Tensile strength of flax fabrics to be used as reinforcement in cement-based composites: experimental tests under different environmental exposures

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ABSTRACT

The use of Textile-Reinforced-Matrix (TRM) systems is gaining consensus as a possible technical solution for strengthening masonry structures. In this context, the use of natural fabrics (among which those made of flax) instead of synthetic ones can have a positive impact on several sustainability-related aspects, such as renewability, recyclability, biodegradability, low price. However, both mechanical properties and durability performance of natural fibres and fabrics needs to be further investigated with the aim to make it possible their use in composites for construction. Furthermore, this paper reports the results of a fundamental study on a bidirectional flax fabric eventually intended as the reinforcement in cement-based composite systems. Specifically, it aims at determining the tensile strength of flax of fibres, threads and the fabrics, and investigating how they are influenced by various environmental exposures and aging processes. The results in the experimental tests reported herein show that fibres and fabrics suffered no significant reduction in tensile strength due to the considered environmental exposure. Despite the common belief that natural fibres may be affected by durability issues, the results demonstrate that the flax fabric under investigation can be utilised as a reinforcement in TRM systems, which is the main novelty and original contribution of this paper.

KEYWORDS:

Plant/natural fibres

Flax fabric

Mechanical properties

Natural composites

1. INTRODUCTION

During the last decades the sensitivity of the public opinion toward environmental issues has significantly increased. Starting from the first definition of “sustainable development” given by the well known Brundtland Report “Our Common Future” in 1987 [1], up to the current elaborated model of circular economy, limiting the environment “impact” of human activities is nowadays considered as a priority in all industrial fields. Among the others, the construction sector needs get “greener” by reducing both the demand of energy and raw materials, and the emission of green-house gas [2]. Moving in this direction, new sustainable building materials are conceived by promoting the reuse of waste-materials and the use of the so-called eco-friendly raw material sources characterised by a low environmental impact [3].

Composite materials represent a category in which several solutions can be implemented to obtain more sustainable systems. For instance, the use of natural fibres, *in lieu* of industrial ones, as reinforcement of both organic and inorganic matrices, is one of the possible features of a new class of materials generally referred to as *biocomposites*. Based on their origin, natural fibres can be classified as plant, animal and mineral fibres [4]. Plant fibres, in turn, are subdivided into wood fibres and non-wood fibres. The latter include different kinds of fibres depending on the part of the plant they are taken out: leaf (sisal, pineapple, àbaca), bast (flax, hemp, jute, kenaf, ramie), seed (cotton), fruit (coir, kapok), straw (rice, corn), grass (bamboo). The interest in the use of the natural fibres mainly lies in several advantages compared to industrial ones, such as low cost, low environmental impact, biodegradability, renewable nature [5] and in their large range of properties that make them suitable for a great number of engineering cases [6]. Among the several applications [7] [8] [9] many fields are involved, such as the automotive sector [10], packaging industries [11], construction [12] and infrastructural applications [13].

Several experimental studies are devoted to the mechanical characterisation of plants fibres [14] and to the assessment of properties, such as impact performance [15] or dynamic behaviour [16], of composite systems obtained by their use. Many researches focus their attention on the use of plant fibres as reinforcement of Fibre Reinforced Polymeric (FRP) matrix composite systems instead if the most common synthetic fibres such as carbon, glass, PBO, etc. These systems, often referred to as NFRPs (Natural FRPs), showed a large potential either in systems reinforced by one type of plant fibres and in hybrid composites [17] [18] [19]. However, the applications of natural fabrics are still limited by their lower mechanical and fire resistance and higher water absorption compared to the more common synthetic textiles [20] [21]. Many research studies are carried out to cover this gap in order to improve the fire resistance [22] [23] [24], the strength [25] and the adhesion with matrix [26] by studying either the dry textile or composite systems. In the last years innovative composite systems were conceived for structures retrofitting intervention by using cement-based matrices in place of the organic ones. This led to a new branch of research in civil engineering field, interested in analysing the behaviour of the so-called Textile Reinforced Mortar (TRM) composite systems and in comparing its performance with the FRPs ones [27]. Clearly, a great attention is devoted to the characterisation of the several types of fabrics used as reinforcement in order to investigate mechanical properties and compatibility with cement-based mortars. For instance, research studies focus their attention on the influence of the fibres structure and density with the strength and stiffness of glass [28] and carbon [29] fabrics. Similarly, experimental investigation are carried out to analyse the fabric behaviour under extreme exposures [30]. Therefore, also the use of plant fabrics as reinforcement in TRMs systems is a current object of study. Several studies focus their attention on the compatibility between natural fibres and cement-based matrices and on the behaviour of natural TRMs [31] [32]. Among the various available plant fibres, flax fabrics, widely produced in Europe, gained a lot of attention thanks to their good mechanical properties [33] [34], and applications in both polymeric [35] and cementitious [36] matrices were studied.

Although these applications show promising results that encourage the use of plants fibres also in this field, several drawbacks emerge as well. The high water absorption capacity of plants fibres affect the properties of the whole composite systems [37]. Unlike synthetic fibres, natural textiles are characterised by production processes that lead to a non-homogeneity in the geometry that results in a variability of the mechanical properties [38]. Moreover, degradation phenomena are observed in both water conditions [39] and in contact with cement-based matrices [40].

This paper reports the results of an experimental research intended at determining the fundamental properties of flax fibres, threads and fabrics and assess their behaviour when subjected to various environmental exposures and aging protocols. In fact, it is a common belief that the use of natural fibres in engineering composites is significantly limited by their low mechanical properties and, even more, by the durability issues that are expected to emerge when natural fibres are exposed to aggressive environmental conditions like those that have to be generally considered for civil structures. Conversely, this study aims, on the one hand, at demonstrating that the flax fibres and fabrics under consideration are characterised by tensile strength and stiffness that make them suitable for being used in TRM system and, on the other hand, that aggressive environmental exposure and aging phenomena do not significantly affect the aforementioned mechanical properties. In confirmed, this results may pave the way towards using the flax fabrics under consideration in this study in engineered TRM systems.

As it is common in researches on natural fibres [41], the experimental work moves from determining the relevant geometric properties, such as length, section shape and relevant sizes, and physical parameters, such as the water absorption capacity. Then, tensile tests on differently sized flax samples lead to determining the tensile strength and its natural variability. Finally, regarding durability, different aging protocols are considered with the aim to reproduce specific environmental conditions, such as the exposure to water, salt-water and alkali solutions.

2. MATERIALS AND METHODS

The flax fabrics under consideration in this paper has been provided by the company Innovation s.r.l. with the name of *FIDFLAX Grid 300 HS20*®.

The identification of the physical and geometric properties moves from the study of single filaments constituting the fabric yarns, up to the assessment of the thread's density. As for the mechanical characterisation, it mainly aims at determining the tensile strength and stiffness of the textile, which are evaluated on samples composed of a variable number of threads.

Three different aging protocols are adopted for scrutinising the durability performance. The first one aims to check if in the short term the textile mechanical performance may be affected by specific environment exposures, such as water, marine or alkaline. The second one aims to reproduce the conditions of either a hydraulic lime and cement mortars that will be eventually employed as matrices. Finally, the third one aims to simulate a long exposure time by an accelerate aging procedure.

2.1 Materials

The textile consists of a bi-directional woven flax fabric with plain weave. Warp and weft threads are arranged so that they realise a simple cross pattern. Threads are laid in twos along the same row in both the directions. Each one is a combination of two smaller yarns, assembled to create a double twisted thread. The yarns are in their turn characterised by a bundle of filaments that represent the smaller components of the fabric structure. The double twisted thread is considered in this study as the reference sample and hereinafter it is referred to it simply as thread. Figure 1 shows the fabric structure at different scale levels.

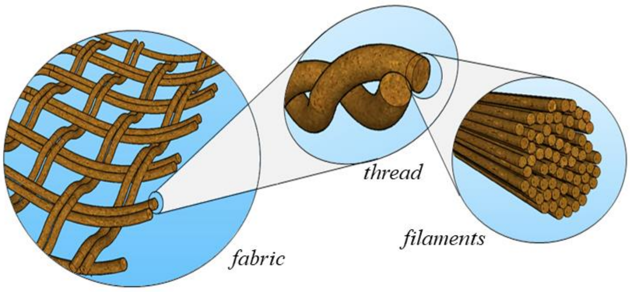

Figure 1: Flax fabric structure

The textile grid, with 4.3 threads per centimetre in both directions, is accurately sized to be used as reinforcement in cement-based matrices, allowing the transit of aggregates of different size. Because of their nature and of the manufacturing processes, plants fibres do not present homogeneity both on the physical and mechanical point of view. Therefore, it is essential to investigate in depth the geometry of the textile in addition to the mechanical behaviour.

One of the main aspects in the identification of plant fibres is the size of the filaments. A Scanning Electron Microscope (SEM) analysis is adopted to assess the mean diameter of the flax filaments (Figure 2). Specifically, 4 SEM images with a magnification of 1000X, and representing 4 different samples, are analysed providing a value of the filament diameter by means of 28 measurements.

