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Effectiveness of Flax-TRM composites under traction

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Abstract

The scientific research in the field of masonry structures is increasingly welcoming the adoption of innovative and sustainable rehabilitation techniques aimed at the safeguarding of the Built Cultural Heritage. Textile Reinforced Matrix (TRM) composites are the most widely investigated strengthening systems for ancient masonry structures, thanks to their high compatibility level with the material substrates in terms of fire resistance, chemical/physical aspects, reversibility property, little impact on dimensions, stiffness and weight. Nevertheless, in the last years, the growing concern on sustainability increased the interest in products with low environmental impact, for promoting circular economy approaches in the design of the structural interventions. In particular, efforts have been done to replace the most common composites with materials less harmful to the environment, such as natural fibres, for developing compatible and sustainable rehabilitation techniques for masonry structures. This paper presents the preliminary results of experimental tests conducted by the authors on specimens of TRM composites made with natural, vegetable, flax-fibre grids and natural hydraulic lime mortar. The mechanical characterization tests aimed at detecting the tensile behaviour of the natural TRM system compared to the results available in the literature on different vegetable-fibre composites and TRMs made with natural basalt fibres. The experimental tests highlighted the promising mechanical effectiveness of natural TRM systems under traction and offered a hint to further research aimed at improving their mechanical strength and stiffness.

Keywords: TRM; FRCM; Inorganic Matrix Composites; natural fibres; vegetable fibres; basalt fibres; tensile behaviour; experimental testing.

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1. Introduction

Textile Reinforced Mortar (TRM) systems are a class of composite materials adopted for decades for rehabilitation of existing constructions, with particular regard to ancient masonry buildings. As a matter of fact, TRMs can be made with cement- or lime-based inorganic mortar matrix, and the most commonly adopted materials for reinforcing layers are generally steel, glass, PBO and basalt made in the form of grids with mesh size great enough to let the fibre-mortar bond interaction properly develop. These systems are the most widely investigated strengthening systems for ancient masonry structures, thanks to their high compatibility level with material substrates in terms of fire resistance, chemical/physical aspects, reversibility property, little impact on dimensions, stiffness and weight. Numerous studies are currently available in technical literature concerning the mechanical characterisation of the tensile behaviour of classical TRMs from both experimental and numerical standpoint [among others, RILEM TC 232 2016, De Santis et al. 2017, Leone et al. 2017, Monaco et al. 2019, ACI 549 2020, Monaco et al. 2020, D'Anna et al. 2021]. However, in last years, the growing concern on sustainability increased the interest towards products with low environmental impact, for promoting circular economy approaches in the design of structural interventions. In particular, efforts have been done to replace most common composites with materials less harmful to the environment, as natural fibres, for developing compatible and sustainable rehabilitation techniques for masonry structures. Some emerging studies are available today on these innovative sustainable composite materials made with vegetable fibres; in particular, the results that will be considered in this paper are those obtained by Codispoti et al. (2015), Ferrara et al. (2021) and Trochoutsou et al. (2021). All these studies are developed by means of experimental tests: Codispoti et al. (2015) tested the effectiveness of several vegetable fibres such as jute, sisal, flax and hemp in combination with organic and inorganic matrices; Ferrara et al. (2021) focused the experimental tests on the characterisation of TRMs with impregnated and non-impregnated flax fibres while Trochoutsou et al. (2021) tested Flax- and Jute-TRM systems with different number of reinforcing layers, from one to three. In this paper, the abovementioned results are compared with some preliminary results obtained by authors on specimens of Flax-TRM composite made with inorganic lime-based mortar matrix and one reinforcing layers. Tests were aimed at both the characterisation of composite system and its constituent materials separately: in fact, mechanical characterisation of mortar has been conducted as well as uniaxial tensile tests on bare flax-fibre meshes. The experimental tests available in the literature and preliminary results obtained by the authors are useful to increase current knowledge on this topic and highlight the promising mechanical effectiveness of natural TRM systems under traction. Results are also compared with mechanical performance of natural TRM systems of mineral origin, such as basalt-TRM: the comparison offered hints to further research aimed at improving mechanical strength and stiffness by optimization of main geometrical and material parameters such as mesh size and density. Reference experimental tests on vegetable and mineral fibres will be presented in Section 2; Section 3 will collect experimental results obtained by authors on Flax-TRM systems; comparison between the mechanical performance of vegetable- vs. basalt-TRMs will be proposed in Section 4; finally, some concluding remarks and open issues will be synthetized in Section 5.

