Experimental analysis on the tensile response and cracking process in jute/flax lime-based textile-reinforced mortars

Original
Experimental analysis on the tensile response and cracking process in jute/flax lime-based textile-reinforced mortars / Pepe, Marco; Sellitto, Eduardo; Paolillo, Bruno; Lombardi, Rosario; Ferrara, Giuseppe; Agnetti, Stefano; Stochino, Flavio; Martinelli, Enzo. - In: PROGRESS IN ENGINEERING SCIENCE. - ISSN 2950-4252. - 3:2(2026), pp. 1-11. [10.1016/j.pes.2026.100284]

Publisher:
Elsevier

Published
DOI:10.1016/j.pes.2026.100284

Progress in Engineering Science 3 (2026) 100284

Contents lists available at ScienceDirect

Progress in Engineering Science

journal homepage: www.sciencedirect.com/journal/progress-in-engineering-science

Experimental analysis on the tensile response and cracking process in jute/flax lime-based textile-reinforced mortars

Marco Pepe, PhD [a,b], Eduardo Sellitto [a], Bruno Paolillo [a], Rosario Lombardi [a],
Giuseppe Ferrara, PhD [c], Stefano Agnetti, PhD [d], Flavio Stochino, PhD [e],
Enzo Martinelli, PhD [a,*]

[a] Department of Civil Engineering, University of Salerno, via Giovanni Paolo II 132, Fisciano, SA 84084, Italy
[b] TESIS srl, Piazza Vittorio Emanuele 10, Fisciano, SA 84084, Italy
[c] Politecnico di Torino, INSTM R.U. PoliTO-LINCE, Department of Applied Science and Technology, Corso Duca Degli Abruzzi 24, Torino, TO 10129, Italy
[d] Kimia SpA, Via del Rame 73, Perugia, PG 06134, Italy
[e] Department of Civil, Environmental Engineering and Architecture, University of Cagliari, Via Marengo 2, Cagliari, CA 09123, Italy

ARTICLE INFO

Keywords:
Textile Reinforced Mortars
Natural fibres
Lime-based mortar
Bond behaviour
Crack development

ABSTRACT

Growing environmental awareness is increasingly justifying the development and adoption of sustainable solutions in various industrial sectors. The civil engineering sector is no exception: new materials sourced from renewable, locally available resources are being developed and explored worldwide. Alongside this widespread effort, a class of emerging materials is receiving particular attention: bio-based composite systems. This study investigates the mechanical response of a textile-reinforced mortar (TRM) system that incorporates two layers of flax and jute fabric into a hydraulic lime-based mortar matrix. Specifically, the bond interaction between the natural fabrics and the mortar matrix is analysed using direct pull-out tests, as well as by examining cracking patterns observed in tensile tests on natural TRM systems. These analyses reveal the substantial mechanical response in both cases, offering insights into the potential application of natural textile reinforcement in restoring and reinforcing existing masonry elements and structures.

1. Introduction

The loss of human life and historical heritage following the collapse of masonry buildings in past earthquakes highlighted the need to reinforce masonry buildings [1–3]. Therefore, in the last decade, the use of a class of inorganic composite systems, generally referred to as Textile Reinforced Mortar (TRM), has attracted a significant interest as a possible solution to strengthen masonry members [4–6]. In fact, they are emerging as a more appropriate solution for strengthening historical constructions than the fibre-reinforced polymers (FRPs) due to the incompatibility between the resin and the substrates [7].

Among all the textile reinforcement that can be embedded inside TRM systems, natural fibers are gaining more and more attention [8,9]. In fact, as shown in the literature, the current interest for sustainable construction materials is fostering research into the use of natural fibers, also for composite systems [10–12]: the natural fibers are renewable, have good economic feasibility and the end of life of natural fibers results in energy and carbon credits. Available studies in the literature clearly demonstrate that depending on the type of matrix and reinforced systems the TRM technology can be used both in concrete and masonry structures. However, natural TRM seems to be more compatible with historical masonry structures representing a relevant building stock Europe and Worldwide [9,10]. As a matter of principle, they also offer a higher degree of flexibility that prevents over-stiffening effects and they are more compatible in applications on masonry elements for their better compatibility with masonry substrates [13–15]. Recyclability and CO_2 emissions are some of the main indicators of environmental sustainability in the composite systems [16]. Without mentioning that the properties of natural fibres include abundantly available, minimal health hazards during processing and are more affordable than the synthetic ones for the development countries [17].

It is worth mentioning that the possible use of natural fibers/textile

---

* Corresponding author.
E-mail addresses: mapepe@unisa.it, m.pepe@tesis-srl.eu (M. Pepe), esellitto@unisa.it (E. Sellitto), brpaolillo@unisa.it (B. Paolillo), rolombardi@unisa.it (R. Lombardi), giuseppe.ferrara@polito.it (G. Ferrara), stefano.agnetti@kimia.it (S. Agnetti), fstochino@unica.it (F. Stochino), e.martinelli@unisa.it (E. Martinelli).

https://doi.org/10.1016/j.pes.2026.100284
Received 18 February 2026; Received in revised form 27 March 2026; Accepted 13 April 2026

in composite systems has the potential to be applied not only to existing buildings, but also to other types of civil engineering structure and infrastructures requiring adequate tensile resistance and/or ensuring structural stability.

In this contest, different types of plant fibers (e.g., sisal, jute, flax, hemp, coir and curauá [18–20]) were employed for investigating the mechanical behaviour of mortar-based composites. The results obtained in some studies are concordant that fibres exhibit mechanical properties suitable for structural applications [21]. On the other hand, several studies highlight how difficult it is to find a theoretical formulation to assess and predict the resulting response of these types of composites [22]. Another critical issue has emerged related to the variability of the natural fibre properties, which has led to a higher heterogeneity in the behaviour of Natural TRMs when compared to conventional TRMs [23–25]. Despite their variability, some results proposed in the literature demonstrate that higher mechanical properties can be achieved by increasing the volumetric ratio of textile reinforcement [14]. In this context, studies in the literature on such composite systems have shown a limited mechanical response, typically characterized by the formation of a single crack followed by slippage and eventual tensile rupture of the reinforcing fabric. In light of these critical issues, it is essential to investigate the influence of certain key parameters, such as the number of textile reinforcement layers, on the mechanical performance of the composite [26–32]

1.1. *Research significance and novelty*

In this context, the present study aims to analyse the mechanical response of two different natural TRM systems, made with Jute and Flax textiles, each consisting of two layers of textile reinforcement per sample, starting from the physical and mechanical characterization of the individual natural yarns.

It is worth mentioning that the rationale behind selecting two layers of textile reinforcement (representing the first research significance of this study) is based on preliminary results proposed by the authors in the literature [23] in which only one layer of textile was used either for Jute and Flax TRM: in that case, the authors demonstrated that, for the type of textile employed in the experimental plan, the overall amount of reinforcement embedded in the lime-based matrix was not sufficient to achieve a composite behavior generally characterizing TRM system for structural applications.

On the other hand, thanks to the possibility to determinate the relevant mechanical properties (i.e. stress-strain curves) by means of tensile tests run in accordance with international guidelines. Moreover, the resulting performance of the tested natural TRM composites have also been investigated through the analysis of crack patterns, representing a fundamental parameter for practical applications.

Furthermore, the analysis proposed herein also included the study of the bond stress at the interface between the matrix and reinforcement of the Natural TRM system, investigated both directly, through pull-out tests, and indirectly, through the analysis of the distribution and width of cracks. This represents one of the key relevant aspects of the present study: as a matter of principle, these parameters are key elements for evaluating the overall behavior and efficiency of different types of natural TRMs.

The present paper is structured as follows: the following “Section 2” describes the materials and methods adopted during the experimental activities; then, “Section 3” summarises the key experimental results and proposes a detailed analysis of the cracking pattern and, consequently the bond interaction among the natural textile and the surrounding lime-based matrix.

2. Materials and methods

2.1. *Jute and flax textiles*

The natural reinforcements employed in this study to analyse the Natural TRM systems are obtained from bi-directional Jute (Fig. 1**a**) and Flax (Fig. 1**b**) textiles.

