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Tensile behavior of Textile Reinforced Mortars made with Flax fabrics

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Abstract

Nowadays, several industrial sectors are more and more motivated to develop and adopt sustainable solutions. In this context, the construction industry is not an exception: new materials, possibly obtained from renewable and locally available sources, are being worldwide developed and explored. As part of this common effort, special attention is being paid to an emerging class of materials generally referred to as bio-based composite systems. This study investigates the mechanical properties of a Textile-Reinforced Mortar (TRM) system produced with flax textiles embedded within a hydraulic lime-based mortar. The research also aims at analyzing the cracking patterns exhibited by the Natural TRM systems under investigation. The proposed analyses highlight the relevant mechanical response observed in the experimental results and allows to have a comprehensive overview of the feasibility of using natural textiles for strengthening existing structures.

Keywords: Textile reinforced mortars; Plant-fibers; Crack formation,;Crack pattern.

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1. Introduction

The urban areas of the major European towns are rich in constructions that are often in need for maintenance and rehabilitation (Valluzzi et al. (2014); Modena et al. (2013); Triantafillou et al (1997)). In this context, the Countries of the Mediterranean basin deserve particular attention, as they are generally characterized by medium-to-high seismic hazard levels (Kaplan et al. (2010)). Nowadays, the most common techniques for the strengthening used are the encapsulation with reinforced concrete, steel or plating and wrapping with composite material, for instance, as also proposed by national regulations (NTC 2018). Despite these techniques allows at an increase in terms of global resistance of the structure, they are not distinguished for their easily installation techniques and for their low environmental impact.

Almost three decades ago, Fiber Reinforced Polymer (FRP) systems, which were already in use in mechanical and aeronautic engineering, appeared in the field of construction and revolutionized the retrofitting practice due to their excellent mechanical properties and various other advantages such as lightweight and speed of execution Carozzi et al. (2015). However, the organic matrix in which the fabric is embedded can presents various issues: working hazard, damp incompatibility, lack of vapour permeability and weak bond between reinforcement and substrate (Leonidas et al. (2018); Triantafillou et al. (2006)). Consequently, the use inorganic matrix instead of the organic one can represented a valuable alternative (Coppola et al. (2023)) and, thus, more recently, a new class of composite systems consisting in a mortar matrix internally reinforced by a textile fabric is gaining more attention.

The possible substitution of the energy-consuming synthetic fabrics with natural textiles can be also considered for the production of a new class of composites. As a matter of the fact, the literature demonstrated a good potential in the use of fabrics made of natural fibres as internal reinforcement in inorganic matrix composites (Ferrara et al. (2021); Pepe et al. (2023); Ferrara et al. (2020); Ferreira et al. (2017); Ferrara et al. (2018) while at the same time investigating the environmental impact in the use of plant fibres, highlighting the beneficial effects in terms of carbon dioxide emissions and in terms of renewability (Sen et al. (2014); Misnon et al. (2014)). Other studies demonstrated the mechanical properties of several TRM trough a combinatory approach that analyse different fabric with different matrix (Mercedes et al. (2023)). Structural applications of plant based TRM were also investigated analysing in- and out-of-plane mechanical behaviour of eternally strengthened masonry elements both through laboratory tests and numerical analysis (Gkournelos et al. (2022); de Carvalho et al. (2021); Mercedes et al. (2020); Trochoutsou et al. (2022); Cassese et al. (2021)).

This work aims at investigating the mechanical properties of two flax TRM made with one and two layers of reinforcement fabric and presents the improvements that can bring the adding of one layer to a natural TRM. The paper shows the main results obtained from the experimental campaign performed at the University of Salerno (Italy). The experimental campaign was structured in two parts: a first characterization of the raw materials (the dry fabric strips and the mortar) and a second phase in which the TRM samples were realized and tested under tensile load according to Rilem (2023). The paper firstly presents a comprehensive description of the materials and methods then, the discussion of stress strain charts and main mechanical properties is proposed in section 3.

2. Materials and methods

The materials used to prepare the TRM samples under consideration are textile strips and a mortar matrix. Specifically, a lime-based mortar and flax fabrics were employed. In the following, the two raw phases of the TRM composite system are characterized individually in terms of both physical and mechanical properties.