2. Tensile characterisation of natural TRM in the literature

Natural TRM systems made with both vegetable and mineral fibres will be considered in this study for comparison with the results obtained by the authors, the latter widely described in the following section.

For an overall view, the key aspects of the considered experimental works are summarized in Table 1. Information related to specimens and main results (average values of tensile strength and strain) are provided for each study.

More in detail, concerning vegetable fibres, TRM coupons made with flax, hemp and jute are taken into account. In this regard, Codispoti et al. (2015) presented an experimental investigation on the mechanical properties of different natural fibres, namely flax, hemp, sisal and coir fibres. Bare textiles were tested and the fibres with better performance were studied together with three different matrices, two organic and one inorganic, to produce three typologies of composites. Mechanical characterization tests were carried out on both matrix and fibre materials. Different production methods were considered to cast the composites, and their mechanical performance was analysed in detail. Results showed that natural fibre-based composite materials present a wide variety of mechanical properties. In general, a good bond between natural materials and matrices was observed. Outcomes showed clearly that epoxy resin can guarantee good tensile performance of the composite system. Regarding fabrics impregnated with mortar, authors suggested further studies, in particular with reference to mortar thickness and water ratio to be applied.

More recently, Ferrara et al. (2021) studied the mechanical performance of a TRM system produced with flax textile embedded within a hydraulic lime-based mortar. The research was aimed to investigate the TRM efficiency considering the influence of volume fraction and textile impregnation of fibres. The impact of these two variables was investigated with reference to tensile response and cracking patterns shown by the TRM composites. The tensile behaviour of bare flax textile, impregnated and non, was also investigated. The outcomes pointed out that coating can improve the tensile performance of the grid, with a reduction of deformability. Referring to the composite, higher reinforcement ratio increased the tensile response. Indeed, when untreated grid was used, failure mode changed from textile slipping to textile rupture. Additionally, increasing the reinforcement amount, the number of cracks increased, with a consequent crack width reduction. Moreover, grid impregnation guaranteed a significant optimization of the composite performance, with a reduced crack spacing and crack width at fixed reinforcement ratio. The estimation of the average bond strength of the composite confirmed the beneficial effect of textile impregnation. It should be noted that, despite benefits, coating strategy caused a certain variability in the test results, hence the authors pointed out the importance of a standardized impregnation procedure, in order to obtain reliable results.

Trochoutsou et al. (2021) investigated the tensile response of flax and jute lime-based composites. The mechanical contribution of the composite constituent materials was investigated following a multi-scale experimental approach. Influence of textile geometry, number of reinforcement layers (from one to three) and mortar overlay thickness (3 and 5 mm), were analysed in detail. Bare fibres and mortar matrix were also fully characterised. Outcomes underlined that all fibres showed mechanical properties suitable for structural applications. Generally, Flax-TRM composites presented a more ductile behaviour and the highest strength and ultimate strain. Results confirmed that textile geometry and reinforcement amount considerably affect the composite performance, ensuring multiple cracks formation, in the denser fibre, and a more uniform stress distribution. Moreover, higher number of reinforcement layers led to higher load capacity and more ductile behaviour; however, the strength and the ultimate strain did not increase significantly. Regarding Jute-TRM, the weak fibre-matrix interaction did not guarantee a good performance of the composite. Finally, thicker mortar overlays did not necessary improve the mechanical response of the composite and could be detrimental in case of low mechanical reinforcement ratios.