The natural textiles under consideration are characterized by filaments ordered in yarns, which can be considered as the fundamental element of the mesh. Physical and mechanical properties of the yarns (20 samples for both types of source are considered in this study) were evaluated in accordance with different reference standard in order to obtain: *(i)* the tensile strength (BS ISO 3341:2000 [33]); *(ii)* the linear density (EN ISO 1889: 2009 [34]); *(iii)* density (ASTM D8171–18 [35] and [36]) from which it is, then, possible to evaluate their cross section area (as also describe in [23]); *(iv)* as well as the number of yarns for cm. The main results obtained for the natural yarns under consideration are summarised in the following Table 1.

In addition, Fig. 2 proposes some representative Scanning Electron Microscope (SEM) images highlighting the cross section representative shape/geometry and the lateral surface for Jute (Fig. 2**a**) and Flax (Fig. 2**b**) yarns: the proposed images remark the relevant heterogeneity generally observed for natural yarns/textile which also can further explain, for instance, the relevant range of variation of the yarn strength under tensile load as reported in Table 1.

The results related to the physical properties of the natural yarns highlight that the density of the Flax textile is slightly higher (around 5%) than the Jute one (Table 1). Moreover, “the number of yarns for cm” is higher (around 50%) for Flax than Jute. On the other hand, the Jute fibers are characterised by a significantly higher cross section being almost 3 time greater than the Flax yarns (see also Fig. 2). Consequently, also the linear density (expressed in Tex = [g/km]) is significantly higher (around 3 time) than Flax (Table 1).

For each type of textile, five strips 60 mm in width (corresponding to 29 and 39 yarns for Jute and Flax, respectively) and a gauge length of 400 mm, were obtained and tested under tensile loads (Fig. 2). Tensile tests executed in displacement control with a loading rate of 0.50 mm/min, tab length equal to 100 mm, total length equal to 500 mm, considering, however, half the portion from the center of gravity of the tab in accordance with the reference standard [38].

The tensile 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. Finally, samples of natural textiles were also cut to realize the strips which have been employed for manufacturing the Natural TRM composite specimens as described in the following “Section 2.4”.

2.2. *Mortar*

The inorganic matrix employed here is based on the use of a premixed hydraulic lime-based mortar [39] incorporating fine aggregates characterised by a nominal (maximum) diameter equal to 0.6 mm. The dry mortar was mixed and produced in accordance with the following steps: initially mix the dry raw materials (fine aggregates and lime-based binder) with 3/4 (75%) of the total amount of the required water and then, gradually add it until a smooth mixture is formed. The adopted mix composition is composed as follow: for each kg of lime-based dry mixture (made of NHL 3.5 lime and fine aggregates), 22% in weight of free water are used. Once the mortar was produced, part of it was employed to produce six samples (160 mm×40 mm x 40 mm) for the mechanical characterisation (compressive strength tests and bending tests) in accordance with the EU reference standard [40]. The average compressive strength of the mortar was found to be equal to 8.90 MPa, meanwhile the average flexural equal to 4.80 MPa.

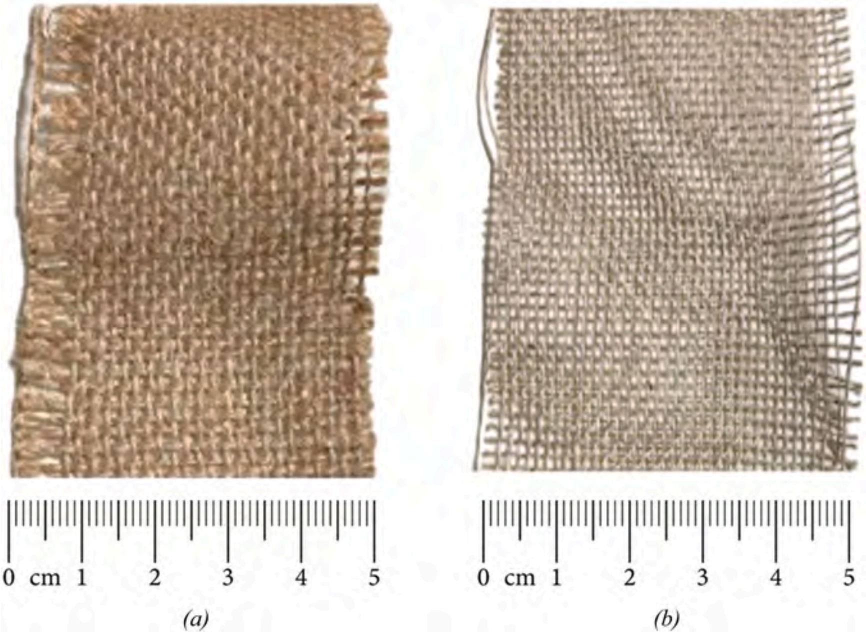


Fig. 1. Representative samples of (a)Jute and (b) Flax textile.

Table 1
Properties of Jute and Flax yarns.

Parameter	Jute textile	Flax textile
Linear density *[Tex]*	268.70	98.10
n° yarns/cm *[cm^{-1}]*	4.57	6.75
Density *[g/cm^3]*	1.37	1.44
Yarns cross section *[mm^2]*	0.196	0.068
Average yarn strength - $\boldsymbol{\sigma}_{\mathbf{max,yarn}}$ *[MPa]*	127.28	481.24
(range of variation)	*(83.21–176.15)*	*(412.36 – 601.60)*

2.3. Pull-out tests for yarns-matrix bond behaviour evaluation

Pull-out tests are conducted with the aim of evaluating the bond behavior between the reinforcing yarn and the surrounding lime-based mortar (representing the relevant compound of the Natural TRM composite system under consideration). As a matter of principle, the key relevant parameters defining the bond adhesion are analyzed by extracting the yarn from the surrounding mortar: the proposed approach allows to directly identify the yarn-matrix interface bond for a fundamental understanding of the overall response of the TRM composite system when subjected to a tensile load. The lime-based mortar employed for this phase of the experimental campaign is the one described and characterized in the previous paragraph (see Section 2.2), meanwhile the natural yarns were obtained from Jute and Flax textile (see Section 2.1). More specifically, a total of 20 yarn-matrix specimens were produced, 10 for each type of source, with a yarn embedded length within the matrix equal to 10 mm, as schematically represented in the following Fig. 4.

The test setup is defined in accordance with established procedures proposed in the literature [9,25], with the aim to ensure the reproducibility and consistency of the experimental results. Paper cups are used as formwork for the test specimens, with holes at the base to allow plastic straws to pass through to define the anchoring length of the yarn (Fig. 4). A polystyrene element, suitably shaped and with a diameter equivalent to that of the formwork, was used to improve the verticality of the reinforcement and reduce the volume of mortar required (Fig. 4). The yarn is inserted into the straw and passed through the formwork cover, maintaining an immersion length of 10 mm. During the pouring of the mortar, the reinforcement is kept under slight tension, and the test piece is subjected to manual vibration to promote the compaction of the matrix and yarn-mortar adhesion. Subsequently, the test specimens are left curing for 28 days under controlled laboratory environmental conditions in order to ensure a complete hydration of the lime-based mortar matrix. The pull-out tests are conducted using a Sans Universal Testing Machine equipped with a 10 kN load cell. The free end of the reinforcement is secured to the machine clamps using abrasive paper to prevent slippage, while the base of the test piece is secured at the sides using metal clamps to prevent movement (Fig. 4).

The test was performed under displacement control, divided into three progressive loading phases:

- from 0 mm to 1 mm, displacement rate of 0.10 mm/min;
- from 1 mm to 2 mm, displacement rate of 0.50 mm/min;
- from 2 mm until complete withdrawal, displacement rate of 1.00 mm/min.

2.4. Production and testing of natural TRM composite systems

The tensile tests have predicted the use of 20 Natural TRM samples were prepared, each reinforced with two layers of reinforced. Specifically, a 10-specimen batch was considered for both *Jute-TRM* and *Flax-TRM* series, following established international guidelines [41]. During casting, each sample was placed in its own mold, alternating layers of fabric and mortar (Fig. 5). More specifically, rectangular samples (nominal length equal to 500 mm and a width of 50 mm) were produced through the following steps: formwork preparation and casting of lime-based mortar; spreading of a thin layer of release agent, in order to allow easier removal of the samples after curing; casting of the first layer of fresh mortar; placing of the first fabric strip and; casting the second layer of mortar; placing of the second fabric strip and, finally casting of the finishing layer of the matrix (Fig. 5). The samples were removed from the molds after 48 h and air cured up to 28 days in environmentally controlled laboratory conditions before testing.