2.1. Textile strips

The strips were cut out of the flax fabric rolls. The aim, at this stage, was oriented to keep constant the overall number of yarns for every strip. Hence, every sample of fabric presented 39 longitudinal yarns (Fig. 1).

From the fabric strips, five of them were extracted and tested to determine both elastic modulus and tensile strength. The tested samples were characterized by the following dimensions: 500 mm of total length and 60 mm of width. According to the reference standard (Rilem (2016); CSLLPP (2018)), the tensile tests on these specimens were realized considering a a gauge length of 200 mm.

The tests were performed at the Structural Engineering Testing Hall (Str.Eng.T.H.) Laboratory of the Department of Civil Engineering of the University of Salerno (Italy) by means of a Zwick Roell Schenck Hydropuls S56, with a maximum capacity of 630 kN. The applied displacement rate was equal to 0.50 mm/min.

Fig. 1. Extracted strips of flax textile samples

2.2. Mortar

In this study a pre-mixed hydraulic lime-based mortar was used, which consisted of fine aggregates with a maximum diameter of 0.6 mm. This product is a commercial mortar made by Kimia SPA (www.kimia.it/en/products/limepor-edo). As a matter of principle, this type of mortar presents physical and a chemical compatibility with the traditional masonry elements. The masonry elements are the main type of structure to reinforce with TRM made of jute and flax.

The mixture composition consisted of 10 kg of lime-based dry mixture and 2.2 kg of water. This proportion is selected according the recommends of the datasheet (www.kimia.it/en/products/limepor-edo).

A part of the fresh mortar was separated from the total amount produced and it was employed to produce six specimens for the mechanical characterization according to EN 1015-11:2019: compressive and flexural strength tests were performed. From these tests, the following results were obtained: the mean compressive strength of the mortar was equal to 8.9 MPa and the mean flexural strength was 4.77 MPa.

2.3. Production and testing of natural flax-TRM

The TRM specimens, realized in accordance with Rilem 232-TDT (2016), were made with either one and two layers of natural flax fabric. The main objective of the experimental campaign executed on these TRM samples was to obtain the corresponding stress-strain curves. From these, some relevant properties of the TRM can be derived, such as the ultimate tensile strength, the number of cracks, the strain at the first crack and the strain at the sample breaking.

The tests were conducted in displacement control with a loading rate equal to 0.20 mm/min. The test machine is the same defined in Section 2.1. Fifteen specimens were realized: ten with two layers of reinforcement and five with one layer.

The samples were characterized by a global length equal to 500 mm of which 100 mm for end is the tab length and 300 mm represents the gauge length. The width was equal to 60 mm – incorporating 39 longitudinal yarns – for the one-layer sample and 50 mm – equal to 2 x 34 longitudinal yarns - for the two-layer samples. The thickness varies for each sample as a result of the stochasticity of the reinforcement material.

Table 1 summarizes the main geometrical and mechanical properties of the two types of the tested TRM samples.

Table 1. Geometrical and mechanical properties of Flax-TRM composites made with one and two layers.

Parameter	1-layer TRM	2-layers TRM
Average thickness [mm]	5.12	8.6
(range of variation)	(5.0-5.3)	(8.3-9.2)
Textile area within the cross section [mm2]	2.65	4.62
Fiber volumetric ratio [%]	0.853%	1.07%
Minimum number of cracks - $n_{crack, min}$	2	10
Maximum number of cracks - $n_{crack, max}$	4	16
Average crack spacing at final stage [mm]	100	25.14
(range of variation)	(75-150)	(20.00 - 33.3)

3. Results

3.1. Mechanical and physical characterization of the textile strips

The characterization of the textile strips allows to determine the main physical properties of the fabric both in terms of yarns and in terms of strips. Table 2 shows the main value obtained from the test for the characterization of the material. The first four rows summarize the physical properties of the fabric. The fifth and sixth rows show the tensile strength of the yarn. The other rows are related to the mechanical properties of the strips as defined in Section 2.1.