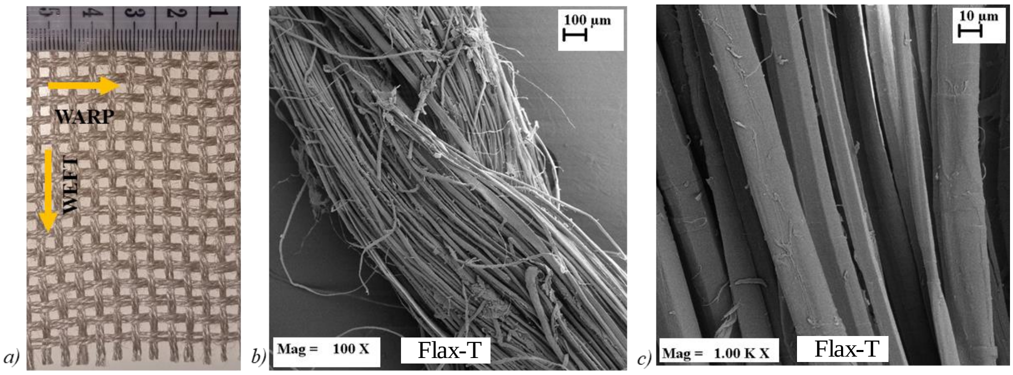

Figure 2: a) flax fabric; b) thread (magnification 100X); c) filaments (magnification 1000X)

The chaotic arrangement of the filaments within the flax thread and the presence of several voids make it very difficult to obtain accurate information about the actual cross section area of the thread by means of direct measurement techniques even by means of high-resolution images from the SEM analysis. As a consequence, the cross-section area is indirectly determined from the density of the textile. Particularly, the specific gravity of 5 saturated thread samples with a length of 15 cm is determined by means of a hydrostatic balance. The indirect estimate of the thread cross-section is obtained by dividing the weight of the samples for their density and length. The flax fibres water absorption rate is identified as well. Five thread samples 15 cm long, are immersed in deionised water and weighted with regular intervals of 24 hours up to the achievement of a negligible weight gain. The value of the water absorption ratio is equal to 222% with a coefficient of variation of 19% and it is in line with previous studies available in the literature [42].

The main values of the physical properties, together with the respective coefficients of variation are listed in Table 1.

Table 1: Flax fabric physical properties

	Mean	Co.V. (%)
filament diameter (μm)	16.78	29.64
density (g/cm^3)	1.19	3.29
linear density (Tex)	302	15.27
n° threads/cm	4.3	-
Cross-section area (mm^2)	0.25	16.62

2.2 Mechanical properties

The mechanical performance of fibres is given by their tensile strength. Plant fibres are typically characterised by a variability in their properties within the fabric. Moreover, being the textile a combination of smaller threads, the size of the sample to be putted in tension may affect itself the estimation. Therefore, four kinds of specimens, differing in the number of flax yarns, are tested in tension to assess the tensile strength and to check its variability with the sample size. The types of specimen considered in the study are as follow:

- *Flax-Y*: it consists of one of the two yarns constituting the main thread. Each sample, having a length of 15 cm, is extracted from threads in weft direction (Figure 3.a).

- *Flax-T (warp and weft)*: it consists of the thread representing the main element of the textile. The samples, having a length of 15 cm, are extracted in both weft and warp directions of the fabric (Figure 3.b).

- *Flax fabric-2cm*: it consists of a flax fabric strip 2 cm large, characterised by 8 threads. The samples, having a length of 15 cm, are extracted from the fabric in weft direction (Figure 3.c).

- *Flax fabric-6cm (warp and weft)*: it consists of a flax fabric strip 6 cm large, characterised by 24 threads. The samples, having a length of 30 cm, are extracted in both weft and warp direction (Figure 3.d).

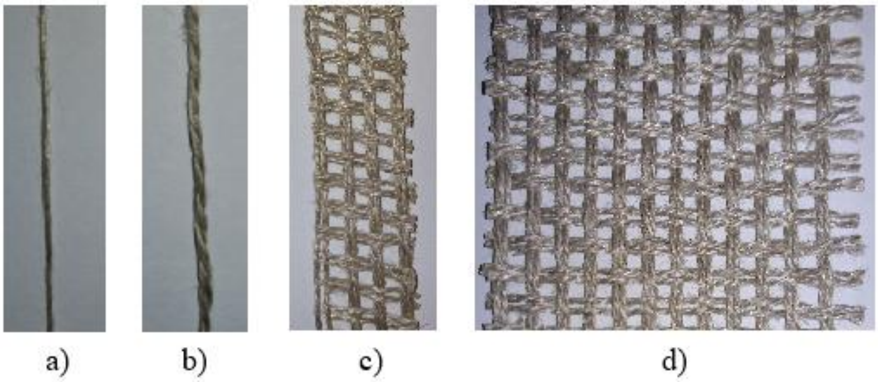

Figure 3: flax samples (a) Flax-y; (b) Flax-T; (c) Flax fabric-2 cm; (d) Flax fabric-6 cm

Tensile test of the samples Flax-T and Flax fabric-6 cm is assessed in both the direction of the fabric in order to check if there is any difference. Each series concerning the specimens Flax-Y, Flax-T and Flax fabric-2 cm is characterised by 12 to 15 samples, having a gauge length of 100 mm and clamped in each edge for a length of 25 mm. Tensile tests on Flax-T were performed at the Department of Industrial Engineering of the University of Salerno by means of a CMT4000 SANS Series dynamometer (by MTS, China), in displacement control with a rate of 4 mm/min by using a cell load of 1kN (Figure 4.a).

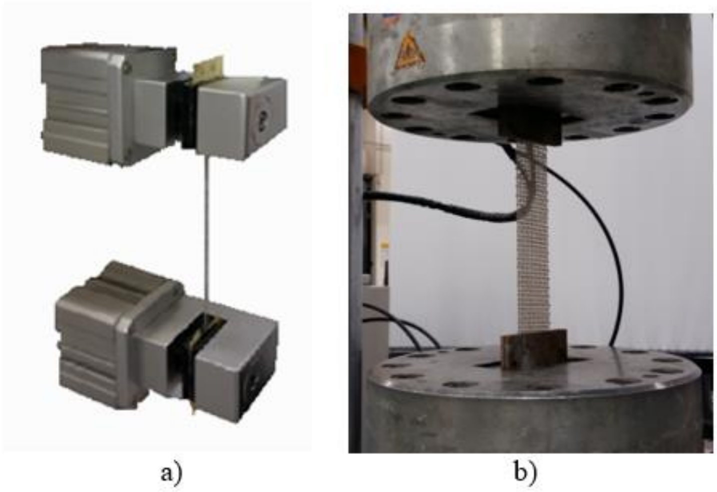

Figure 4: tensile test set-up (a) Flax-T; (b) Flax fabric-6 cm

The two series of samples Flax fabric-6 cm are characterised by 5 specimens, having a gauge length of 200 mm and clamped in both the edges for a length of 50 mm. The gripping is guaranteed by gluing the textile between two steel plates 5 mm thick, by means of an epoxy resin, and by putting the plates within the machine clamps (Figure 4.b). Tensile test is performed at the STRuctural ENGineering Testing Hall (Str.Eng.T.H.) of the University of Salerno, by means of a Zwick Roell Schenck Hydropuls S56, with a maximum capacity of

630 kN and according to the ISO 13934-1 [43]. The test is conducted in displacement control with a rate of 4 mm/min.

2.3 Aging protocols

The flax textile under consideration is meant to be used as reinforcement in composite systems with different kinds of binders (mainly lime and cement) as matrix, depending on the field of application of the composite.. In case the system is used as reinforcement of existing masonry buildings, it is required the use of materials as consistent as possible with the ones the masonry structure is made of. In such cases, the use of hydraulic-lime based mortars is recommended. In many other cases the use of cement-based matrix may result more appropriate.

The use of plant fibres in cement-based materials gives rise to several problems in terms of durability. The two main aging effects that arise in such alkaline environments are the alkaline hydrolysis and the mineralization process [44] of fibres constituents. As known, natural fibres are characterised by three main components:

- cellulose, the main structural component;
- hemicellulose, generally present along with cellulose in almost all plant fibres;
- lignin, a binding phase for cellulose.

The high alkaline water content of the pores leads to the dissolution of hemicellulose and lignin and causes the alkaline hydrolysis of cellulose cells reducing the degree of polymerisation and the strength of the fibres. The mineralisation process, instead, is the result of the migration of hydration products, mainly $Ca(OH)_2$, into the voids and lumen walls of the fibre structure [45].

With the aim of studying the durability performance of flax fibres considering their application in inorganic matrices this work presents three aging protocols. They consist in putting flax threads in specific environments and in testing them after a period of exposure. The samples are flax threads, defined before as Flax-T, 15 cm long and they are tested in tensile by means of a SANS Universal Testing Machine having a capacity of 10 kN, in displacement control with a rate of 4 mm/min by using a cell load of 1kN. The gauge length during the test is 100 mm. Each series of specimens is characterised by 15 samples. The tensile strength obtained by testing the specimens of the series Flax-T is considered as a reference value.

SEM analysis is carried out on some specimens to deeply investigate the state of the fibres after the exposure periods.

2.3.1 Aging protocol 1

According to acceptance criteria reported in the literature [46], fibre reinforced cementitious matrix composite systems are required to comply with various limitations related to the durability of the material. Specifically, three different aging environments have to be considered for the samples to be exposed; exposure time and the target limits in terms of strength decay are also defined.

The different environments consist in water, salt water, to reproduce the marine environment, and alkali water. In this work, as a preliminary step of a more detailed study to be carried out on the entire composite, fibres are exposed to these environments to check their sensitivity on that. A period of exposure of 1000 hours is chosen. The aging conditions are listed in detail as follow:

- *Flax-T Water 1000*: the threads are immersed in 500 ml of deionised water for a period of 1000h (~42 days);
- *Flax-T Salt 1000*: the threads are immersed in 500 ml of a saline solution of deionised water with a concentration of 3.5% in weight of NaCl for a period of 1000h (~42 days);
- *Flax-T Alk 1000*: the threads are immersed in 500 ml of an alkali solution with a pH of 9.5, obtained by adding to deionised water NaOH with a concentration of 0.32% in weight, for a period of 1000h (~42 days).