As also reported in the introduction section, the rationale behind selecting two layers of textile reinforcement is based on preliminary results proposed by the authors in the literature [23] in that case, in fact, was clearly demonstrated that the use of only 1 layer was not sufficient to warrant a composite behavior generally characterizing TRM system for structural applications.

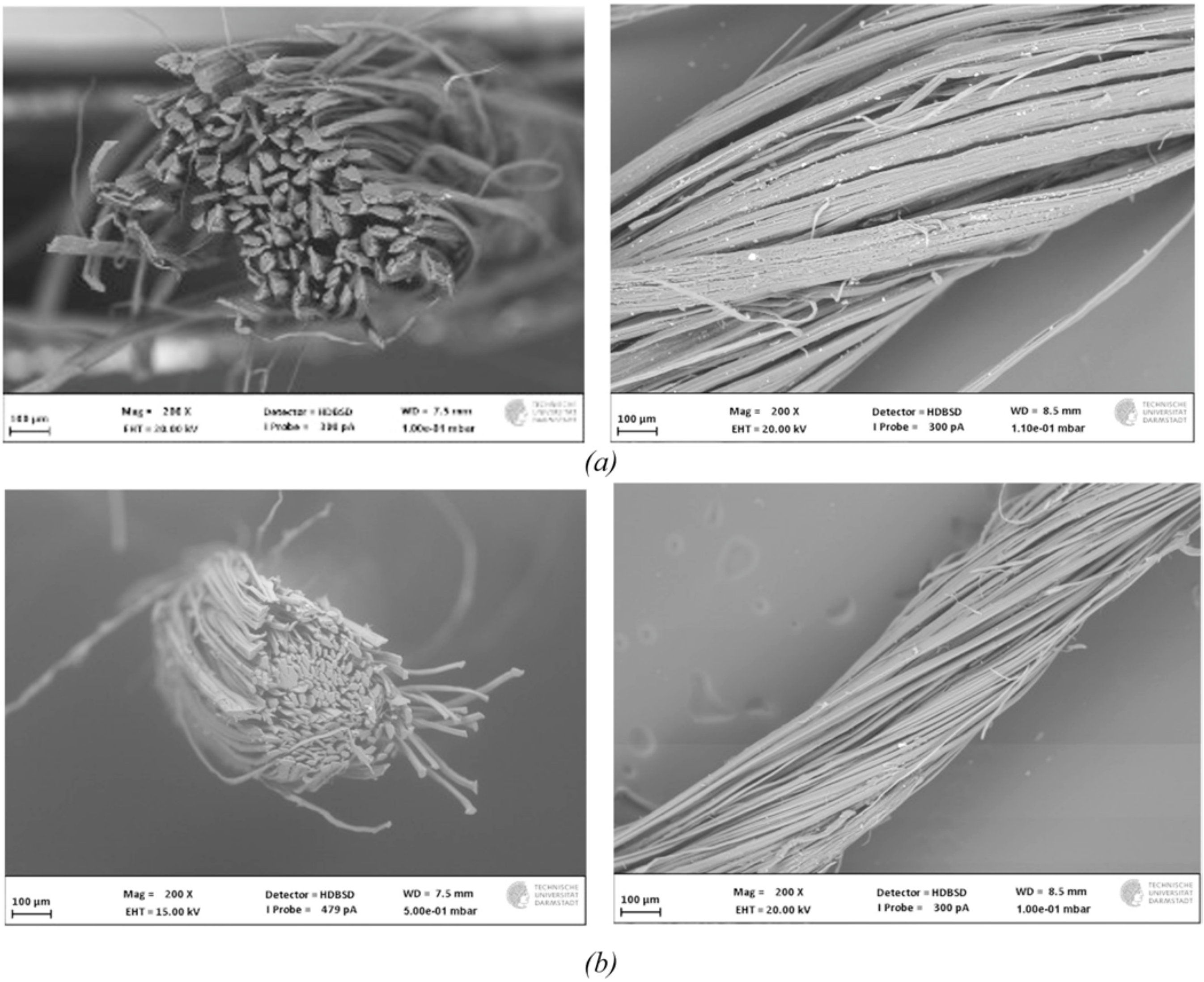


Fig. 2. SEM images for (a) Jute and (b) Flax yarns (adapted from [37]).

Each produced sample, characterised by a 50 mm width, corresponds to 46 (23 yarns layer) and 68 yarns (34 yarns for layer) for *Jute-TRM* and *Flax-TRM*, respectively: the overall geometric properties of the produced natural TRM samples are summarised in Table 2.

All samples were produced using the same molds. However, since production was carried out manually, the overall thickness may slightly vary, up to a millimeter. Each sample, therefore, presented a specific thickness, and the values shown in Table 2 refer to the averages calculated on 10 samples. In particular, the "average thickness" represents the thickness of the composite matrix alone, which may vary slightly depending on the application process and affect both the amount of matrix and the effectiveness of stress transfer. The differences between the two types of composites are mainly due to the different thickness (cross section) of the textiles used (e.g., see also Fig. 1and Fig. 2). Furthermore, to limit the influence of geometry on the analysis, the actual thickness of each sample was measured individually. Indeed, "textile area within the cross section" indicates the total area occupied by the fibers/textile in the cross section of the composite and allows the effective portion of tensile-resistant material to be quantified. The latter was evaluated by multiplying the area of the single yarn by the number of strands present in the coupon. Finally, "fiber volume ratio" expresses in percentage represents the ratio between the volume of the fibers and the overall total volume of the composite: this represents a relevant parameter for evaluating the reinforcement density and the mechanical contribution of the fibers with respect to the matrix.

The tensile tests were executed in displacement control with a loading rate of 0.20 mm/min (see also Fig. 5). Also in this case, the tensile tests were performed at 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. The tested samples were characterised by 100 mm tab length, 300 mm free length and, consequently, 400 mm of gauge length (considering, however, half the portion from the center of gravity of the tab) for a total sample length of 500 mm (see also Fig. 5).

3. Results and analysis

3.1. Mechanical and physical properties of the jute and flax textile

The key mechanical (tensile strength, ultimate strain and Elastic modulus) and physical (mesh density) properties obtained for the natural textiles under consideration are summarised in the following Table 3.

The mechanical response of the Natural TRM samples is shown graphically in Fig. 6, which displays the stress-strain diagrams of the Jute and Flax textile strips. As expected, the average tensile strength of

Fig. 3. Representative tensile test on natural textile: Jute.

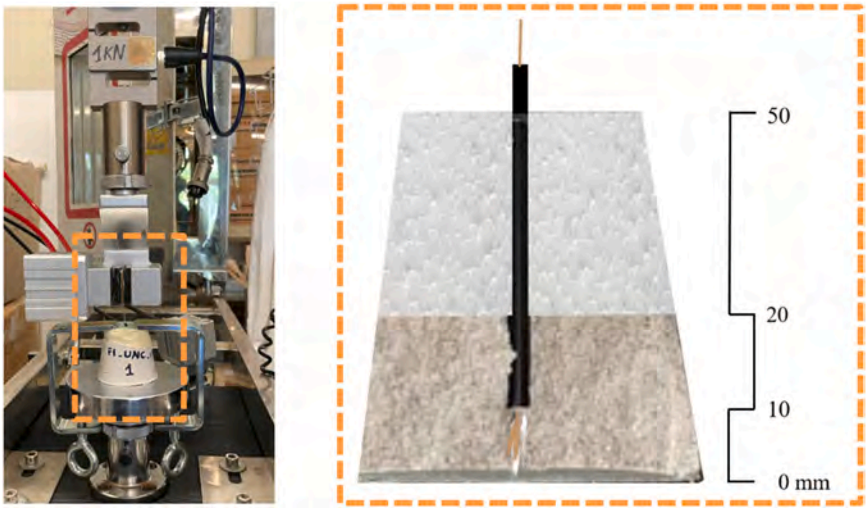


Fig. 4. Test setup for pull-out analysis on yarn-mortar system and definition of embedded length.