Table 2. Characteristics of the Flax fabric

Parameter	Flax textile
Linear density [Tex]	98.1
n° yarns/cm [cm^{-1}]	6.750
Density [g/cm3]	1.440
Yarns cross section [mm^2]	0.068
Average tensile strength (yarn) - $\sigma_{max,yarn}$ [MPa]	481.24
(range of variation)	(412.36 – 601.60)
Average tensile strength (strip) - $\sigma_{max,textile}$ [MPa]	378.5
(range of variation)	(345.8 - 397.6)
Average strain at maximum load (strip) - $\varepsilon_{max,textile}$ [%]	1.66
(range of variation)	(1.37 - 1.95)
Average ultimate strain (strip) - ε_{final} [%]	2.08
(range of variation)	(1.79 - 2.28)
Elastic modulus (strip) - E [GPa]	31.04

It is worth highlighting that, as expected, the average tensile strength for the strips is always lower than the same parameter evaluated on the single yarn. This is related to the increasing number of yarns tested and, consequently, to the higher probability that one of these yarns fails. In that case, a major load should be held by each yarn.

3.2. Mechanical characterization of the natural flax-TRM

The results of the tensile test are firstly reported in terms of force-displacements relationship, which is then converted into stress-strain curves by considering the transverse area of the fabric and the reference gauge length, respectively. Figure 2a reports the results and shows the typical TRM behaviour under tensile test.

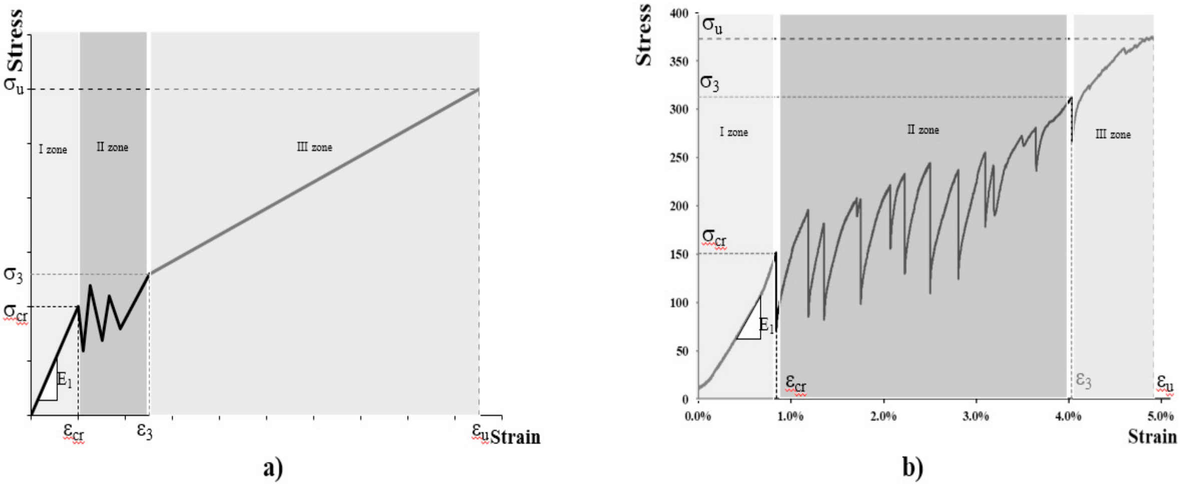

Fig. 2. On the left (a), the typical stress-strain curves for a TRM with the nomenclature used in 0; on the right (b), the stress strain chart derived by the experimental campaign on the two layers flax samples (ID sample: Flax_2layers_05)

As widely documented in the literature (Rilem (2016)), it consists of three main branches or “zones”: zone I is defined as the “uncracked zone”, the zone II zone is labelled as “crack development zone” and zone III is the “cracked zone”. Moreover, Figure 2b presents the stress-strain response observed for one of the specimens produced herein made with two layers of flax.