All the above mentioned aging conditions are performed at laboratory temperature and relative humidity (20°C and 50%, respectively)

2.3.2 Aging protocol 2

Flax fibres are embedded in mortar for a given period of exposure and then tested in tension to check any loss of strength. Two types of mortar are chosen:

- a hydraulic-lime based mortar: a structural grout of natural hydraulic lime for the impregnation of fabrics for structural reinforcements provided by the company Innovation s.r.l. with the name of *FIDCALX NHL5®;*

- a cement-based mortar: a mortar based on hydraulic binders for bonding and embedment of fabrics provided by the company Innovation s.r.l. with the name of *Kimisteel LM Sta-0217*.

Both of them are suitable to be used as matrix in fibre reinforced composite systems. For each type of mortar three series of flax threads are considered respectively having a time of exposure of 7, 28 and 56 days. This method allows monitoring the loss of strength with the time of exposure. According to the technical data sheets provided by the manufacturers the compressive strength of the mortars employed is respectively of 15 MPa for the hydraulic-lime based one and of 45 MPa for the cement-based one. The aging conditions are listed in detail as follow:

- *Flax-T H-lime (7-28-56 days)*: the threads are embedded in hydraulic-lime mortar for a period of 7,28 and 56 days;
- *Flax-T Cement (7-28-56 days)*: the threads are embedded in cement mortar for a period of 7,28 and 56 days.

Both the aging conditions are performed at laboratory temperature and relative humidity (20°C and 50%, respectively)

2.3.3 Aging protocol 3

The aging protocol 3 considers a specific water solution, appropriately designed to reproduce hydraulic-lime or cement-based mortar conditions [30]. Two solutions are considered differing in the type of chemical components. Controlled temperature conditions are chosen to reproduce an accelerated aging process. The aging conditions are listed in detail as follow:

- *Flax-T Environment A (7-28-56 days)*: the threads are immersed for a period of 7, 28 and 56 days in a solution thought to reproduce hydraulic-lime conditions (16 wt% of $Ca(OH)_2$ in distilled water, pH = 12.37). A closed container with fibres completely immersed in the solution was kept at 55°C.;
- *Flax-T Environment B (7-28-56 days)*: the threads are immersed for a period of 7, 28 and 56 days in a solution thought to reproduce cement conditions (16 wt% of $Ca(OH)_2$, 1% of Na(OH) and 1.4% of K(OH) in distilled water, pH = 13.1). Also in this case a closed container with fibres completely immersed in the solution was kept at 55°C.

3. Experimental results

Axial displacements and applied force are recorded in each tensile test. They are easily converted to stress and strains and the corresponding results are reported in this section. Specifically, the tensile strength, f_t, the Young's modulus, E, and the strain at the peak, ε_u, are determined with the aim to characterise the mechanical behaviour of fibres.

Due to geometric reasons, the tensile behaviour is always characterised by a lower initial stiffness that increases up to a constant value before failure. For this reason, the Young's modulus is calculated in the linear branch within the stress range from 20% to 50% of the maximum strength.

Figure 5 shows the stress-strain response of the different series of flax fibres tested in tension.

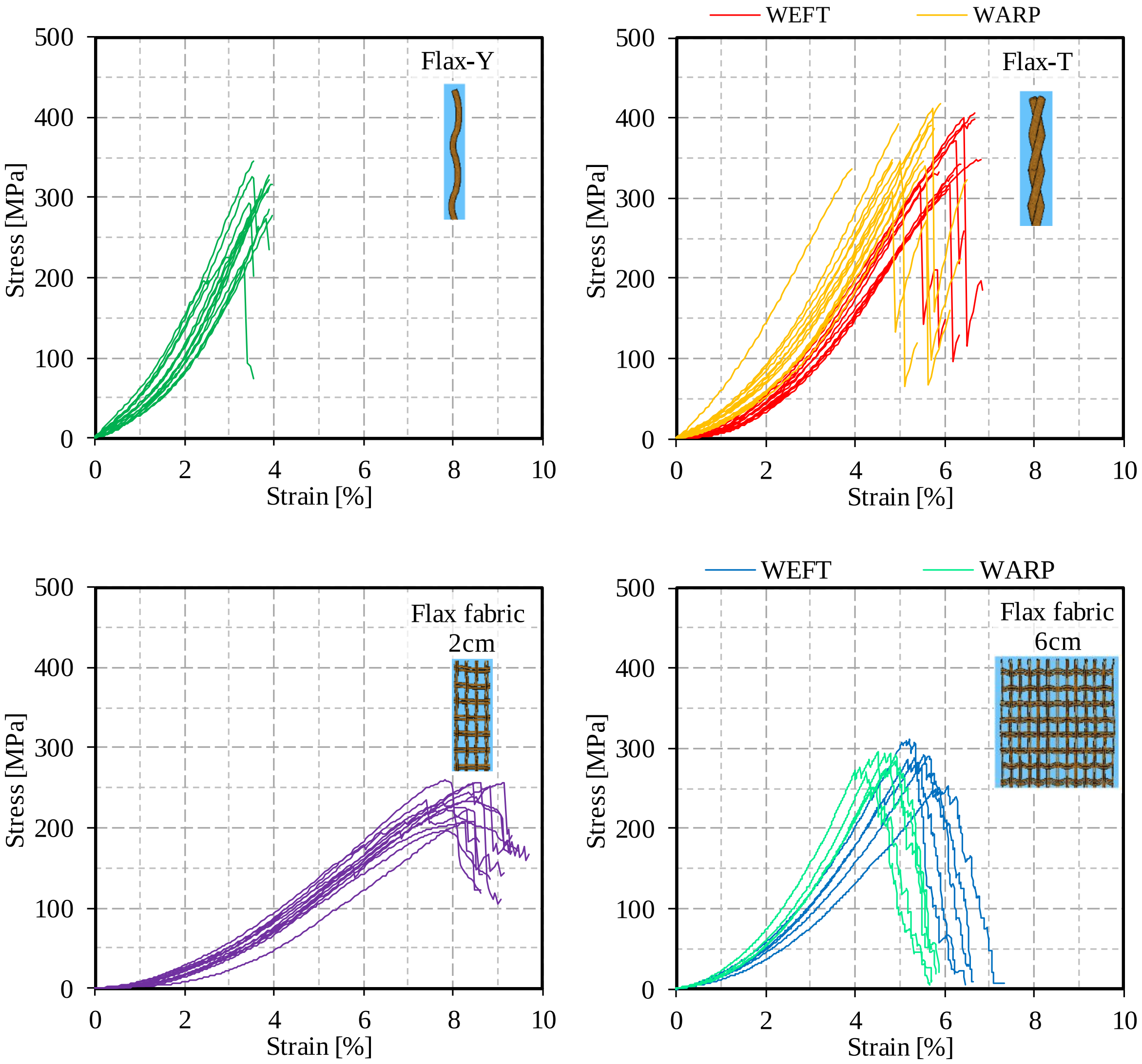

Figure 5: Tensile stress-strain diagrams of flax specimens

The cross-section area considered to get the stress values for all the type of samples is obtained from the value estimated from the threads of the Flax-T series, knowing that a thread consists in two twisted yarns, and the 2cm and 6cm flax strips are respectively characterized by 8 and 24 threads. The mechanical response of the Flax_T and Flax fabric-6cm series in both the direction of the textile is shown. The main values of the mechanical properties obtained from the tensile test, with their respective coefficient of variation, are listed in Table 2.

Table 2: Mechanical properties of flax samples tested in tension.

	Directior	Number of tests	P_u		f_t		E		ε_u	
			Mean (N)	Co.V. (%)	Mean (MPa)	Co.V. (%)	Mean (GPa)	Co.V. (%)	Mean (%)	Co.V. (%)
Flax-Y	Weft	15	37.39	15.54	293.40	15.54	11.61	10.03	3.58	11.76
Flax-T	Weft	12	87.95	12.75	345.04	12.75	8.53	6.44	6.14	9.46
Flax-T	Warp	14	92.05	10.47	361.15	10.47	10.07	6.95	5.20	10.75
Flax fabric-2cm	Weft	14	476.11	8.60	233.49	8.60	4.39	8.40	8.27	6.13
Flax fabric-6cm	Weft	5	1758.81	7.50	287.52	7.50	8.25	9.93	5.56	6.02
Flax fabric-6cm	Warp	5	1743.71	3.91	285.05	3.91	9.81	3.14	4.63	5.34

P_u = Maximum Load; f_t = Tensile Strength; E = Young's Modulus; ε_u = strain at failure

Figure 6 shows the stress-strain response of the series of specimens subjected to the aging protocol 1. Specifically, the three graphs concern the threads immersed for 1000 hours respectively in water, salt water and alkali solution. The threads are extracted from the fabric in the warp direction, therefore, the series Flax-T-warp must be considered as a control series representing the response before the aging process. The main values of the mechanical properties, with the respective coefficient of variation, are listed in Table 3.

Table 3: Mechanical properties of flax samples subjected to the aging protocol 1.

