Durability of flax textile-reinforced mortar systems

Sixth International Conference on Sustainable Construction Materials and Technologies. https://www.scmt-conferences.com/proceedings

DURABILITY OF FLAX TEXTILE-REINFORCED MORTAR SYSTEMS

Niki Trochoutsou[1], Mattia Baldassari[2], Alessia Monaco[3], Pietro Cornetti[4], Maurizio Guadagnini[5]

[1]*Department of Civil and Structural Engineering, The University of Sheffield, Mappin Street, S1 3JD Sheffield, UK, e-mail: n.trochoutsou@sheffield.ac.uk*
[2]*Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy, e-mail: mattia.baldassari@polito.it*
[3]*Department of Architecture and Design, Politecnico di Torino, Viale Mattioli 39, 10125 Torino, Italy, e-mail: alessia.monaco@polito.it*
[4]*Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy, e-mail: pietro.cornetti@polito.it*
[5]*Department of Civil and Structural Engineering, The University of Sheffield, Mappin Street, S1 3JD Sheffield, UK, e-mail: m.guadagnini@sheffield.ac.uk*

ABSTRACT

This paper presents the preliminary results of an experimental programme on the tensile performance of flax-TRM systems subjected to accelerated ageing. Composites consisting of two layers of flax textiles embedded in a lime-based mortar were conditioned in water for 1000 h and 2000 h at controlled temperatures of 23°C and 40°C. Bare textiles were also conditioned in a lime solution for the same duration and temperature conditions to assess and decouple the deterioration mechanisms at the textile and composite scale. The mechanical behaviour of both unconditioned and aged textiles and composites was characterised through uniaxial tensile tests. Based on the preliminary results of this study, the key degradation mechanisms seem to mainly involve the textile reinforcement. The tested FTRM systems exhibited a strength retention of approximately 86% after an exposure time of 1000 h. However, when exposure time increased to 2000 h, a retention rate of only 60% was achieved.

Keywords
Natural fibres, flax, TRM, durability, mechanical characterization

INTRODUCTION

The use of structural textiles embedded in an inorganic matrix (Textile-Reinforced Mortars - TRM) is currently regarded as one of the most effective retrofitting solutions for masonry structures, as they can guarantee excellent compatibility with the substrate and minimal invasiveness (Kouris and Triantafillou, 2018). Although advanced textiles (e.g. carbon, steel cords) are generally used in TRM applications, their mechanical properties can be largely unexploited, as the performance of such systems is often governed by premature debonding (Askouni and Papanicolaou, 2017).

Given the urgent need for more sustainable structural solutions, natural fibres (typically plant-based) have emerged as a potential solution for structural reinforcement in TRM systems, as they offer the required mechanical performance while minimizing environmental impact. Among the different natural fibre textiles examined to date, flax textiles have been reported to be the most suitable for strengthening applications as they can develop good composite action when embedded in a lime-based mortar (Trochoutsou *et al.* 2021a, Monaco *et al.* 2023). Although examples of structural applications are still rather scarce in the literature, the use of multi-layer Flax-TRM systems were shown to increase significantly the in-plane shear strength and deformability of unreinforced masonry walls, promoting the development of energy dissipation mechanisms while ensuring structural integrity (Trochoutsou *et al*. 2022).

However, the durability of these novel bio-based systems, which is fundamental to guarantee their long-term effectiveness, is yet to be investigated. At a fibre level, it has been evidenced that when embedded in an inorganic matrix, natural fibres can undergo severe degradation due to two main mechanisms (Yan *et al.* 2016): i) moisture absorption and drying, with the natural fibres absorbing moisture from the surrounding matrix and then adapting to the drier environment, thus swelling and shrinking during the process and leading to cracking; ii) dissolution of the main chemical components in highly alkaline environments and additional fibre mineralization due to the migration of the hydration products. Related studies have shown that a 50% reduction in the tensile strength was observed in flax fibres after immersion in a lime-solution for 84 days (Olivito *et al.* 2014). At a composite level, only one study (Ferrara *et al.* 2019) has evaluated the performance of single-layer flax-TRM coupons after immersion for 3000 h (125 days) in water, salt and alkaline solution under ambient conditions, which were reported not to cause any significant decay on the mechanical characteristics. However, a systematic investigation on the effect of harsher environments on the overall performance of single- and multi-layer flax-TRM composites and their constituents is required in order to identify the key degradation mechanisms at the textile and composite scale.

This paper presents the preliminary results of a larger experimental programme on the long-term performance of different flax textile-reinforced lime-based mortar systems subjected to accelerated environmental conditioning. The wider scope of the project is to provide an insight into the degradation mechanisms of FTRM systems and assist in the development of tailored solutions to meet application-specific criteria, while guaranteeing load-carrying capacity and environmental exposure resilience.

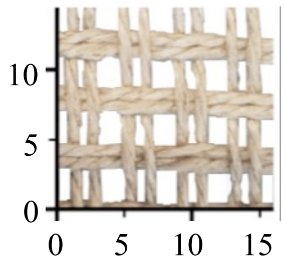
EXPERIMENTAL PROGRAMME

Materials

The FTRM system used in the experimental programme consisted of a balanced bidirectional flax textile embedded in a natural hydraulic lime-based mortar. The textile comprised two-ply yarns arranged in pairs, and its characteristics are summarised in Table 1, as supplied by the manufacturer.