the textile strips (see Table 3) is lower than that of the individual yarns (see Table 1), with a reduction of approximately 15% for Jute and 30% for Flax. This result is consistent with the usual scale effect, since larger samples are more likely to have defects that precede failure, as well as with the non-uniform distribution of stresses between the different strands of the fabric. The curves shown in Fig. 6 have been reworked in accordance with the stiffness measured in the elastic range; therefore, they represent only the elastic behavior of the material, while the initial phase with higher deformability (which is insignificant and attributable to the tensioning of the fibers) is not included. The Flax textile reach higher tensile strength, while the Jute ones show a first part with an appreciably lower stiffness. The strips' high deformability at low level of deformation is associated to the geometric arrangement of the yarns. As a matter of fact, the textile is formed by yarns incorporating thread that are diffused variably within the cross-section. The yarns are not aligned with the tensile stresses, in fact, they always require a starting strain to be tensioned and lead adding their contribution to the axial stiffness. Furthermore, there is a various distribution of tensile stresses among the yarns (29 for Jute and 39 for Flax) because they are not subjected to the same tension, since they are not loaded to the same stress level.

Flax textiles presented a tensile strength slightly lower than 400 MPa while in the case of Jute, the textile strength is slightly higher than 100 MPa (Table 3). On the other hand, the strain at maximum load and the final displacement are quite comparable for both series of natural textiles (Table 3). Finally, the progressive rupture of the yarns leads to the breaking of the specimen. The failure, given by the breaking of the yarns taken place for each sample, is randomly diffused along the sample's free length. It is important to note that the axial stresses were assessed by taking into account their uniform distribution throughout the area of the specimen's section and, similarly, the axial strain was determined by dividing the average displacement of the sample by the free length of the sample. The stress–strain curves indicate a marked variability in the mechanical response of the natural textiles, which appears more pronounced for Jute textiles (Fig. 6).

As a matter of the fact, a coefficient of variation of the maximum load (an indicator of the variability of maximum load values among samples)

Fig. 5. Production, testing and schematic representation of the Natural TRMs.

Table 2

Geometrical properties of the produced Jute-TRM and Flax-TRM composites.

Parameter	Jute-TMR	Flax-TRM
Average thickness *[mm]*	9.50	8.60
(range of variation)	*(8.80–10.50)*	*(8.30–9.20)*
Textile area within the cross section *[mm^2]*	9.02	4.62
Reinforcement volumetric ratio *[%]*	1.90	1.07

Table 3

Mechanical and physical properties of Jute and Flax textiles.

Parameter	Jute textile	Flax textile
Average tensile strength (textile) - $\sigma_{max,textile}$ *[MPa]* *(range of variation)*	112.30 *(90.05–134.80)*	375.19 (329.30–397.60)
Average strain at maximum load (textile) - $\varepsilon_{max,textile}$ *[%]* *(range of variation)*	1.85 *(1.58–2.01)*	0.93 *(0.77–1.37)*
Average ultimate strain (textile) - ε_{final} *[%]* *(range of variation)*	1.76 *(1.54–2.16)*	1.13 *(0.98 – 1.32)*
Elastic modulus (textile) - **E** *[GPa]*	14	43
Mesh density *[g/m^2]*	320	125

is observed to be 14.70% for Jute and 7.28% for Flax samples. This aspect is related to the origins of these textiles, their production chain, and to their arrangement within the threads. In fact, it is a typical behaviour for all the natural textiles used in natural composite systems.

Finally, the elastic modulus was calculated (for each curve) as the slope of the elastic phase that best approximates the stress-strain curve in the elastic field, between the values of 40% and 60% of the tensile strength. The experimental results show that the Flax textile is significantly more rigid than the Jute one since the Flax elastic modulus is almost 4 times higher than Jute (Table 3).

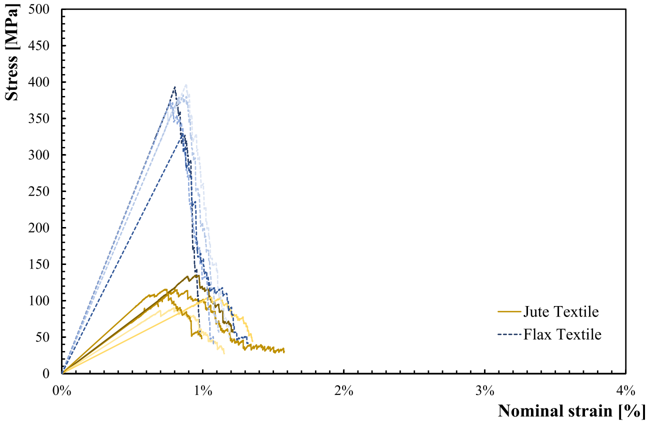


Fig. 6. Stress-strain curves for Jute and Flax textiles under tensile loads.

3.2. *Tensile response of the Natural TRM composites*

The following Fig. 7 schematically reports the typical stress-strain curve generally observed for TRM subjected to tensile loads, which is characterized by the three clearly identifiable stages described below:

Stage I: during the first part of the stress-strain curve the reaction is linear until the development of the first crack; the first crack corresponds to the reaching of a tensile stress equal to the mortar tensile strength. In this phase, the mortar is uncracked, and the behaviour of the composite system is similar to the behaviour of the mortar;

Stage II: the second phase of the chart is characterized by the development of various cracks. During this stage, the shape and

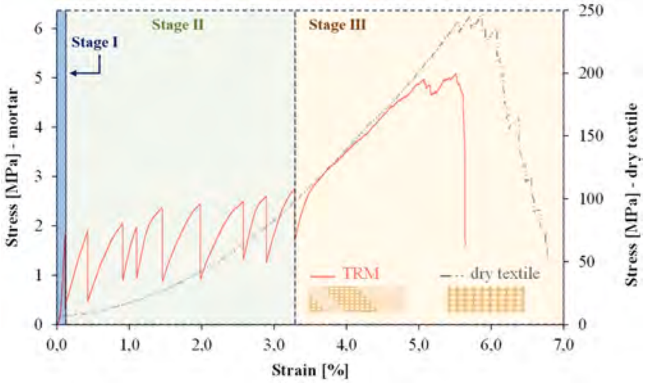
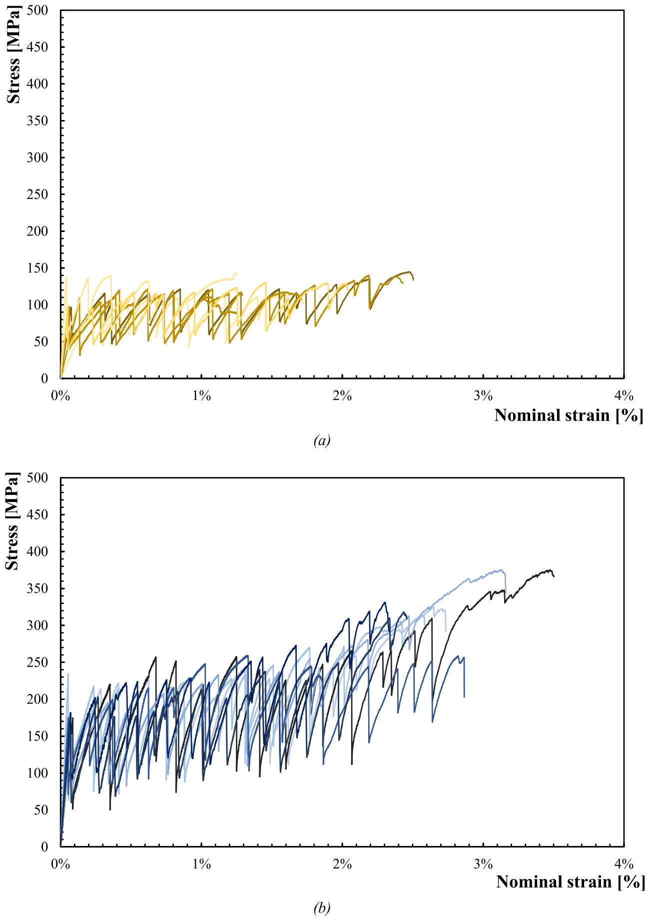


Fig. 7. Representative tensile response of TRM (adapted from [42]).

evolution of the curve are mainly affected by the matrix mechanical properties, the amount of textile reinforcement, the specimen geometry, and the boundary conditions acting during the test; this stage allows evaluating the efficiency of the TRM and inferring relevant statistics. In fact, it is possible to derive the number of cracks, the crack path, and some information like the crack spacing and the crack width.