	Aging environment	Curing period	Number of tests	P_u		f_t		ε_u	
				Mean (N)	Co.V. (%)	Mean (MPa)	Co.V. (%)	Mean (%)	Co.V. (%)
Flax-T	Control	-	12	92.05	10.47	361.15	10.47	5.20	10.75
Flax-T	Water	1000 h	12	96.17	10.75	377.30	10.75	6.08	12.94
Flax-T	Salt water	1000 h	13	102.27	13.19	401.23	13.19	6.29	6.94
Flax-T	Alkaly water	1000 h	13	95.92	8.74	376.34	8.74	6.34	6.81

P_u = Maximum Load; f_t = Tensile Strength; ε_u = strain at failure

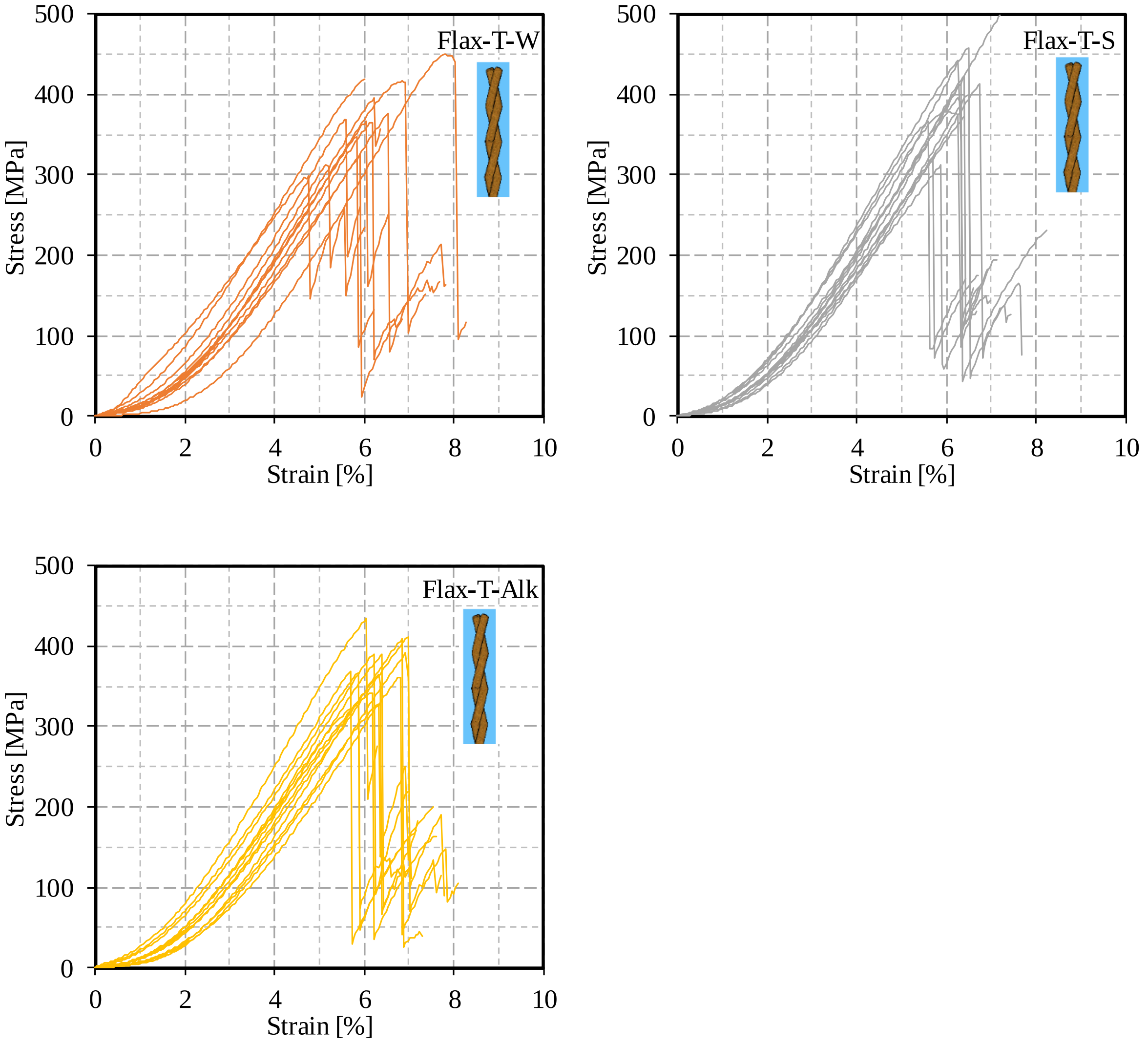

Figure 6: Tensile stress-strain diagrams of flax threads subjected to the aging protocol 1

According to the aging protocol 2 either the samples embedded in a cement or hydraulic-lime based mortar are tested after conditioning periods of 7, 28 and 56 days. The tensile response, in terms of stress- strain, for each conditioning environment and for each conditioning period, is shown in Figure 7 and Figure 8.

Table 4: Mechanical properties of flax samples subjected to the aging protocol 2.

	Aging environment	Curing period	Number of tests	P_u		f_t		ε_u	
				Mean (N)	Co.V. (%)	Mean (MPa)	Co.V. (%)	Mean (%)	Co.V. (%)
Flax-T	Hydraulic lime mortar	7 days	15	77.98	10.46	305.95	10.46	5.50	6.95
Flax-T		28 days	12	75.11	7.71	294.70	7.71	5.36	8.58
Flax-T		56 days	15	74.76	5.99	293.31	10.43	4.98	7.55
Flax-T	Cementitious mortar	7 days	15	72.40	10.43	284.05	10.43	5.99	13.06
Flax-T		28 days	14	71.26	10.33	279.58	10.33	5.29	13.14
Flax-T		56 days	15	66.71	12.86	261.73	12.86	4.36	12.80

P_u = Maximum Load; f_t = Tensile Strength; ε_u = strain at failure

The main values of the mechanical properties, with the respective coefficient of variation, are listed in Table 4.

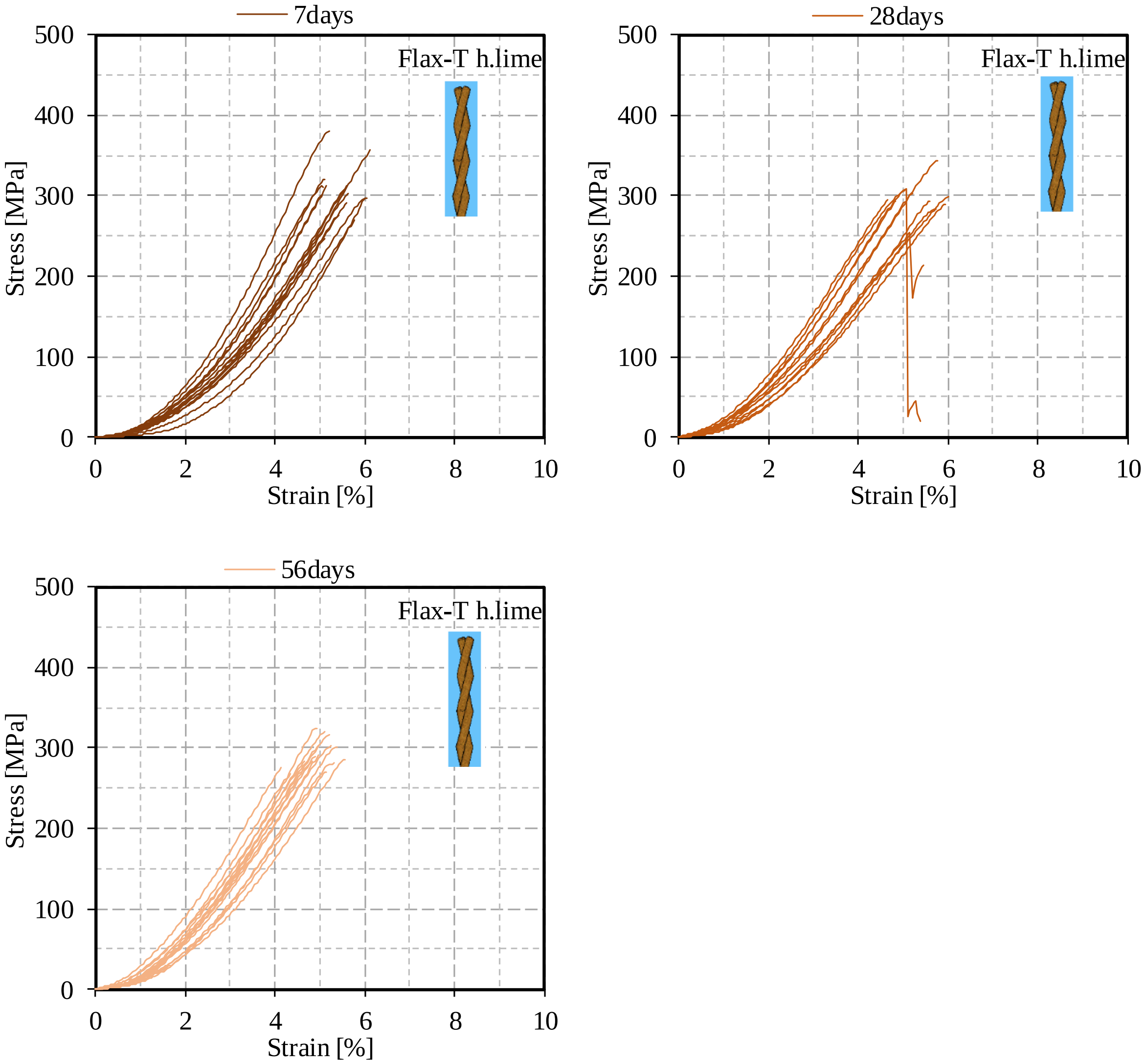

Figure 7: Tensile stress-strain diagrams of flax threads in hydraulic lime environment (aging protocol 2)