Concerning natural mineral fibres, TRM coupons tested by D'Anna et al. (2021) are considered for comparison. The authors performed an experimental study for the tensile characterization of basalt TRM composite. Tensile tests were carried out on coupons reinforced with one, two and three layers. Fibres and mortar matrix were also tested to relate the mechanical properties of constituent materials to the composite response.

Table 1. Geometrical and mechanical characteristics of composite specimens from literature.

Authors	Specimen label	N° of specimens	Geometry [mm]	Matrix	Textile	N° of reinforcing layers	Tensile strength [MPa]	Tensile strain [%]
Codispoti et al. (2015)	Jute1	5	300x50x5	Cement-free mortar made with pozzolana lime	Jute	1	25.9	5
	Jute3	5			Jute	1	35.6	10.38
	Hemp	5			Hemp	1	33.1	3.84
	Flax	5			Flax	1	57.2	7.41
Ferrara et al. (2021)	TRM-1L	5	500x60x7.9	Hydraulic lime-based mortar	Flax	1	120	3.1
	TRM-1L-imp	5	500x60x6.3		Flax	1	179	4.8
	TRM-2L	5	500x60x8.8		Flax	2	196	6.3
	TRM-2L-imp	5	500x60x8.1		Flax	2	120	5.1
Trochoutsou et al. (2021)	F1L1-3	6	600x50x6	Natural hydraulic lime-based mortar	Flax	1	82.2	4.1
	F1L1-5	3	600x50x10		Flax	1	57.6	3.4
	F1L2-3	6	600x50x9		Flax	2	83.0	4.4
	F1L3-3	6	600x50x12		Flax	3	89.3	4.7
	F2L1-3	6	600x50x6		Flax	1	177.8	7.3
	F2L1-5	3	600x50x10		Flax	1	223.4	8.3
	F2L2-3	6	600x50x9		Flax	2	208.9	7.9
	F2L3-3	6	600x50x12		Flax	3	205.0	7.5
	JL1-3	6	600x50x6		Jute	1	62.7	0.8
	JL2-3	6	600x50x9		Jute	2	64.6	0.8
	JL3-3	6	600x50x12		Jute	3	74.0	1.2
D'Anna et al. (2021)	SP_1L	8	400x40x8	Cement-based mortar	Basalt	1	1467.28	2.32
	SP_2L	5			Basalt	2	1263.64	1.91
	SP_3L	1			Basalt	3	1103.14	1.47

The main results showed that the tensile strength of the coupons decreased with the increase of the number of reinforcing layers; indeed, maximum average strength was reached by the series with the lowest reinforcement ratio. Average peak stresses and stiffness of all samples, in last stage of tensile curves, were found to be lower compared to dry basalt textile. The crack pattern analysis showed that the higher the number of layers, the higher the number of cracks, which were closer together. Moreover, the crack opening during the tests was found to be influenced by the reinforcement ratio, with tighter cracks in case of over-reinforced specimens.

3. Preliminary experimental tests on Flax-TRM coupons

Some preliminary tests were conducted at the Laboratory of Materials and Structures of Politecnico di Torino. In particular, Flax-TRM coupons with one reinforcing layer were made and tested under uniaxial traction. The mechanical characterization of the mortar was also performed and tensile tests on bare fibre meshes were conducted. Tensile characterisation of both TRM coupons and flax fibre meshes was developed with the support of the Digital Image Correlation (DIC) for the assessment of the strain values.

3.1. Mechanical characterization tests of mortar specimens

TRM composites were manufactured using a natural hydraulic lime-based mortar NHL5 specifically designed for structural reinforcement, commercialized by the Italian company BIEMME SRL (Lucrezia di Cartoceto, Pesaro-Urbino, Italy) and labelled BM IDRO FRCM - M15, with a maximum aggregate size smaller than 2 mm. Flexural and compressive strengths were experimentally found by three-point bending tests on 12 prisms, followed by compression tests on the resulting halves (24 specimens). The average values of flexural and compressive strength at 28 days were found to be 2.65 MPa (17 % CoV) and 16.7 MPa (3% CoV), respectively. Compressive and flexural strength curves are shown in Fig.1 together with pictures of the specimens during the casting and testing phases.

