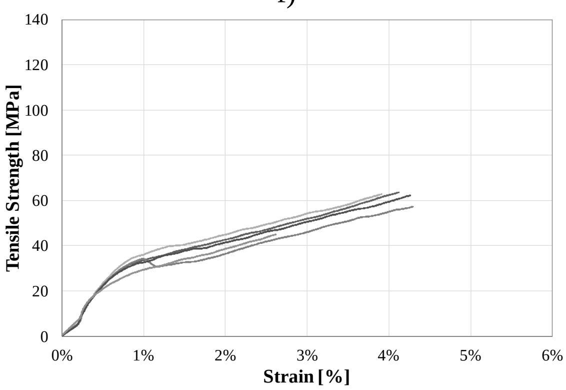


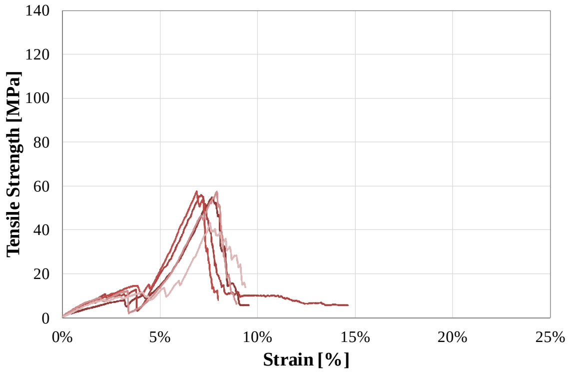
f)



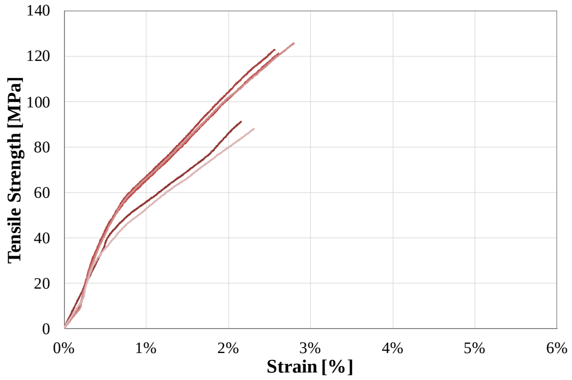
c)



g)



d)



h)

Figure 9: tensile stress - strain diagrams: JFRG (a); JSFRG (b); HFRG (c); FFRPG (d); JFRP (e); JSFRP (f); HFRP (g); FFRP (h)

3. BRAIDING TECHNOLOGY

Braiding technique was used to produce natural fiber axially reinforced fibrous structures [8]. This technique has been used for two centuries and is being increasingly used in technical applications. The braided architecture has greater ability of twisting, shearing and impact than woven fabrics, combined with low cost fabrication routes. The technique consists in the braiding in the transverse and longitudinal directions forming a tubular structure. The external yarns rotate in two opposite orientations, anticlockwise and clockwise direction. The stability of the braided structure depends on the detailed fiber architecture and above all on the angle formed between the longitudinal axis and the direction of insertion of the braiding yarns; its dimension can be different according to the braiding yarn diameter, diameter of the axial structures and of the circulation velocity.

3.3 Testing procedure and results

The braided fibrous structures were produced in a vertical braiding machine (figure 7). The machine worked with 16 bobbins of cotton braiding and the braids obtained have a regular structure (triaxial braid), in a tubular form of biaxial yarn direction. In the centre of the tubular braid additional fibers (axial yarns) were inlaid. In particular braids with 1-2-4-8 axial yarns were produced (figure.7-c) and tensile tests were carried out [6]. Two different types of sisal fibers were used, later on called Sisal_1 and Sisal_2, with different values of linear density (TEX). A total of 7 specimens for each number of axial yarns were tested. Before each test, a pre-load of 1,5N was applied and a crosshead speed equal to 250mm/min was used. Table 4 summarizes the results obtained.

a)

b)

c)

Figure 7: (a) Braiding yarns; (b) Axial yarns; (c) Braiding process

The breaking load of produced braided yarns increases linearly with the number of axial sisal yarns as well as with the linear density of braids. Therefore, it is quite easy to produce a braded yarn with required tensile strength by adjusting the number of axial sisal yarns (figure 8-9).