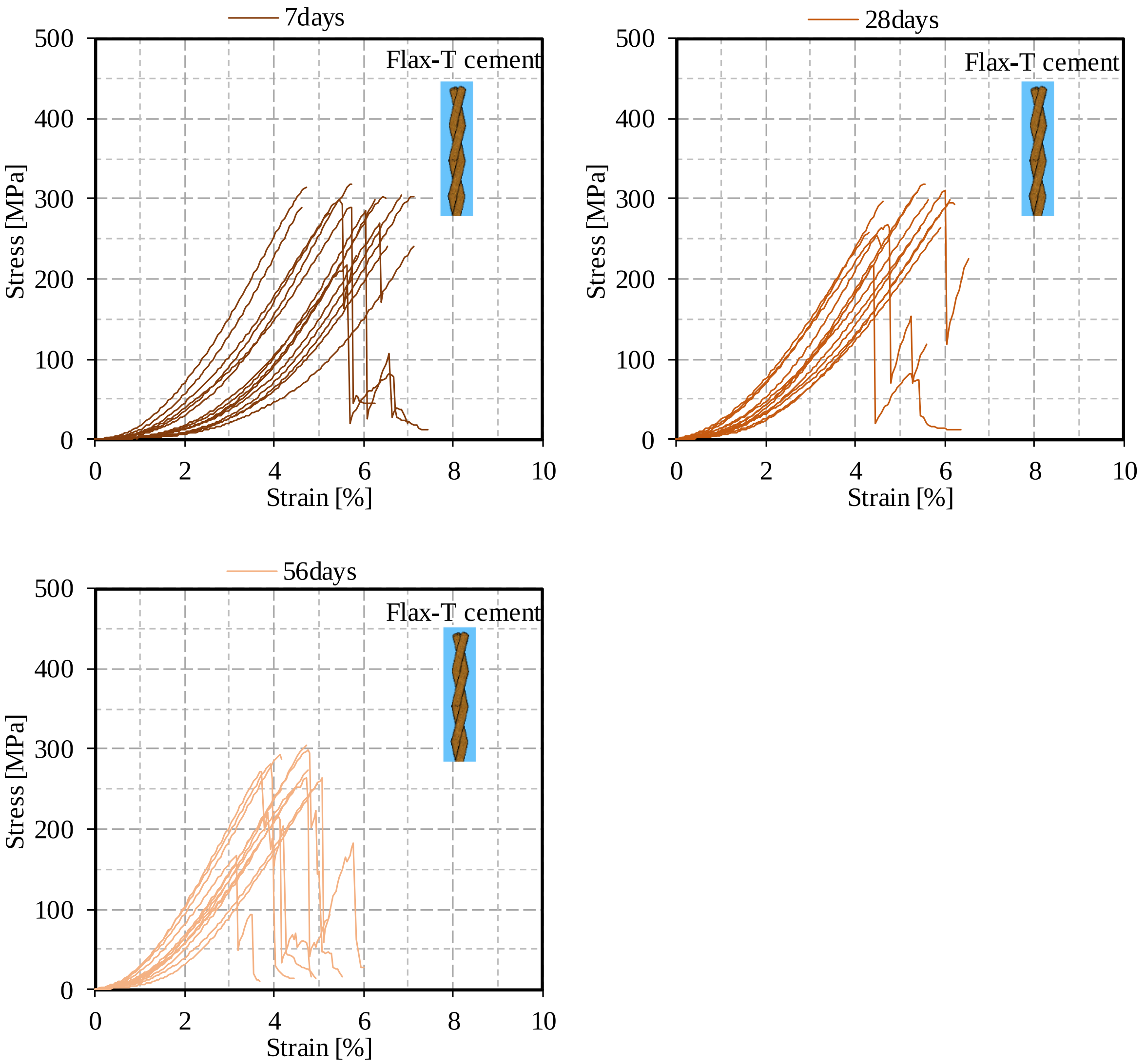

Figure 8: Tensile stress-strain diagrams of flax threads in cement environment (aging protocol 2)

The results in terms of stress strain curves concerning the specimens subject to the aging protocol 3 are shown in Figure 9 and Figure 10. Tensile tests are performed respectively performed after 7, 28 and 56 days. Due to the high degradation of the specimens subject to the Environment A for a conditioning period of 56 days, any tensile response is recorded concerning this series. The main values of the mechanical properties, with the respective coefficient of variation, concerning the samples aged in Environment A and B are listed in Table 4.

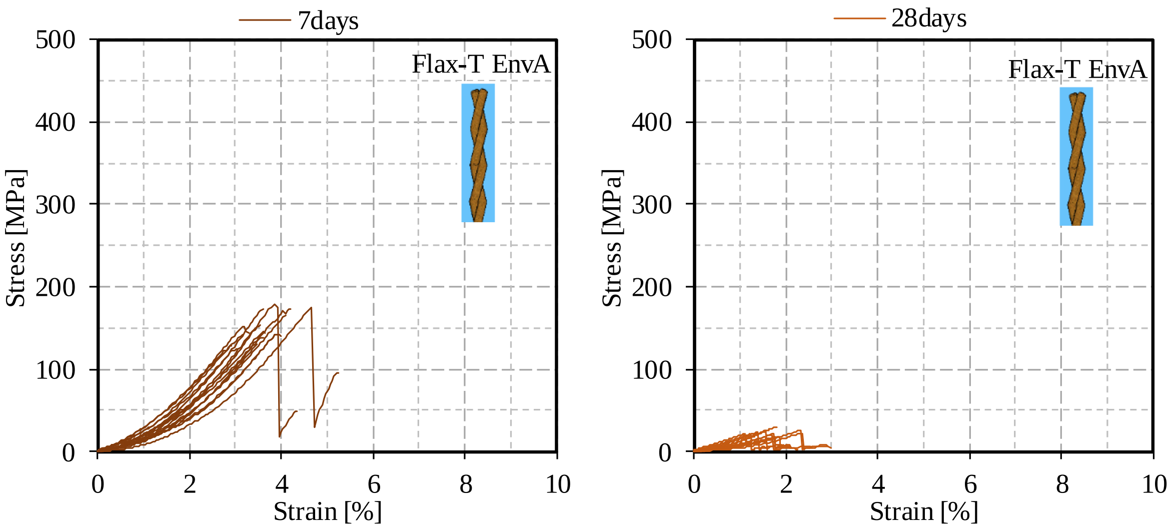

Figure 9: Tensile stress-strain diagram of flax threads in Environment A (aging protocol 3)

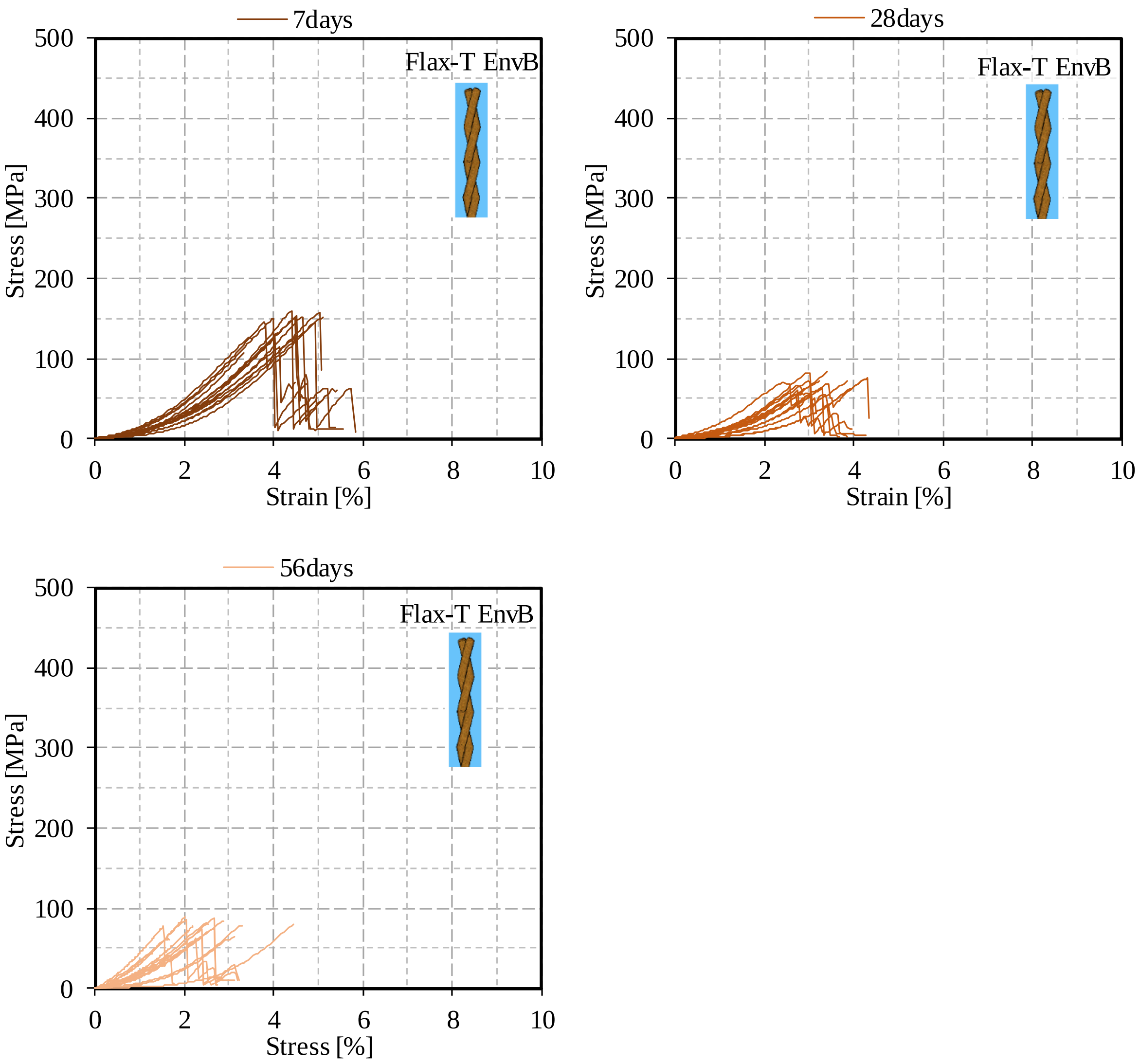

Figure 10: Tensile stress-strain diagram of flax threads in Environment B (aging protocol 3)

Table 5: Mechanical properties of flax samples subjected to the aging protocol 3.