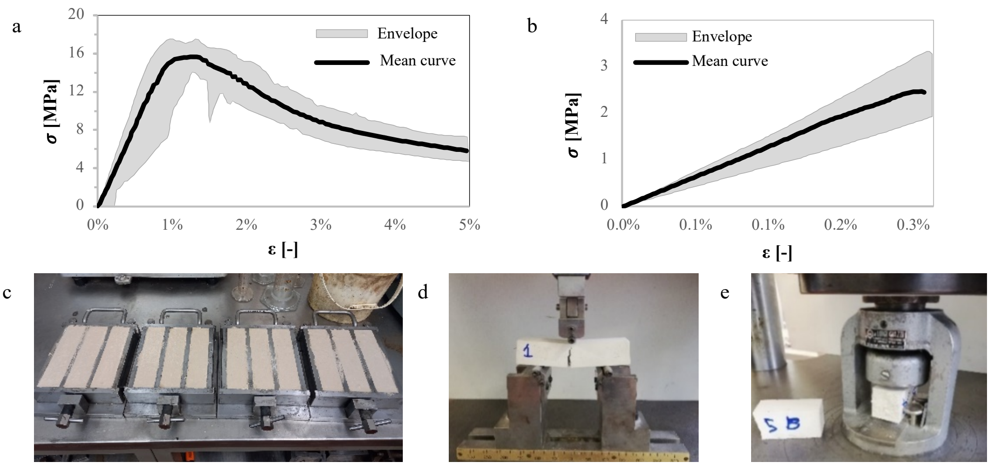

Fig. 1. Mechanical characterization of mortar specimens: (a) stress-strain curve of the compressive behaviour; (b) stress-strain curve of the flexural behaviour; (c) casting phase; (d) three-point bending test; (e) uniaxial compression test.

3.2. Tensile tests on flax fabrics

The textile used for reinforcement is made by flax fibres, with a mesh grid of approximately 3.5 mm, specifically designed on request (Fig. 2a). Tensile properties were determined by executing tensile tests on 5 textile strips of 45 mm width and 310 mm height, each strip containing 12 flax yarns, with a free gauge length of 150 mm. Aluminium tabs of length 80 mm were glued to the extremities of the specimens to generate a good gripping area. The sample geometry and the test set-up are represented in Fig. 2b. Tests were carried out in a 50 kN universal testing machine, under displacement control with test speed equal to 0.5 mm/min, according to RILEM TC 232-TDT recommendations

(RILEM TC 232 2016). Displacements were acquired using the DIC, by creating a contrast between the front lit fibres and a black background ad-hoc prepared. Then, the software program Ncorr (Blaber et al. 2015) was used for the post-processing of the images, which were acquired with a Canon D3500 digital camera, with a resolution of 12 pixel per mm. Displacements were measured generating virtual extensometers on the surface, composed by two square facets with a gauge length equal to 150 mm. No local transducers were used for the displacement measurement, except for the LVDTs integrated in the testing machine. In this regard it is noteworthy to mention that the accuracy achievable with this instrumentation, i.e. integrated LVDTs and DIC set-up, is highly reliable with data acquisition obtained with further measurement methods such as extensometers, sensors and strain gauges applied to the specimens (Tekieli et al. 2017). Stresses were evaluated dividing the forces by the nominal area of the fibres. In this preliminary phase, the transversal area of the fibres was estimated by measuring the yarn thickness taken with a calliper with precision 0.01mm; then, the area of the single yarn was multiplied by the number of the yarns contained in the specimen, i.e. 12 yarns per sample grid. Therefore, the assessed transversal area of each textile strip is equal to 3.7 mm^2. It is known that a more accurate assessment of the transversal area of the fibre is achievable by determining the physical properties of the textile, such as the density and the equivalent thickness. Hence, physical characterisation of the flax mesh will be the object of further studies already planned by the authors.