Stage III: The last step starts when the last crack has appeared, and it is defined by an almost linear branch until the breaking: the textile governs the behaviour of the composite in the Stage III and the axial stiffness of the tends to the one of the reinforcing fabrics only.

Fig. 8 represents the textile stress-strain curves for each series of the Jute-TRM and Flax-TRM systems analysed herein. The graphs proposed in Fig. 8 highlights that the strain-hardening response in more evident in the case of *Flax-TRM* series (Fig. 8**b**) than in the case of *Jute-TRM* series (Fig. 8**a**). Aa a matter of principle, the tensile tests show a clear difference between the mechanical response of the two series of natural TRMs analysed herein.



(a)

(b)

Fig. 8. Stress-strain response under tensile loads for (a) Jute-TRM and (b) Flax-TRM composites.

In both cases, the first stage develops up to an average range of 0.4% - 0.5% of average axial strain with the first crack occurring at stress levels of about 2.00 MPa (average value ranging between 1.90 MPa and 2.10 MPa). As also well confirmed in the literature [43], the average value of the first crack strength (matrix side) is lower than the tensile (and flexural) strength of the mortar (measured in accordance with standard methods for mortar). This result can be attributed to the fabric embedded within the composite system that causes local concentration of tensions close the yarns.

Consequently, this discordance is evident in the comparison with the ideal uniaxial direct tensile conditions. Other relevant studies in the literature [44] point out that the resulting stress values at the transition point between stages I and II are always lower (between 15% and 60%) than the tensile strength of the mortar and, this variation is affected by the type and amount of reinforcement as well as to the geometrical properties of the whole composite.

Once the first crack occurs, the cracking stage starts and runs up to 2% of deformation in the case of *Jute-TRM* series (Figs. 8**a**) and up to 3% of deformation in the case of *Flax-TRM* series (Fig. 8**b**). The stress drops reported in the figures represent the crack formation. In the case of Jute textile, 6–13 cracks occurred while in the case of Flax textile the average number of registered cracks is slightly higher ranging between 10 and 16 (Fig. 9) as also reported in Table 4.

It is worth mentioning that during this stage, as expected, the stiffness of the stress-strain curves tends to decrease (drop-by-drop) up to reaching the textile stiffness measured in the tensile tests proposed in the previous subsection. Furthermore, in both cases, the exploitation ratio, defined as the ratio between the maximum TRM tensile stress and the tensile strength of the reference yarn (Table 4) reached significantly high values: around 98% in the case of *Jute-TRM* composites and 65% in the case of *Flax-TRM* composites. The higher exploitation ratio observed in *Jute-TRM* composites cannot be directly attributed to the reinforcement ratio (slightly below 2% for Jute and slightly above 1% for Flax) but rather to the smaller relative difference between the tensile strength of Jute yarns/textile and that of the mortar.

In comparison with other data available in the literature [26–31], the results obtained herein demonstrate that by optimizing the reinforcement ratio (higher than 1% in both Jute-TRM and Flax-TRM series) it is possible to achieve an efficient composite system with a significant numbers of cracks formation and, consequently, presenting high efficiency of the whole composite system.

3.3. Cracking pattern

Investigating the crack process development in the TRM during the tensile tests, both in terms of crack spacing and width, gives the possibility to have another relevant information on the possible application of *Jute/Flax-TRM* composite systems. Moreover, the analysis of crack pattern and its development is of interest also for evaluating the possible durability issue related to the application of this strengthening composite systems. As a matter of the fact, the crack spacing represents a key parameter for evaluating the efficiency of a TRM system, as it provides insights into its behavior as a bi-phase composite. More specifically, stress–strain curves exhibiting a stiffer behavior are typically associated with a shorter crack spacing, indicating the formation of a higher number of cracks. The crack spacing is plotted point by point, considering the average distance between two consecutive cracks corresponding to the strain at each crack. In this aim, Fig. 10 shows the evolution of the crack spacing for the two series under investigation. Both Fig. 10**a** (*Jute-TRM* series) and Fig. 10**b** (*Flax-TRM* series) demonstrate that in all cases a regular trend is registered. This is more

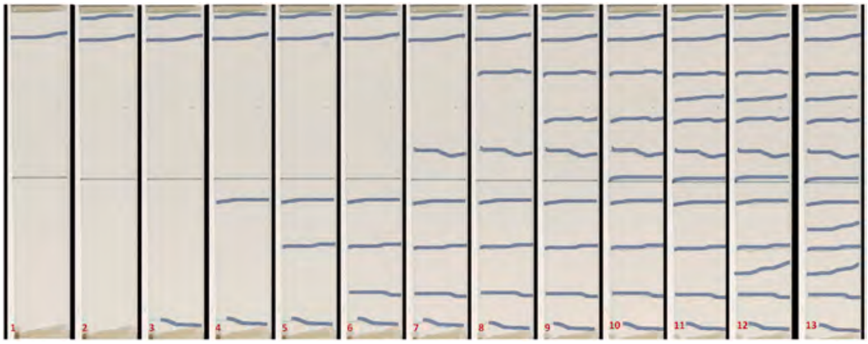


Fig. 9. Representative crack formation for TRM composites: Flax-TRM.

Table 4
Mechanical response of Jute-TRM and Flax-TRM composites.

Parameter	**Jute-TMR**	**Flax-TRM**
Average textile stress at maximum load - $\sigma_{\mathbf{max,TRM}}$ *[MPa]* *(range of variation)*	121.39 *(113.51–126.32)*	295.18 *(249.08–374.21)*
Exploitation ratio *[%]* *(range of variation)*	95 *(72–136)*	61 *(60–62)*
Minimum number of cracks - $\mathbf{n}_{\mathbf{crack,\ min}}$	6	10
Maximum number of cracks - $\mathbf{n}_{\mathbf{crack,\ max}}$	13	16
Average crack spacing at final stage *[mm]* *(range of variation)*	52.23 *(33.33–80.00)*	27.75 *(25.00 – 36.36)*

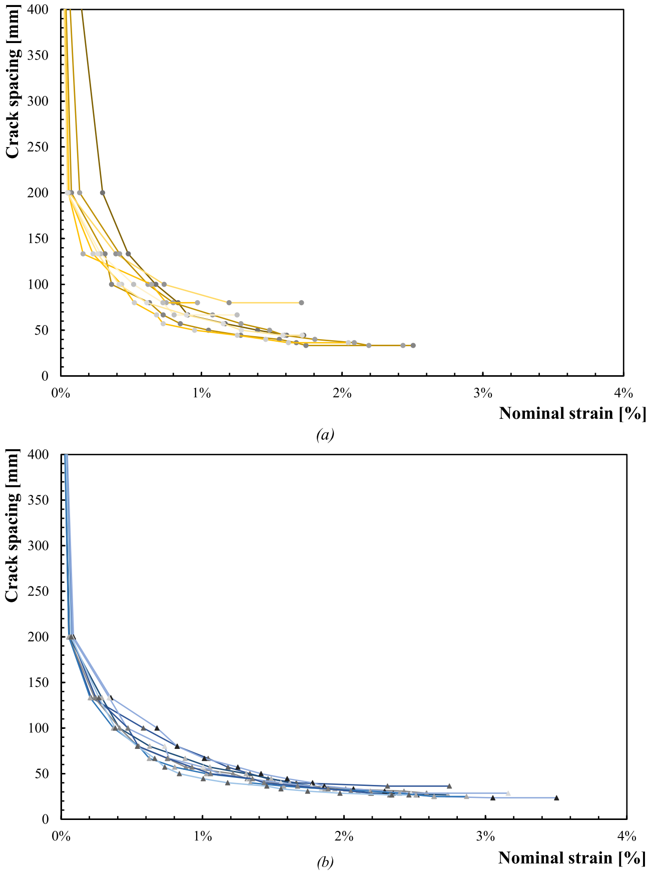


Fig. 10. Crack spacing charts for (a) Jute-TRM and (b) Flax-TRM composites.

apparent for the *Flax-TRM* series where all the samples reached an average final value below 30 mm (Table 4). On the other hand, the final values in the case of *Jute-TRM* series is higher than Flax and also the variability for the Jute samples is more marked: this can be attributed to the lower average number of cracks registered for this series (Table 4).