	Aging environment	Curing period	Number of tests	P_u		f_t		ε_u	
				Mean (N)	Co.V. (%)	Mean (MPa)	Co.V. (%)	Mean (%)	Co.V. (%)
Flax-T	Env A	7 days	15	38.57	11.91	151.31	11.91	3.65	12.75
Flax-T		28 days	14	5.34	10.43	20.95	10.43	1.60	27.77
Flax-T		56 days	-	-	-	-	-	-	-
Flax-T	Env B	7 days	15	35.83	11.36	140.57	11.36	4.30	12.43
Flax-T		28 days	14	17.82	12.08	69.92	12.08	3.26	17.45
Flax-T		56 days	15	19.49	11.91	76.45	10.43	2.54	28.37

P_u = Maximum Load; f_t = Tensile Strength; ε_u = strain at failure

4. Discussion

4.1 Mechanical properties

The tensile tests carried out on different kinds of flax threads and fabrics confirm that flax fibres, as all the other types of plant fibres [38], present a variability of the mechanical properties both between samples of the same size and in terms of main values among the different series of specimens. The tensile strength assumes values varying in the ranges of 290÷360 MPa concerning the threads and 230÷290 MPa concerning the fabric strips. The Young's Modulus assumes values between the range of 8.3÷11.6 GPa in both the threads and fabric specimens except from the series Flax-fabric-2cm in which a significantly lower value of stiffness is observed. The aforementioned values result in line with research carried out by using flax textile [36] in which a loss of stiffness is recorded as well by increasing the size of the samples. The strain at the failure, varying in the range 3.6÷6.1% is in line with similar studies in which the analysis is conducted at the level of thread rather than of the single fibre filaments. In Figure 11 the main value of the strength of the different series are compared. The series Flax-T achieves the best performance in tension exhibiting the maximum main value of the tensile strength equal to 353.72 MPa. The lower strength observed in the flax strips is due to a non-uniform stress distribution in the different threads, yarn and filaments constituting the fabric. However, this aspect, seems to provide a greater uniformity in the mechanical response of the material as confirmed by the coefficient of variation associated to the tensile strength that significantly decreases by increasing the size of the specimens (Table 2).

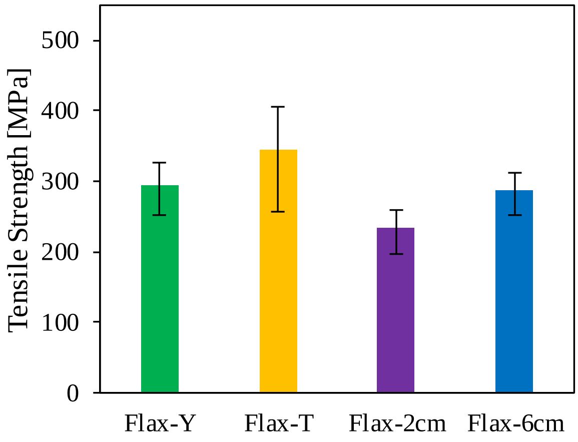

Figure 11: Tensile strength of the different sized flax samples.

The characterisation carried out provides mechanical parameters of fundamental importance in designing process of composite materials reinforced with flax fabric. However, to better identify the nature of the fibre with respect to all the other plant fibres available on the market, together with the geometry identification of the single filaments, a characterisation of their tensile strength would be needed.

4.2 Aging protocol 1

The aging protocol 1 represents a preliminary analysis of the durability of the fibres in view of its application of the textile reinforced composite itself according to what suggested by the acceptance criteria in [46]. As shown in Figure 12 any reduction in terms of strength is observed for each conditioning environments is considered with respect to the reference series of not aged specimens.

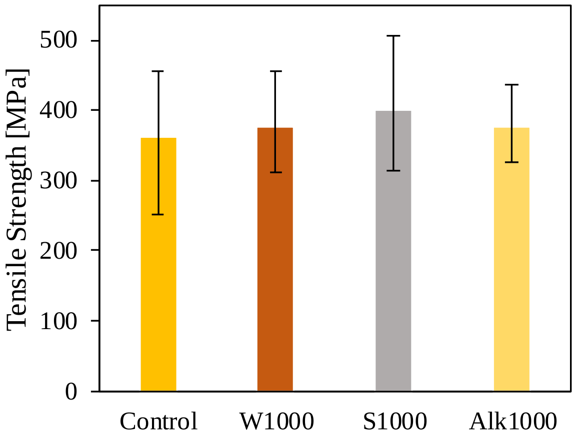

Figure 12: Tensile strength of the series belonging to the aging protocol 1.

A similar behaviour is observed in another study available in the literature [47]: the small strength variation recorded after the conditioning period are attributed to causes of statistic nature. Although representing a preliminary study that precedes an investigation at the level of the composite material, this analysis highlights the low aggressive nature of the conditioning protocol that does not trigger any aging phenomena. A greater immersion period and/or higher temperature conditions may enhance the efficiency of the aging protocol applied on the flax threads and possibly also on the composite system itself.

4.3 Aging protocol 2

The main values of the tensile strength of the specimens subjected to the aging protocol 2 are shown in Figure 13. A loss of strength is observed in hydraulic lime and cement matrix based conditioning environments.

Concerning the kinetics of the aging phenomena in both cases the damage seems to mainly occur during the first days of the mortar hydration process and to stop then in the next days up to 56 days. The reduction of tensile strength consists of about the 16 % in case of hydraulic lime-based matrix environment, and about 22 % in case of cement-based matrix. Although the short period of analysis, the results seems to confirm that the cement mortar environment is more aggressive than the hydraulic lime-based mortar one [45].

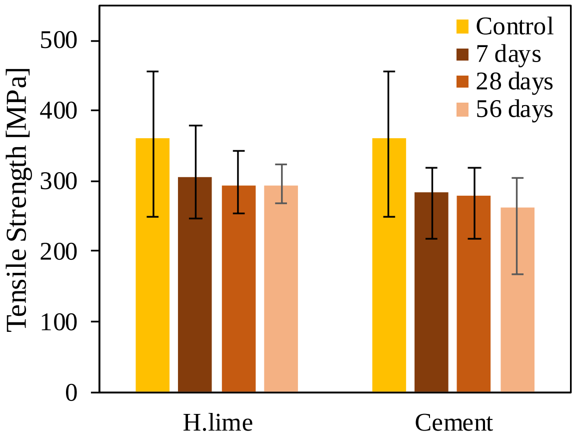

Figure 13: Tensile strength of the series belonging to the aging protocol 2.

With the aim to investigate in depth the degradation phenomena a Scanning Electron Microscope analysis is performed. Figure 14 and Figure 15 represent flax thread filaments after 28 days of immersion in hydraulic lime and cement mortar, respectively. For comparison, a non-aged reference sample is shown in Figure 16. The pictures show the widespread presence of hydration products on the flax filaments surface attesting a good interaction, in terms of adhesion, between fibres and the matrix. Due to the alkaline hydrolysis process, the external wall of the filaments results clearly damaged with respect to the non-aged filaments, causing on a global scale a reduction in terms of tensile strength. However, fibre/matrix adhesion is very important in fibre reinforced composites for the stress transfer at the interface both for synthetic and natural fibres [48] [49]. Thus, even if fibres mechanical properties slightly decrease, an increase of surface roughness can improve fibre/matrix adhesion and, consequently, fibre reinforced composite mechanical properties.

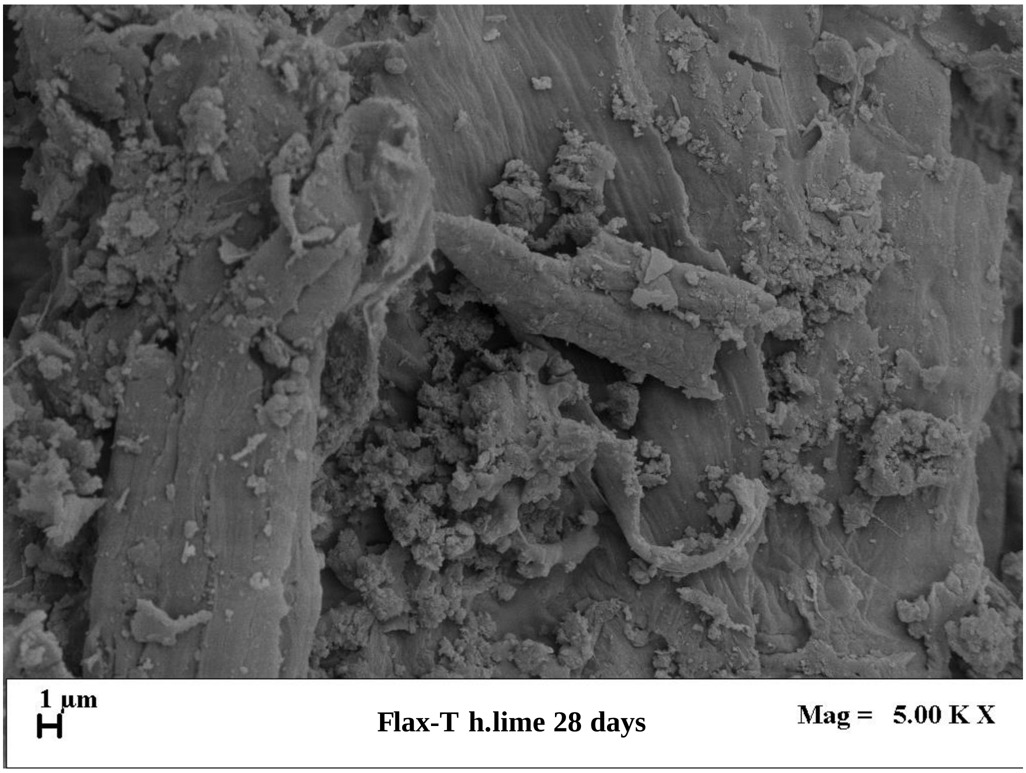

Figure 14: SEM image of a Flax-T h.lime 28 days sample (5000X).