Fig. 2c shows the experimental outcomes in terms of stress-strain response: the test results exhibited good consistency, providing average values of maximum strength and elastic modulus of 55 MPa (7.3% CoV) and 2890 MPa (7% CoV), respectively, with a maximum strain equal to 3.92 %. The stress-strain curves reported in Fig. 2c, show an almost linear trend up to the peak stress, with a post-peak softening due to progressive failure of single yarns. Displacements were recorded also by means of the DIC: Fig. 2d shows their colour map in correspondence of the ultimate failure of one of the tested textile specimens taken as an example of the typical failure achieved in each test.

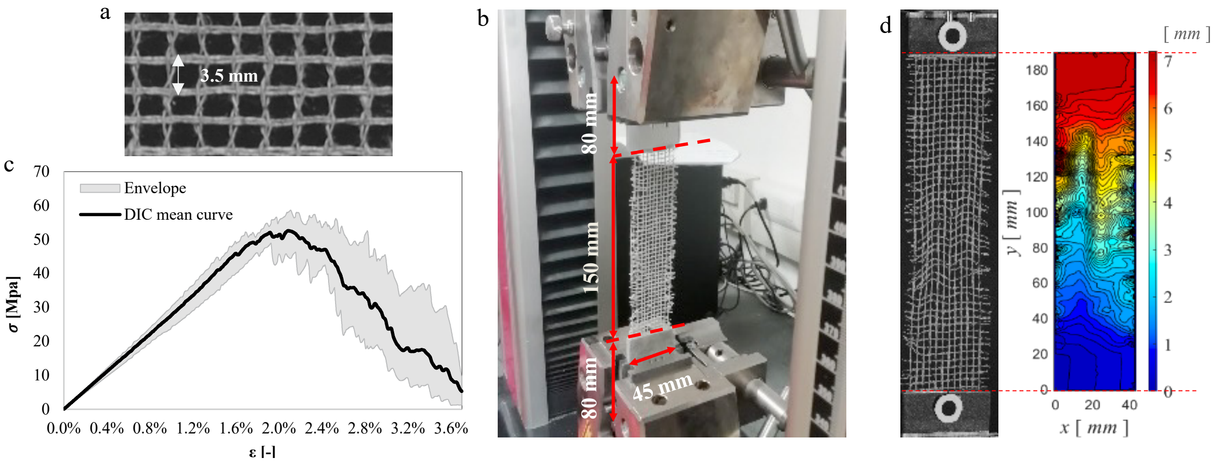

Fig. 2. Tensile tests on flax fibre textile strip samples: (a) flax fibre mesh; (b) textile sample within the testing machine; (c) stress-strain response obtained from DIC system and envelope of the integrated LVDT measurements; (d) colour map of displacements obtained with the DIC set-up.

3.3. Tensile tests on Flax-TRM coupons

Single layer Flax-TRM composite specimens were manufactured with a geometry of 400×45 mm and thickness of 8 mm (Fig. 3), every sample containing a single textile layer with 12 yarns and a gauge length of 240 mm. All coupons were cured under wet burlap, covered with plastic bag for 28 days at room temperature. Prior to testing, 2 mm thick aluminium tabs were epoxy-bonded to the ends of the composites for a length of 80 mm to ensure the effective load transfer of the Flax-TRM system. Specimens were then prepared for DIC acquisition creating a high-contrast texturing effect using white paint with black speckle pattern. Direct tensile tests on the Flax-TRM specimens were performed based on RILEM TC 232-TDT recommendations (RILEM TC232, 2016). The tests were carried out on three specimens (FL-TRM-01, FL-TRM-02 and FL-TRM-03) on a universal testing machine of 50 kN capacity, with a displacement rate of 0.2 mm/min. The DIC displacement acquisition was performed on two over three tested specimens, namely samples FL-TRM-02 and FL-TRM-03. The strain measurements recorded using the DIC system were compared to those obtained by the LVDT integrated in the testing machine. Virtual extensometers were defined on coupon's surface with a length of 240 mm. Results obtained from tests are reported in Fig. 4 and summarized in Table 2. Tensile stresses and tangential moduli are determined considering the transversal area of fibres (3.7 mm^2).