Zone I shows a development concordant with the linear elastic response of the uncracked matrix in tension. For this reason, a linear regression line can be drawn to evaluate the elastic modulus (E1) of the TRM. This line can be evaluated between the value $0{,}4\varepsilon_{cr}$ and $0.7\varepsilon_{cr}$.The first crack defines the start of the crack development zone. In this case, eleven cracks can be clearly identified in zone II: each crack is identified with a tensile drop in the chart. A higher or lower number of cracks defines the axial deformation capacity of the TRM system in tension up to failure. Zone II is longer depending on several parameter, such as the reinforcement ratio, the geometry, the matrix characteristics, the reinforcement characteristics and the boundary conditions imposed during the test.

The last zone is governed by the textile stiffness and by the textile ultimate strength. In fact, the last area presents a behaviour similar to the dry textile. In order to evaluate the similarity between the TRM strength and the strips strength, an interesting value is evaluated: the exploitation ratio, representing the ratio of the maximum stress reached in the TRM and the tensile strength of the yarn (Table 2). This is a relevant parameter to assess and qualify the mechanical performance of the tested TRM systems (De Felice et al. (2018)).

3.3. One-layer TRM

To highlight the increase in strength due to the growth of the reinforcement ratio, this section aims to show the observed stress-strain relationships for one layer Flax TRM. Figure 3 shows the four curves of the one later TRM, whereas the fifth specimen, which failed during the preparation, are not reported. The graph shows a low number of cracks and the curves shape is floating. Moreover, the deformation capacity of three over four sample is not favourable, the values do not extend beyond 2.0% of strain. There is a sole exception of one curve that reaches 3.6% of strain.

The variability observed in terms of experimental results can be attributed to the significant variability affecting both geometry and mechanical properties of the natural fibers.

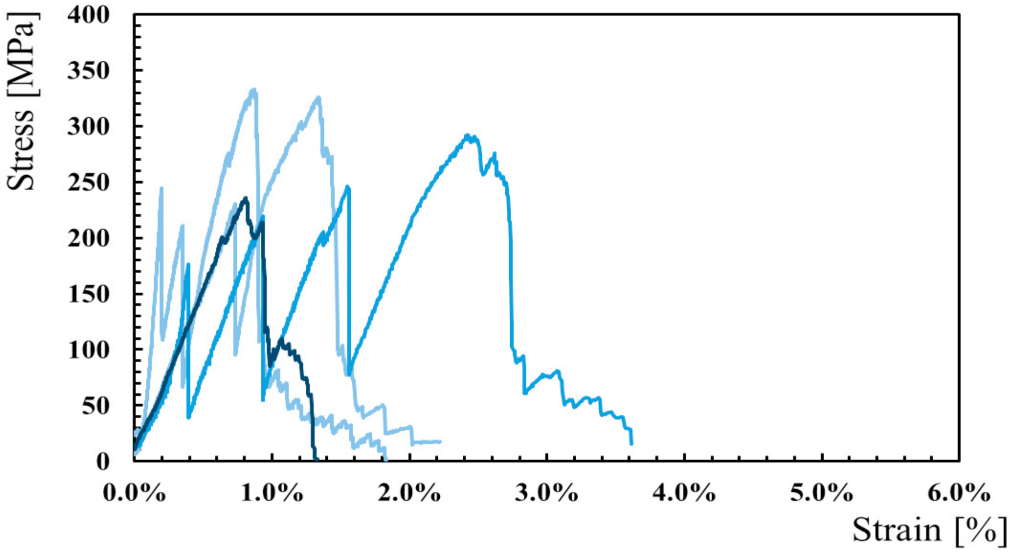

Fig. 3. Stress strain charts for the four samples of Flax_1layer TRM

3.3.1. Two-layers TRM

Figure 4 shows the nine curves of the two layers flax-TRM. Unfortunately, as in the previous case, one sample broke until the test start and its curve is not reported. It is very interesting noticing the great number of cracks, as shown in Table 1, reached by each sample made with two layers of flax fabric reinforcement. Contrarily to what was observed in the case of one-layer TRM, these samples reach up to 16 cracks until the break (see Table 1). This characteristic is highlighted by the average crack spacing at the final space. This value shows the great difference between the two TRM in terms of efficiency and capacity to deform until the breaking.

In this case, the conformation of the curves is very similar between them. This is highlighted by the overlap of the curves in the chart, in fact, they occupy the same area of the chart.