Table 4: Average values obtained from tensile tests on braids

Material	n° axial yarns	Linear Density [Tex]	ft [MPa]	Tenacity [N/Tex]	ε_{peak} [%]	E [MPa]
Sisal_1	1	310,5	175,38	0,2702	4,82	3650,39
	2	621	81,74	0,2607	5,474	1493,42
	4	1242	19,18	0,2613	6,276	306,29
	8	2484	11,89	0,1942	6,530	182,002
Sisal_2	1	2910,8	105,65	0,1847	6,448	1655,08
	2	4383,5	71,13	0,1604	5,4476	1312,07
	4	8719,5	22,74	0,1436	6,05	376,76
	8	16904,2	10,24	0,1246	5,866	174,91

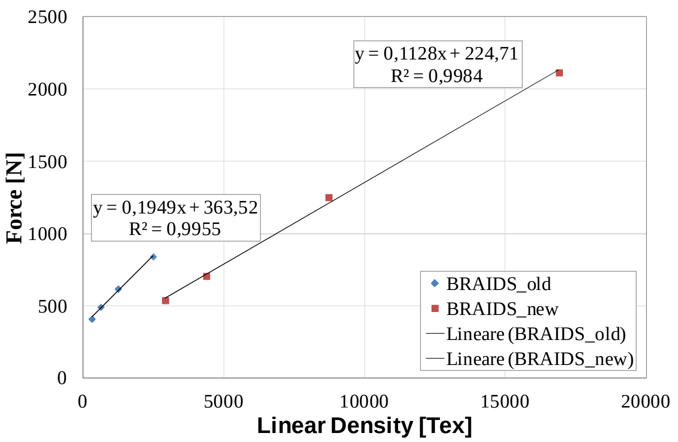
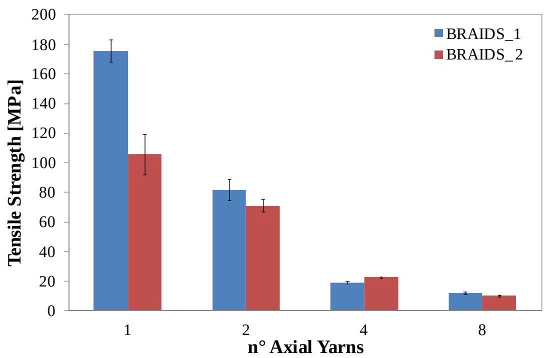


Figure 8: Linear Density - Force Diagram on Braids



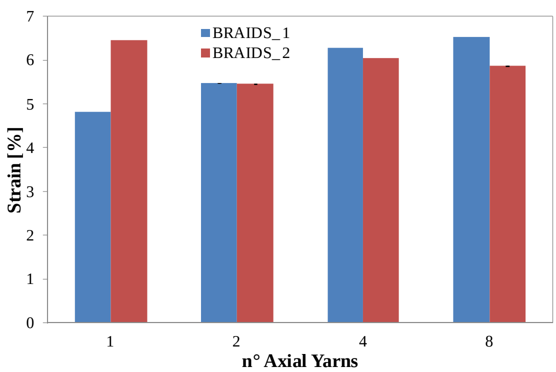


Figure 9: Tensile strength/Strain - n° Axial Yarns Diagram

4. CONCLUSIONS

In this paper the mechanical characterization of natural fiber composites has been carried out. The results obtained show that the fabrics with an organic matrix, like epoxy and polyester resin, considerably increase the mechanical properties of natural fiber non-impregnated compared with matrix of natural origin (mortar). Furthermore, the technique of braiding technology showed good mechanical properties of the single braids compared with the strength values obtained from NFRP. Consequently fabrics produced with this technology could ensure the resistance values greater than the common natural fiber fabrics.

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