All specimens show the same global behaviour, described in the follow with reference to Fig. 4. A single crack (clearly visible in Fig. 3b,c) is observed at the peak stress σ_1, at the end of the first linear elastic stage (Stage I), which appears ruled by the stiffness and strength of the mortar. Conversely, the following stages are governed by the behaviour of the fibre and the fibre-matrix interaction. In particular, after a significant stress drop due to the crack formation (Stage II), the stress increases up to a peak corresponding to σ_3 (Stage III), the latter being averagely 40 % lower than the peak stress previously attained at the end of Stage I. Subsequently, a progressive softening phase is observed, due to the failure of the yarns (Stage IV) until the attainment of a plateau with a residual strength σ_{res} (Stage V) due to the cohesive interaction between fibres and mortar matrix. The ultimate strain value of this stage, ε_u, is chosen at 20% increase of ε_4.

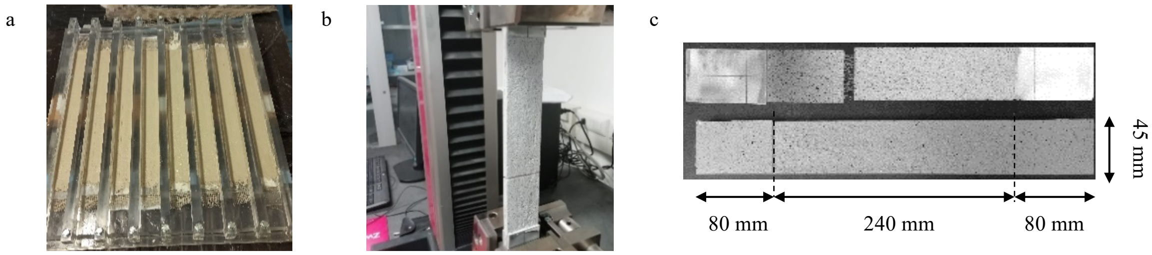

Fig. 3. Flax-TRM coupons: (a) casting phase; (b) specimen equipped with alluminium tabs and speckle pattern within the testing machine; (c) cracked specimen compared with the uncracked sample.

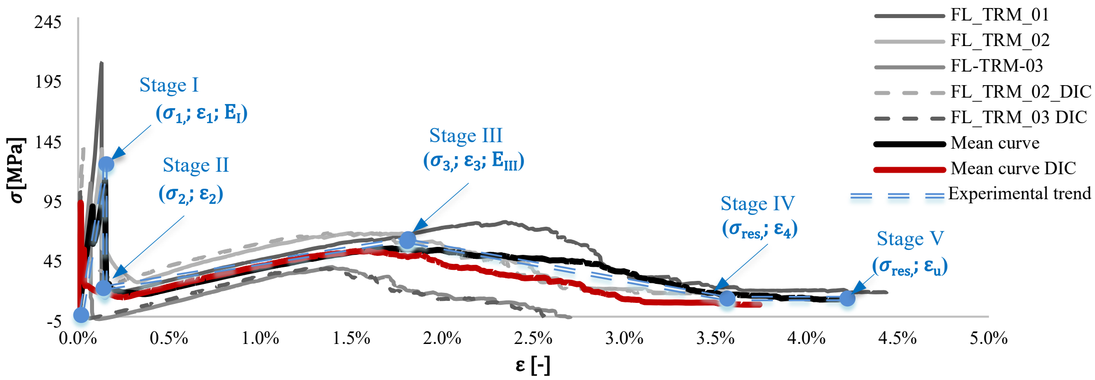

Fig. 4. Tensile stress–strain response of Flax-TRM samples: DIC mean curve (black solid line), testing machine curves (greyscale lines), schematic experimental trend (blue double dashed line).