As a matter of fact, the Flax samples are characterized by the formation of more cracks. Both series show a clear stage-of-cracks in which diverse cracks come out. Furthermore, concerning the *Flax-TRM* group it is worth to mention that it presents a steeper trend characterised by closer crack spacing which is a direct consequence of a higher number of occurred cracks and a higher strain value. There aren’t significant differences in the slope of the two series of curves, and this means that the number of cracks, in the first phase, is similar. All these findings can be also attributed to the intrinsic properties of the employed yarns/textile. In fact, the Flax yarns are characterised by a significantly lower nominal diameter (0.068 mm^2) in comparison with the companion Jute samples (0.196 mm^2) as remarked in Table 1. In addition, the higher scatter registered in the case of Jute-TRM samples (for instance, see Fig. 10**a**) can be attributed to the more heterogeneous and irregular shape of the employed yarn characterising the Jute textile (for instance, see Fig. 2).

Furthermore, looking also at some durability-related issues of the strengthening system, the presence of crack openings represents a relevant aspect. It is worth to highlight that the average crack width (w_m) can be calculated, at each strain stage (ε), using the following formula:

$$w_m(\varepsilon) = \frac{\varepsilon - \varepsilon_{1crack}}{n_{cracks,\varepsilon}} \cdot L \quad [mm] \tag{1}$$

where:

- ε_{1crack} is the value of the strain at the appearance of the first crack, expressed in [%] (definition of Stage 1 as described in “Section 3.2”);
- L represents the longitudinal gauge portion of the TRM samples, expressed in [mm];
- $n_{cracks,\varepsilon}$ is the number of cracks observed on the gauge length at the determined strain ε.

In this equation it is assumed that the matrix exhausts its whole elastic deformation before the first crack occurs. During the following two stages, Stages 2 and 3 as described in “Section 3.2”, the strain is attributed only to the textile deformation. In this context, Fig. 11 proposes a comparison between the average crack width-strain curves for the natural TRMs under evaluation.

The average crack width of the Flax is lower than that exhibited by the Jute specimens for the same deformation level of the TRM composite. This can be associated with the higher nominal diameter of the Jute yarns (Table 1) although it leads to a significantly higher reinforcement ratio in the case of *Jute-TRM* series (Table 2). The graph proposed in Fig. 11 describes the first step into a logical pragmatic and realistic method for evaluating the feasibility of using natural TRM composites for the strengthening of masonry structure and retrofitting. As a matter of principle, the main parameter that can be controlled at the

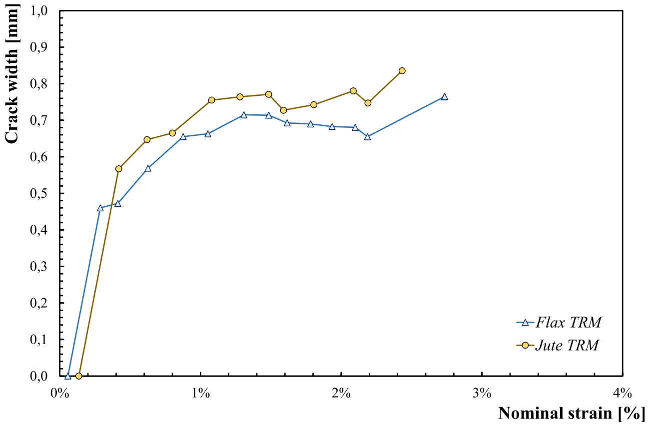


Fig. 11. Average crack width Jute-TRM and Flax-TRM composites.

design stage is the reinforcement ratio which can guarantee adequate mechanical performances while at the same time keeping under control the crack width that can be associated with the durability-related issue.

3.4. Pull-out: comparison of bond strength between direct and indirect method

One of the main mechanical parameters defining the response of TRM systems is the average value of the adhesion stress between the natural reinforcement and the lime-based matrix in which the yarns/textile are embedded.

In principle, this parameter can either be obtained from direct pull-out tests (i.e., *direct method*), or from the TRM tensile test results (i.e., *indirect method*), following the approach proposed in the literature by the authors of this study [32]. On the one hand, the “direct” evaluation of the average bond strength is based on pull-out tests and can be estimated as follows:

$$\tau_m = \frac{F_{\max,pull}}{l_{emb}\cdot p_{yarn}}\left[\frac{N}{mm^2}\right] \tag{2}$$

where:

- $F_{max,pull}$ is the maximum pull-out force applied to the yarn, expressed in [N];
- l_{emb} is the embedded length of the yarn in the matrix, in this case always equal to 10 mm;
- p_{yarn} is the perimeter of the yarn embedded in the matrix, equal to “$\pi \bullet D$” (where “D” is the nominal diameter of the yarn, expressed in [mm]).

On the other hand, the “indirect” determination of the average bond stress (τ_m) is based on assuming that the tensile strength developed at distance Δx from the crack is equal to the maximum tensile strength of the mortar matrix:

$$\tau_m = \frac{f_{t,matrix}\cdot A_{m.eq}}{\Delta x\cdot p_{textile}} \quad \left[\frac{N}{mm^2}\right] \tag{3}$$

where:

- $f_{t,matrix}$ is the matrix tensile strength (by assuming that $f_{f,matrix}=1.1\cdot f_{t,matrix}$), expressed in [N/mm^2]
- $A_{m,eq}$ is the equivalent transverse section area of the mortar, expressed in [mm^2];
- Δx is the half of the average crack spacing, expressed in [mm];
- $p_{textile}$ is equal to the product between the perimeter of the single yarn and the number of yarns contained in the specimen cross-section: 46 and 64 for *Jute-TRM* and *Flax-TRM*, respectively (assuming the single natural yarn presents a circular cross section, the single yarn perimeter is evaluated from the average cross section reported in Table 1), expressed in [mm].

It is worth highlighting that in these calculations the equivalent area of the mortar transverse section $A_{m.eq}$ is determined by considering by subtracting the textile volume from the gross TRM volume:

$$A_{m.eq} = \frac{V_{TRM} - V_{textile}}{L_{TRM}} \quad [mm^2] \tag{4}$$

where:

- V_{TRM} is the gross volume of the sample, expressed in [mm^3]*;*
- $V_{textile}$ is the volume of the fabric, expressed in [mm^3]*;*
- L_{TRM} is the gauge length, in this case equal to 400 [mm].

As explained in a previous study [32] the value of *Δx* can be assumed as the half of the average space between two consecutive cracks, which was calculated during the analysis of data collected during the experimental campaign (Table 4) at the final stage of the test.

All the obtained values related to the bond strength evaluation in accordance with Eqs. 2 and 4 are plotted in Fig. 12. The bar charts in Fig. 12 clearly show that the main bond strength of Flax textile is significantly higher than Jute and this can be associated with the lower nominal diameter and greater stiffness of the Flax yarns. In addition, being the Flax yarn nominal diameter lower than Jute (Table 1), it is also possible that the assumption of the circular cross section is less consistent for the Flax yarns and, consequently, the theoretical perimeter of the yarns evaluated in this section is underestimated, leading to an overestimation of the resulting bond strength. The very interesting and relevant result is that the values obtained with the two different methods are very similar; in fact, for Flax, almost the same value was recorded. The analytical model, although simplified, assumes that cracking occurs when the maximum bond stress is reached uniformly across the entire interface surface. Despite this idealized assumption, the model accurately describes the behavior of the composite, in good agreement with experimental results.

The average bond strength values reported in Fig. 12 also further clarify and explain the results summarised in the previous section. As a matter of principle, as also well stated in the literature [26] this parameter play a fundamental role in defining the resulting mechanical response of the TRM system under tensile loads and, consequently, leading to have a higher number of cracks and lower cracks width as also highlighted in Fig. 8 and Fig. 11.