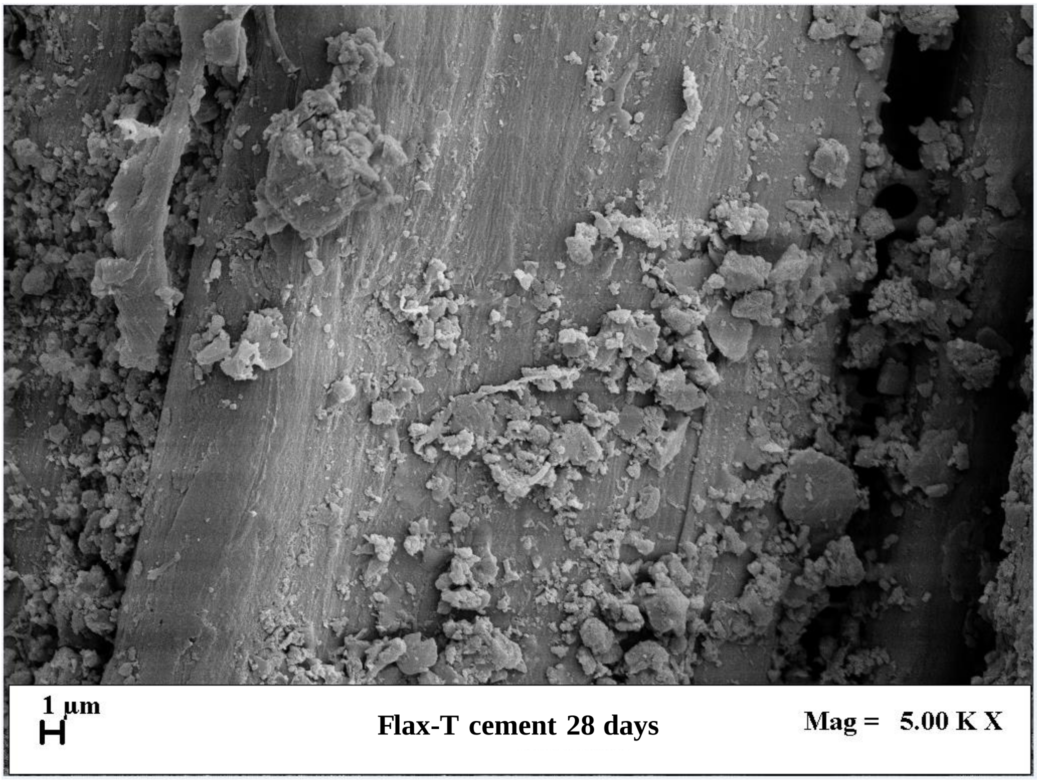

Figure 15: SEM image of a Flax-T cement 28 days sample (5000X).

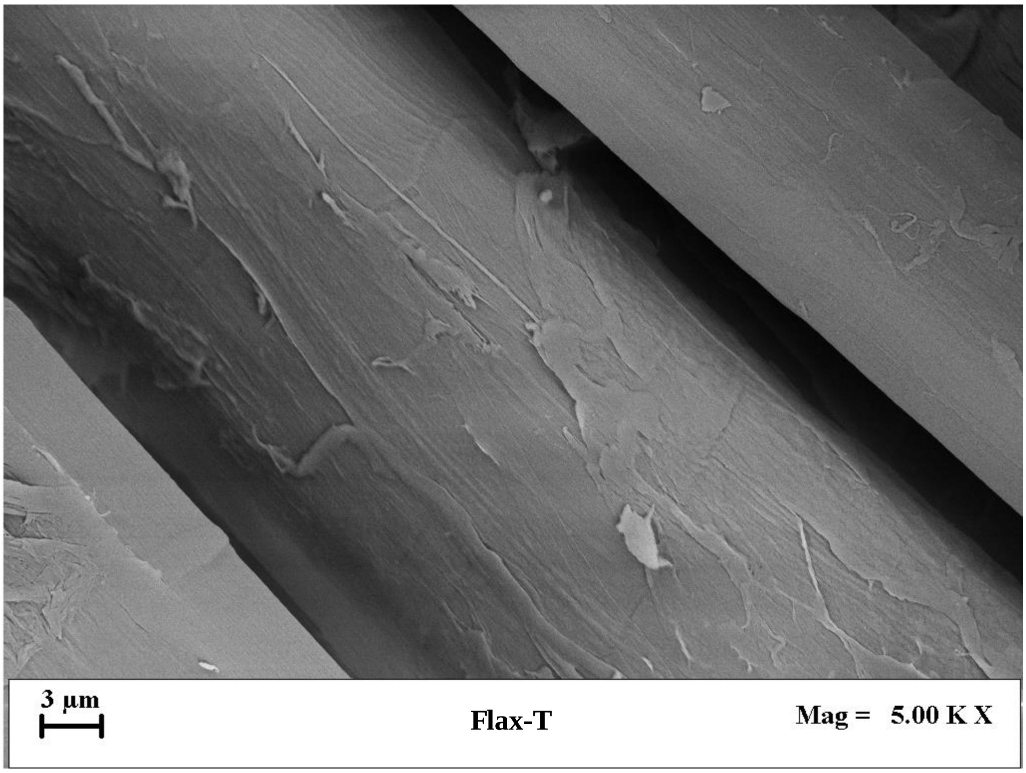

Figure 16: SEM image of a reference Flax-T sample (5000X).

4.4 Aging protocol 3

The aging protocol 3 consists in 2 specific water solutions designed to accelerate the effects of the hydraulic lime and cement mortars on the mechanical behaviours of the reinforcement. Although the use of high temperatures helps to accelerate the degradation phenomena providing information on a long-term, it creates difficulties in quantifying the corresponding time in natural temperature conditions. According to [30], 7, 28 and 56 days of accelerated exposure at a temperature of 55 °C should respectively correspond to about 3, 11 and 20 years in natural conditions. The main values of the tensile strength concerning the series of specimen subject to the aging protocol 3 are shown in Figure 17.

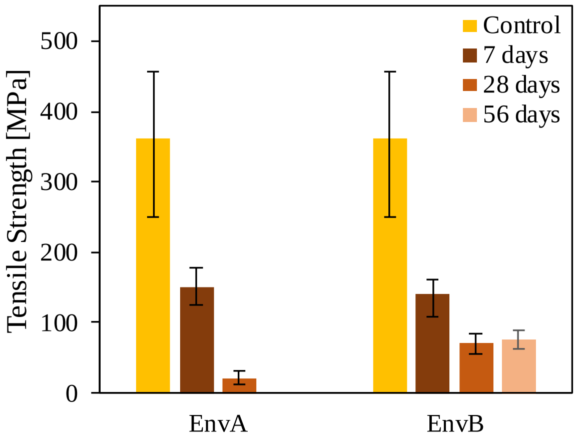

Figure 17: Tensile strength of the series belonging to the aging protocol 3.

Both the series exposed to Environments A and B show a loss of tensile strength of about 60 % after 7 days of conditioning. Flax threads exposed to the Environment A for a period longer than 7 days are characterised by a strength decay of the 95 % after 28 days, and result completely disintegrated after 56 days. Flax fibres exposed to the Environment B show a decay of the mechanical properties of about 80 % after 28 days staying mainly constant up to 56 days. The degradation of the fibres may be attributed to the alkaline hydrolysis of lignin and non-cellulosic constituents of flax, accelerated by the exposure to 55 °C. Figure 18 and Figure 19 show SEM images of samples exposed for 28 days to Environment A and B, respectively; while a reference sample is shown in Figure 20. By comparing the pictures it can be seen that Environment A results to be more aggressive than Environment B, in terms of impurities, waxes and non-cellulosic compounds removal, confirmed by the higher amount of degradation products mixed to solution residues (Figure 18) compared to Flax-T Env_B 28 days sample (Figure 19). Moreover, as reported in the literature [50], increasing the alkalinity of the solution an increase of the crystallinity index is obtained, probably due to a better packing of cellulose chains thanks to the removal of non-cellulosic materials. Thus, the higher mechanical properties of Flax-T Env_B samples can be explained considering an increase cellulose crystallinity.