Table 2. Experimental results of the tensile tests on Flax-TRM coupons

Series	P_{max} [N]	σ_1 [MPa]	Parameters measured by testing machine: ε_u [%]	Tangential modulus E_I [GPa]	Tangential modulus E_{III} [GPa]	Parameters measured by DIC: ε_u [%]	Tangential modulus E_I [GPa]	Tangential modulus E_{III} [GPa]
FL_TRM_01	793.8	212.2	4.5 %	148.7	3.4	-	-	-
FL_TRM _02	527.5	141.0	3.8 %	106.1	4.1	3.7%	647.1	4.1
FL_TRM _03	410.4	112.4	2.7 %	165.8	4.0	2.6%	754.4	4.2
Average	580.6	155.2	3.6 %	140.0	3.8	3.2%	700.8	4.2
(*CoV*)	(*33%*)	(*33%*)	(*24%*)	(*22%*)	(*9%*)	-	-	-

Looking at the DIC results, the parameters measured in the post peak phases are in good agreement with the ones obtained by the integrated LVDT, whereas in the initial stage an overestimation of the stiffness E_I is achieved. This is caused by the fact that displacements during the first stage are close to the maximum accuracy detected by the DIC system (which is equal to 0.01 mm), causing noisier measurement with less accurate estimation of displacements.

4. Effectiveness of natural vegetable systems vs. basalt-TRMs

In this section, the effectiveness of natural TRMs is evaluated considering the main mechanical parameters evidenced by the tests. According to the symbols previously introduced in Fig. 4, the following parameters are analyzed for comparison: tensile stress achieved at the end of the uncracked stage (i.e. σ_1); stiffness of the initial stage (i.e. E_I); ductility of the composite material (in terms of ultimate strain ε_u). Moreover, the overall maximum stress exhibited by the TRM systems in all stages is analyzed, indicating this strength as σ_{max}. The effectiveness of vegetable TRM systems is compared to basalt composites. Data are expressed using as reference area the nominal area of fibres. Only results on one-layer, not-impregnated specimens are considered for the comparative analysis.

Graphs in Fig. 5 compares the stress achieved in the uncracked stage, σ_1, with the maximum one reached by the composites in all the stages, σ_{max}. Codispoti et al. (2015) only provide data regarding $\sigma_{max,}$ which are the only reported in the graph. Stresses achieved by vegetable fibres are 5 to 15 times lower than those provided by basalt fibres, however still suitable for a reinforcement material. Results shows a good consistency in terms of σ_1 achieved by all the vegetables fibres. This is due to the strength of the mortar which governs the first linear elastic stage. Moreover, it can be interesting to notice that in Flax 1- and Jute- specimens tested by Trochoutsou et al. (2021) as well as in the current experimental results, σ_1 equals σ_{max}. This is caused by the fact that, in post-peak stages, TRM composite achieved only strength value lower than σ_1, hence no benefits in terms of the strength increase are shown.

Fig. 6 reports the graphs of the ultimate strain ε_u. Aside from jute fibres tested by Trochoutsou et al. (2021), it emerges that coupons made by vegetable fibres show values of ε_u 2 to 5 times higher than those obtained with basalt fibres. Moreover, current results prove to be coherent with those reported by all authors for flax coupons.

Finally, Fig. 7 shows the initial tangential modulus values, E_I. Regarding Ferrara et al. (2021) and Codispoti et al. (2015) tests, E_I values are not reported in the result tables presented by the authors in their reference papers. Hence, for Ferrara et al. (2021) it was extrapolated by the stress-strain curves given in the reference paper, while for the specimens tested by Codispoti et al. (2015), it was not possible to provide the estimation of E_I, thus the values are not considered in this comparative analysis. Due to the unreliability of the data obtained by DIC in Stage I of the tests, the elastic moduli used for comparison are the ones obtained by the integrated LVDT of the testing machine. Results of natural fibre TRMs shows 6 to 30 times lower values of E_I compared to those obtained in basalt-TRM coupons. Conversely, they exhibit comparable values between themselves, since the stress-strain slope E_I in the initial stage is mainly affected by the mortar characteristics, which are similar in all coupons made with vegetable fibres.