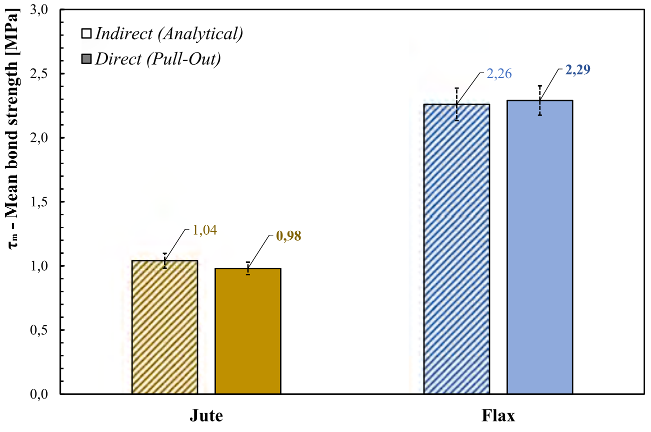


Fig. 12. Estimation of main bond strength for Jute-TRM and Flax-TRM composites.

4. Conclusions

The present study summarized the results of an experimental campaign aimed at investigating the mechanical response and the efficiency of two different series of natural TRMs internally reinforced with Jute and Flax textiles. The following main aspects can be remarked:

- the two types of natural textile reinforcement analysed herein present relevant different properties in terms of physical/geometric characteristics and mechanical performances; in fact, the Flax textile is characterized by single yarns presenting lower nominal diameter, higher tensile strength and higher elastic modulus in comparison with the Jute ones;
- the high (above 1%) reinforcement ratio for both analysed TRM systems demonstrates the composite behaviour of the improved samples tested under tensile loads: as a matter of the fact, in both cases a significant number of cracks was observed, which is the result of an effective bond interaction between the two composite phases;
- the exploitation ratio was quite high in both analysed cases and almost close to 100% in the case of Jute-TRM composites: this can be mainly attributed to higher reinforcement ratio (almost 2%) characterizing the TRMs containing the Jute fabrics;
- an higher number of cracks was registered on average in the case of *Jute-TRM* systems, and, consequently also the average crack width was slightly lower in Flax-TRM systems;
- the average bond strength established between the matrix and the reinforcement, for both types of fibers, was determined both through direct and indirect methods by exploiting the results of pull-out and tensile tests, respectively: the two methods led to highly consistent results for both the Flax- and the Jute-reinforced TRM systems considered in the present study;
- it is worth highlighting that the bond strength of Flax textiles was significantly higher than Jute ones and this can be associated with the lower nominal diameter of the Flax yarns; moreover, thanks to its more compact structure, the Flax textiles developed more higher and more stable adhesion values.

As future step of the present research and with the aim to promote some possible practical applications, it is relevant to highlight that further studies are under development to investigate relevant open issues such as: durability and long terms performance of the natural textiles embedded in inorganic matrix (e.g., applying some possible coating/impregnation techniques); numerical simulation of the tensile response of the natural TRM subjected to tensile loads, and experimental/theoretical study masonry elements externally strengthened by natural TRM also in comparison with traditional techniques already adopted in the current practice.

CRediT authorship contribution statement

Eduardo Sellitto: Writing – original draft, Visualization, Investigation. **Bruno Paolillo:** Methodology, Investigation, Data curation. **Marco Pepe:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization. **Stefano Agnetti:** Visualization, Validation. **Flavio Stochino:** Validation, Conceptualization. **Rosario Lombardi:** Methodology, Investigation, Data curation. **Giuseppe Ferrara:** Writing – review & editing, Supervision, Methodology. **Enzo Martinelli:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported in part by the Italian Minister of University and Research as part of the “**MaStRoNG**: *Masonry Structures retrofitting through Robotized sustainable Next-Generation composites*” project (FISA-2023–00029 - CUP: D47G2300036000).

Human and animal rights

This article does not include any studies of human participants performed by the authors.

Data availability

Data will be made available on request.

References

[1] M.R. Valluzzi, L. Sbrogio, Y. Saretta, H. Wenliuhan, Seismic response of masonry buildings in historical centres Struck by the 2016 central Italy earthquake. Impact of building features on damage evaluation, Int. J. Archit. Herit. 16 (12) (2022) 1859–1884, https://doi.org/10.1080/15583058.2021.1916852.
[2] S. Szabó, M.F. Funari, P.B. Lourenço, Masonry patterns' influence on the damage assessment of URM walls: Current and future trends, Dev. Built Environ. 13 (2023) 100119, https://doi.org/10.1016/j.dibe.2023.100119.
[3] B. Bagheri, J.H. Lee, H.G. Kim, S.H. Oh, Experimental evaluation of the seismic performance of retrofitted masonry walls, Compos. Struct. 240 (2020) 111997, https://doi.org/10.1016/j.compstruct.2020.111997.
[4] J. Huang, X. Yang, K. Wu, G. Chen, X. Liu, Z. Zhang, Non-destructive solutions for the strengthening of stone beams with CFRP and high-strength steel strand FRCM systems: Experimental and analytical investigation, Structures 81 (2025) 10168, https://doi.org/10.1016/j.istruc.2025.110168.
[5] P. Zampieri, D. Santinon, L. Niero, C. Pellegrino, J. Gonzalez-Libreros, G. Sas, Effect of the spike anchors on the failure mode of a FRCM system applied to a curved masonry substrate, Structures 79 (2025) 109522, https://doi.org/10.1016/j.istruc.2025.109522.
[6] J.K. Bhaskar, D. Bhunia, L. Koutas, In-plane behaviour of masonry infill walls with openings strengthened using textile reinforced mortar, Structures 63 (2024) 106439, https://doi.org/10.1016/j.istruc.2024.106439.
[7] N. Azimi, A. Dalalbashi, D.V. Oliveira, B. Ghiassi, P.B. Lourenço, Tensile behavior of textile-reinforced mortar: Influence of test setup and layer arrangement, Constr. Build. Mater. 394 (2023) 132185, https://doi.org/10.1016/j.conbuildmat.2023.132185.
[8] M. Corradi, S. Agnetti, C. Quintaliani, E. Speranzini, Experimental investigation on a FRCM bio-composite for sustainable retrofitting of masonry buildings, Compos. Struct. 329 (2024) 117753, https://doi.org/10.1016/j.compstruct.2023.117753.
[9] G. Ferrara, C. Caggegi, E. Martinelli, A. Gabor, Shear capacity of masonry walls externally strengthened using Flax-TRM composite systems: Experimental tests and comparative assessment, Constr. Build. Mater. 261 (2020) 120490, https://doi.org/10.1016/j.conbuildmat.2020.120490.
[10] L. Chen, Z. Chen, Z. Xie, L. Wei, J. Hua, L. Huang, P.S. Yap, Recent developments on natural fiber concrete: A review of properties, sustainability, applications, barriers, and opportunities, Dev. Built Environ. 16 (2023) 100255, https://doi.org/10.1016/j.dibe.2023.100255.
[11] M. Abdullah, S. Saha, K. Ahmed, M.R. Sarkar, M.N. Chowdhuri, Characterization of Epoxy-Based Natural Fiber Biocomposites Reinforced Using Coconut Coir and Sugarcane Fibers, Prog. Eng. Sci. (2025) 100192, https://doi.org/10.1016/j.pes.2025.100192.
[12] F. Stochino, A. Majumder, A. Frattolillo, M. Valdes, E. Martinelli, Jute fiber reinforcement for masonry walls: Integrating structural strength and thermal insulation in sustainable upgrades, J. Build. Eng. 104 (2025) 112210, https://doi.org/10.1016/j.jobe.2025.112210.
[13] L. Mercedes, E. Bernat-Maso, L. Gil, Numerical simulation of masonry walls strengthened with vegetal fabric reinforced cementitious matrix (FRCM) composites and subjected to cyclic loads, Structures 35 (2022) 1232–1242, https://doi.org/10.1016/j.istruc.2021.09.010.
[14] R. Illampas, D.V. Oliveira, P.B. Lourenço, Design of Strain-Hardening Natural TRM Composites: Current Challenges and Future Research Paths, Materials 16 (2023) 4558, https://doi.org/10.3390/ma16134558.
[15] P.D. Gkournelos, L.D. Azdejković, T.C. Triantafillou, Innovative and eco-friendly solutions for the seismic retrofitting of natural stone masonry walls with textile reinforced mortar: In-and out-of-plane behavior, J. Compos. Constr. 26 (1) (2022) 04021061, https://doi.org/10.1061/(ASCE)CC.1943-5614.0001173.
[16] P. Sadrolodabaee, J. Claramunt, M. Ardanuy, A. de la Fuente, Effect of accelerated aging and silica fume addition on the mechanical and microstructural properties of hybrid textile waste-flax fabric-reinforced cement composites, Cem. Concr. Compos. 135 (2023) 104829, https://doi.org/10.1016/j.cemconcomp.2022.104829.
[17] A. Karimah, M.R. Ridho, S.S. Munawar, D.S. Adi, R. Damayanti, B. Subiyanto, A. Fudholi, A review on natural fibers for development of eco-friendly bio-