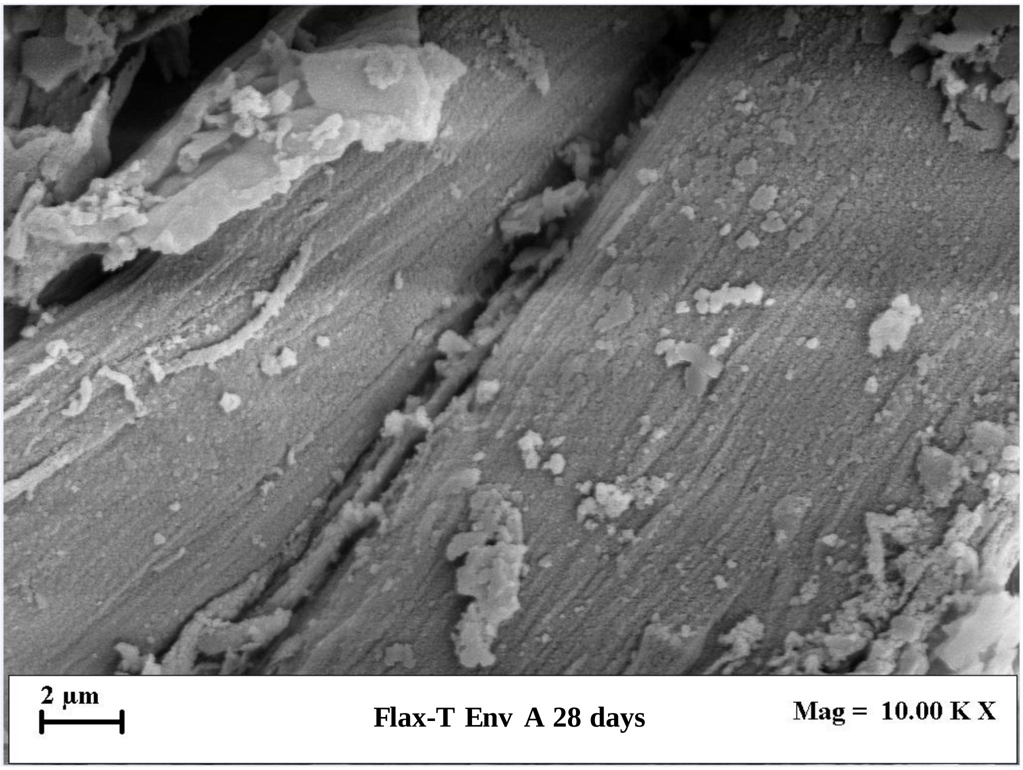

Figure 18: SEM image of a Flax-T Env_A 28 days sample (10000X).

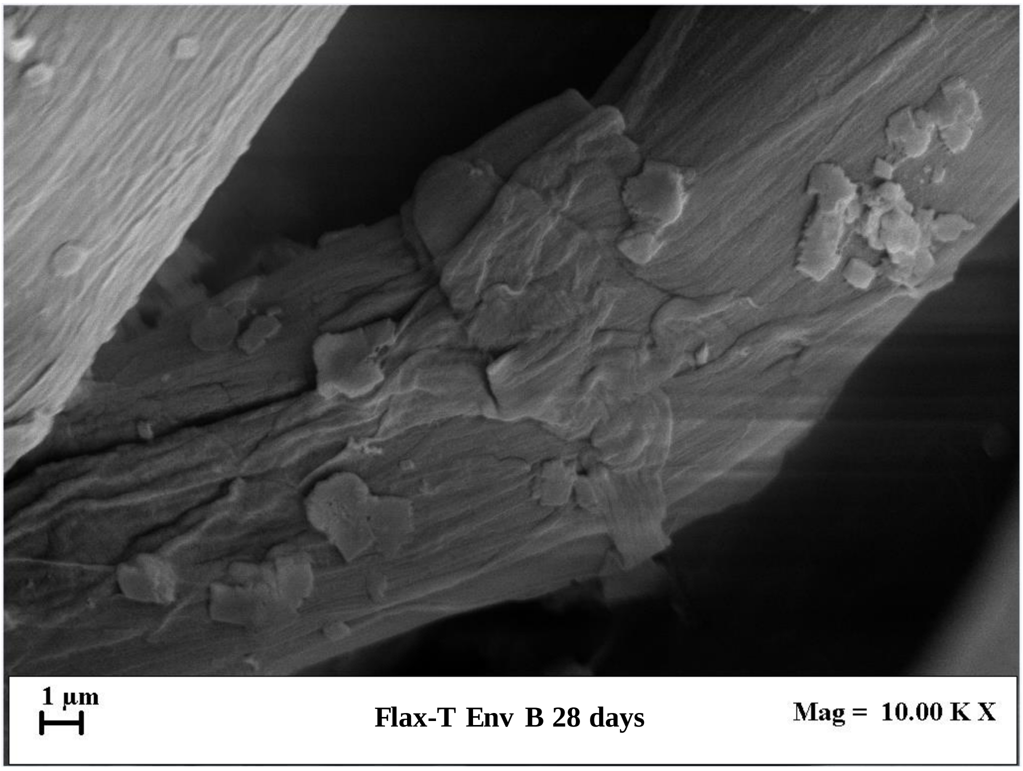

Figure 19: SEM image of a Flax-T Env_B 28 days sample (10000X).

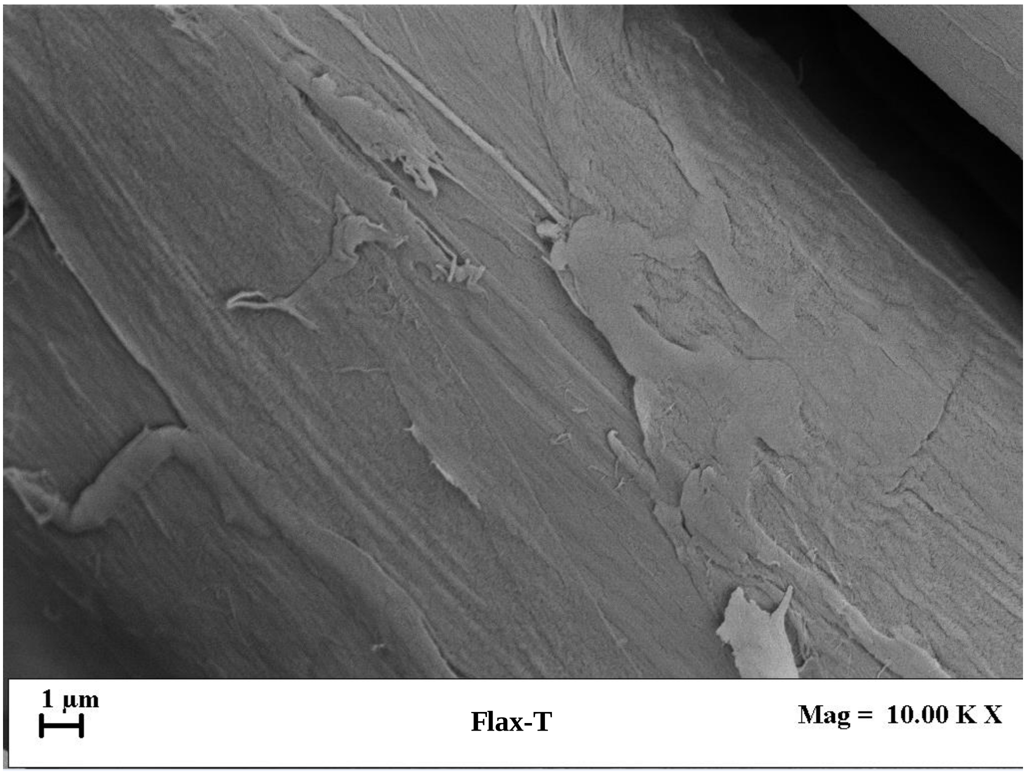

Figure 20: SEM image of a reference Flax-T sample (10000X).

5. CONCLUSIONS

This study proposes a comprehensive characterisation of flax textile to be used as reinforcement in Textile-Reinforced Matrix (TRM) system. Specifically, as the common belief is that natural fibres are not sufficiently strong and stiff to be used in TRM and, moreover, are supposed to be prone to exhibit degradation phenomena when exposed to aggressive environment, this study aims at demonstrating that flax fibres and fabrics do not suffer of these flaws and, hence, can be potentially suited for TRM systems.

The main findings of the research are summarised as follow:

- The flax main thread exhibits a tensile strength of 353.72 MPa, a Young's modulus of 9.36 GPa and a strain at failure of 5.63%, which is consistent with other results recently reported in the literature on similar fibers [6];
- On the contrary, the degradation of mechanical properties induced by the three aging protocols considered in this study is significantly lower than expected;
- Specifically, aging protocol 1 (immersion in water, salt water and alkali water solution for 1000h) does not lead to any significant decay in tensile strength of flax threads;
- Similarly, flax threads after 7 days of immersion in either hydraulic-lime or cement mortar (aging protocol 2) suffer a reduction in strength of about 16% and 22 %, respectively; however, no further reduction is observed in either cases for longer immersion durations until 56 days;
- Conversely, in aging protocol 3, a more significant decay in mechanical properties is observed with a complete loss of strength in the specimens immersed for 55 days at a temperature of 55°C: this is due to the prolonged exposure at harsh aging conditions, in terms of pH and temperature, that promoted flax fibres degradation;
- Finally, SEM investigations proved the good adhesion between fibres and the investigated matrices (i.e. cement and hydraulic lime) thanks to the interlocking positions created onto fibres surface as a result of alkaline hydrolysis.

These results demonstrate that the flax fibres and fabrics under investigation can be utilised as internal reinforcement for TRM systems that appear to be particularly appropriate in strengthening masonry structures. However, further investigations are needed in terms of mechanical analysis and of durability of the TRM system as a whole with the aim to further confirm the potential of this kind of sustainable composite system.

Finally, it is worth highlighting that, besides the specific results obtained on the fabrics under consideration, the comprehensive testing programme reported in this study can be intended as an experimental protocol capable to determining all relevant geometric, physical and mechanical properties needed for natural fibres and fabrics to be employed as a reinforcement phase in composite materials conceived for structural purposes.

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