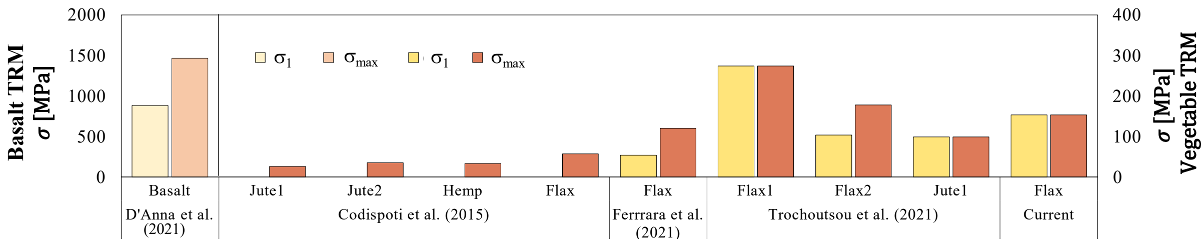

Fig. 5. Comparison between current experimental and literature results in terms of initial cracking stress $\sigma 1$ and maximum stress σmax.

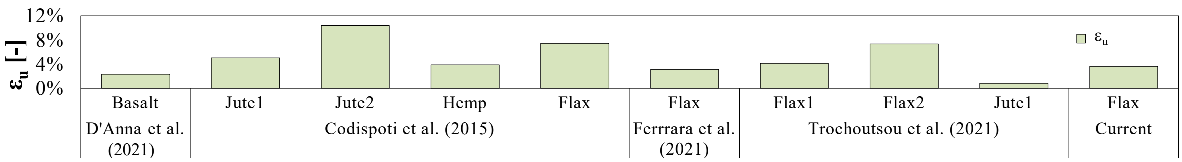

Fig. 6. Comparison between current experimental and literature results in terms of ultimate srain ε_u.

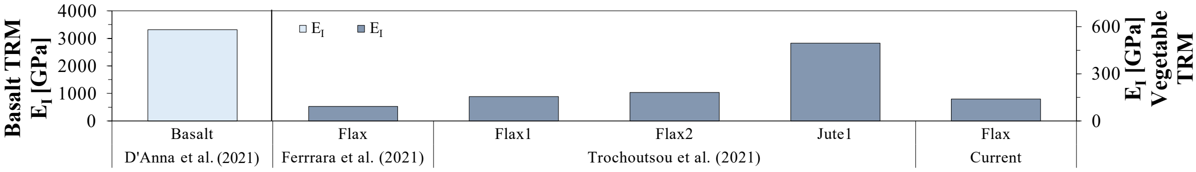

Fig. 7. Comparison of the intial tangetial modulus E_I between current experimental and literature results.

5. Conclusions and future developments

In this paper, the behaviour of natural vegetable TRM composites under traction has been investigated, firstly, by means of experimental tests and then, by a comparative analysis against laboratory outcomes available in the literature. Tests allowed to catch the global behaviour of Flax-TRM systems, which is characterised by an initial uncracked phase ruled by the mortar matrix tensile strength, followed by several cracked stages in which the reinforcing fabric exhibits its tensile strength and significantly interacts with the mortar material until attainment of a residual strength with high ductility capacity. Comparison against similar results in the literature proved a good reliability of the global response of these systems, in terms of tensile strength, initial stiffness and ultimate strain. Behaviour of vegetable TRMs was compared also with the effectiveness of basalt systems evidencing, as expected, lower strength capacity of the vegetable composites, even though still suitable for strengthening purpose, and good ductility performance. Additional insights are necessary for the full characterization of these innovative systems. In particular, further studies should be focused on the physical characterization of mortar and flax fabric, assessment of density, equivalent thickness and transversal area of fibre, tensile characterization of TRM coupons made with multiple flax reinforcing layers and the assessment of the durability of the system through the simulation of different aging environments.

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