composite: characteristics, and utilizations, J. Mater. Res. Technol. 13 (2021) 2442–2458, https://doi.org/10.1016/j.jmrt.2021.06.014.
[18] P.W.M. Huisken, S.B.T. Youbi, I.L.T. Ngassam, G. Tchemou, L. Courard, E. Njeugna, Effect of oil palm mesocarp fibers on the fresh and hardened states of cementitious mortars, Prog. Eng. Sci. (2025) 100125, https://doi.org/10.1016/j.pes.2025.100125.
[19] B. Zukowski, E.R.F. dos Santos, Y.G. dos Santos Mendonça, F. de Andrade Silva, R. D. Toledo Filho, The durability of SHCC with alkali treated curaua fiber exposed to natural weathering, Cem. Concr. Compos. 94 (2018) 116–125, https://doi.org/10.1016/j.cemconcomp.2018.09.002.
[20] R. Bardouh, O. Homoro, N. Reboul, M. Saidi, S. Amziane, Enhancing bio-based concrete mechanical properties: a novel approach with composite sandwiches and confined cylinders, Mater. Struct. 57 (6) (2024) 139, https://doi.org/10.1617/s11527-024-02400-3.
[21] K. Junaid, M. Zyed, A. Nonna, C. Gaochuang, S.L. Amir, Tensile and cracking behaviour of crimped textile reinforced mortar (TRM) based on digital image correlation, Constr. Build. Mater. 417 (2024) 135321, https://doi.org/10.1016/j.conbuildmat.2024.135321.
[22] L. Mercedes, L. Gil, E. Bernat-Maso, Mechanical performance of vegetal fabric reinforced cementitious matrix (FRCM) composites, Constr. Build. Mater. 175 (2018) 161–173, https://doi.org/10.1016/j.conbuildmat.2018.04.171.
[23] M. Pepe, R. Lombardi, G. Ferrara, S. Agnetti, E. Martinelli, Experimental Characterisation of Lime-Based Textile-Reinforced Mortar Systems Made of Either Jute or Flax Fabrics, Materials 16 (2023) 709, https://doi.org/10.3390/ma16020709.
[24] G. Ferrara, From Material Identification to Structural Behavior, in: Flax-TRM Composite Systems for Strengthening of Masonry, Springer Nature, 2021, https://doi.org/10.1007/978-3-030-70273-1.
[25] S.R. Ferreira, M. Pepe, E. Martinelli, F. de Andrade Silva, R.D. Toledo Filho, Influence of natural fibers characteristics on the interface mechanics with cement based matrices, Composites Part B Engineering 140 (2018) 183–196, https://doi.org/10.1016/j.compositesb.2017.12.016.
[26] O.G. Agossou, O. Homoro, S. Amziane, A review of the applications of natural FRCM composites, J. Compos. Mater. 59 (15) (2025) 1881–1915, https://doi.org/10.1177/00219983251318829.
[27] A. Hyseni, C. Caggegi, N. Reboul, F. Micelli, Diagonal shear behaviour of limestone masonry walls strengthened with jute-TRM composite systems, Constr. Build. Mater. 470 (2025) 140572, https://doi.org/10.1016/j.conbuildmat.2025.140572.
[28] O.G. Agossou, O. Homoro, S. Amziane, Evaluation of mechanical behaviour of vegetal FRCM composites through the DIC technique: Effects of textile pre-impregnation and short flax fibres, Constr. Build. Mater. 449 (2024) 138416, https://doi.org/10.1016/j.conbuildmat.2024.138416.
[29] L. Kohan, C.A. Fioroni, A.G. Azevedo, B. Leonardi, J. Baruque-Ramos, R. Fangueiro, H.S. Junior, Jute textiles with enhanced interfacial bonding as reinforcement for cementitious composites, J. Compos. Mater. 58 (16) (2024) 1847–1862, https://doi.org/10.1177/00219983241249237.
[30] A. Monaco, M. Baldassari, J. D'Anna, P. Cornetti, Effectiveness of Flax-TRM composites under traction, Procedia Struct. Integr. 44 (2023) 2278–2285, https://doi.org/10.1016/j.prostr.2023.01.291.
[31] N. Trochoutsou, M. Di Benedetti, K. Pilakoutas, M. Guadagnini, Mechanical characterisation of flax and jute textile-reinforced mortars, Constr. Build. Mater. 271 (2021) 121564, https://doi.org/10.1016/j.conbuildmat.2020.121564.
[32] G. Ferrara, M. Pepe, E. Martinelli, R.D. Toledo Filho, Tensile behavior of flax textile rein-forced lime-mortar: Influence of reinforcement amount and textile impregnation, Cem. Concr. Compos. 119 (2021) 103984, https://doi.org/10.1016/j.cemconcomp.2021.103984.
[33] British Standard BS ISO 3341:2000, Textile Glass—Yarns—Determination of Breaking Force and Breaking Elongation, British Standard: London, UK, 2000, p. 7.
[34] British Standard, 2009, BS EN ISO 1889: - Reinforcement yarns - Determination of linear density2009.
[35] ASTM, 2020, ASTM D8171-18 - Standard Test Methods for Density Determination of Flax Fiberi18.
[36] Sartorius Y.D.K. 01, YDK 01-0D, YDK 01LP - Density Determination Kit User's Manual."
[37] B. Paolillo, M. Pepe, E. Koenders, E. Martinelli, Morphological analysis and physical characterization on bio-coated natural fibre for structural applications: a preliminary study (fib). FIB SYMPOSIUM PROCEEDINGS, The International Federation for Structural Concrete, 2025, pp. 177–184.
[38] Consiglio Superiore dei Lavori Pubblici - Servizio Tecnico Centrale (2018). Linee Guida per la identificazione, la qualificazione ed il controllo di accettazione di compositi fibrorinforzati a matrice inorganica (FRCM) da utilizzarsi per il consolidamento strutturale di costruzioni esistenti (in italian).
[39] Limepor E.D.O. Technical datasheet available at the following lik: ⟨https://www.kimia.it/en/hydraulic-pozzolanic-limes/limepor-edo⟩. Accessed on 27.03.2026.
[40] EN 1015-11:2019. Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar.
[41] RILEM Technical Committee 232-TDT, Recommendation of RILEM TC 232-TDT: test methods and design of textile reinforced concrete, Mater. Struct. 49 (2016) 4923–4927, https://doi.org/10.1617/s11527-016-0839-z.
[42] G. Ferrara, Mechanical Behaviour and Durability of Flax TRMs: Tensile and Shear Bond Tests. Flax-TRM Composite Systems for Strengthening of Masonry, Springer Theses. Springer, Cham, 2021, https://doi.org/10.1007/978-3-030-70273-1_4.
[43] S. De Santis, F.G. Carozzi, G. de Felice, C. Poggi, Test methods for textile reinforced mortar systems, Composites Part B Engineering 127 (2017) 121–132, https://doi.org/10.1016/j.compositesb.2017.03.016.
[44] S. De Santis, G. De Felice, Tensile behaviour of mortar-based composites for externally bonded reinforcement systems, Composites Part B Engineering 68 (2015) 401–413, https://doi.org/10.1016/j.compositesb.2014.09.011.