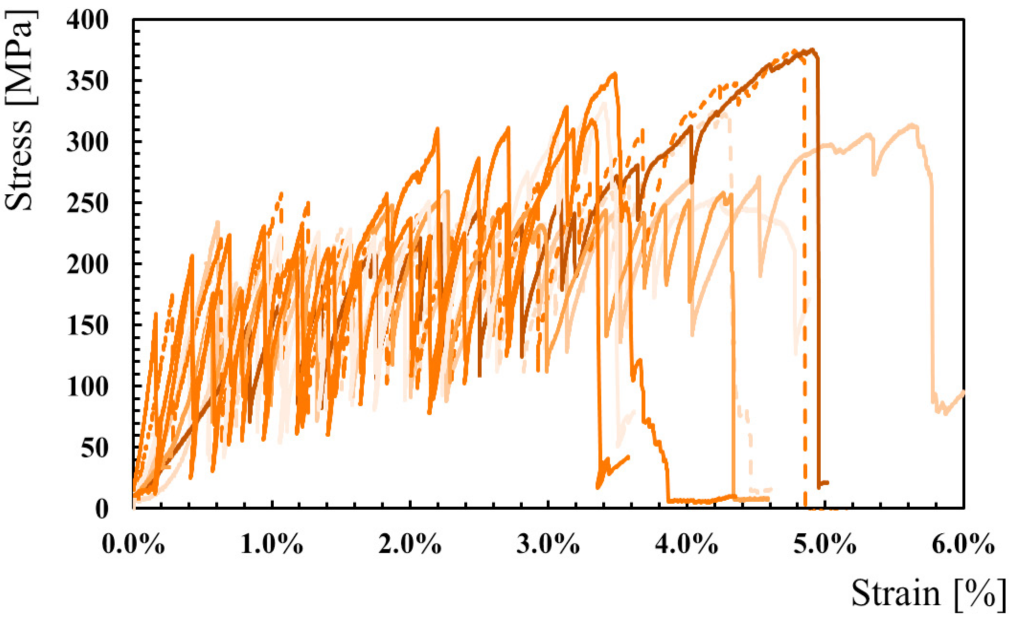

Fig. 4. Stress strain charts for the nine samples of Flax_2layers TRM

The first stage develops up to an average range of 0.4% - 0.5% of deformation. The end of the first stage is signed by the first crack, this occurs to a value around 180 MPa (average value ranging between 160 MPa and 230 MPa). It is worth to note that this value of load corresponds to a matrix first crack strength. The matrix first crack strength is approximately evaluated to 2.00 MPa. As expected, according to the value reported in literature (De Santis et al. (2017); Wang et al. (2021); De Santis et al. (2015)), this value is lower than the tensile strength of matrix evaluated experimentally.

In the present experimental study, the Exploitation ratio assumes the values 78% and 65% for the one layer and two layers, respectively.

Finally, it is interesting to note the increasing of the performances in terms of reinforcement ratio. Values equal to 0.88% and 1.07% are calculated for the one layer and two layers of TRM, respectively. It is noteworthy see the great increase in terms of strain and strength given by the addition of a few textiles in the matrix.

Moreover, it is relevant noting the relation between the exploitation ratio and the reinforcement ratio. The value of exploitation ratio for one-layer was expected to be lower than the two layers value. This unexpected result can be caused by, as already stated, the great stochasticity of the flax fibre and their defects. Indeed, the low number of one-layer TRM tested does not allow to obtain a reduction of the statistical error when the evaluations are based on the average results.

4. Conclusion

The main results obtained during the present experimental study can be summarised as follows:

- Flax fibres present an excellent behaviour as an answer to a tensile stress;
- The one-layer TRM specimens reached a reasonable tensile strength, but they showed a limited displacement capacity, as only few cracks were formed ;
- Moreover, the response of the various one-layer TRM specimens showed a very high test-by-test variability;
- Conversely, the two layer TRM specimens showed a more stable response characterised by a higher axial displacement capacity resulting by the formation of a number of cracks included between ten and sixteen.;

Finally, this study demonstrated that flax fabrics have potential to be employed In TRM systems, whose capacity as strengthening technique for masonry wall will be investigated in the future development of the present research.

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