The mortar used in the FTRM system was a commercial product consisting of natural hydraulic lime and aggregates with a maximum size of 0.6 mm. A water/binder ratio of 0.24 by weight was used as per supplier's recommendations. The 28-day mechanical properties of the mortar were determined following EN 1015-11 (CEN, 1999b) through flexural and compressive tests on 160 x 40 x 40 mm prisms cured in the same environment as the reference FTRM composites (see following Section). The mortar had an average flexural and compressive strength equal to 3.4 MPa (CoV: 10%) and 9.4 MPa (CoV: 6%), respectively.

Table 1. Flax textile characteristics. Scale in mm.



Construction	0º/90º
Areal Weight (g/m^2)	300
Linear Density (TEX)	324
Bulk Density (g/cm^3)	1.5

Specimen Preparation and Conditioning Protocols

The specimens and conditioning protocols examined in this study included:

- FTRM composites conditioned in water for 1000 h and 2000 h at controlled temperatures of 23±2ºC and 40±2ºC (5 replicates for each protocol).
- bare textiles in a 0.16% w/w calcium hydroxide solution conditioned for the same duration and temperature conditions in order to replicate the environment provided by the lime-based mortar (5 replicates for each protocol).

In addition, five FTRM composites were conditioned in water for 21 days at 23±2ºC, and served as reference specimens.

The 25 FTRM composites that were manufactured measured 500 mm x 50 mm (length x width) and comprised two layers of flax textile reinforcement with 3-mm thick mortar overlays, resulting in a total thickness of approximately 10 mm. The corresponding textile and composite cross-sectional areas were equal to 8.64 mm^2 and 500 mm^2, respectively. It should be noted here that the former was assumed to be constant across all specimens despite the exposure conditions, with the associated fibre degradation mechanisms possibly affecting the effective cross-section of the textile. Single-layer FTRM composites were not examined in this study, as preliminary results indicated that the associated reinforcement ratio was insufficient to develop composite action.

The bare textile specimens were of equal dimensions to those of FTRM composites (i.e. 500 mm x 50 mm) and comprised one layer of textile reinforcement of cross-sectional area equal to 4.32 mm^2.

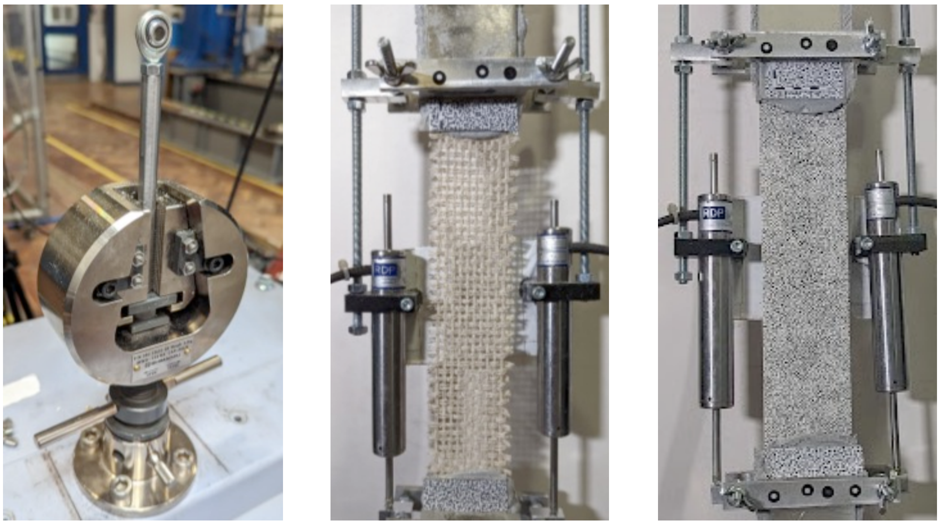
At the end of the conditioning period, the textile specimens were left to dry for a couple of hours and then tested, while the composite specimens were removed from the conditioning chambers and then stored in standard laboratory conditions (approximately 23±2ºC and 60%RH) for at least seven days before testing.

Experimental Setup and Instrumentation

Prior to testing, aluminium plates were epoxy-bonded to the ends of the bare textiles and FTRM composites for a length of 150 mm to ensure effective load transfer, resulting in a free length of 200 mm.

Direct tensile tests were performed on bare textiles and FTRM composites following the EAD 340275-00-0104 (EOTA, 2020). The tests were carried out in displacement control in a universal testing machine of 10 kN capacity, at a displacement rate of 0.5 mm/min for the bare textile and 0.2 mm/min for the composites. The load was transferred through clevis-type grips, allowing for in- and out-of-plane rotation of the specimens while being loaded (Figure 1a).

An overview of the experimental setup is presented in Figure 1. Displacements were recorded by both contact and non-contact instrumentation. Two LVDTs were placed on opposite sides of the specimens and recorded uniaxial deformation. In addition, a bespoke 2D Digital Image Correlation (2D-DIC) setup was employed to obtain full-field displacement measurements of both textiles and FTRM composites. Detailed results from DIC analyses will be presented in future publications.



(a) (b) (c)

Figure 1. (a) Spherical joint of the clevis grips; (b) setup for textiles; (b) setup for FTRM composites.

The specimen ID uses the notation T-y-n and C-y-n, for textiles and FTRM composites, respectively, where y is the temperature of conditioning (23ºC or 40ºC) and n is the replicate number (from 1 to 5). The reference textile and composite specimens are labelled as “T-REF” and “C-REF”, respectively.

EXPERIMENTAL RESULTS

Textiles

The tensile properties of the bare textiles subjected to the different conditioning protocols are reported in Table 2 (average values of 5 specimens), in terms of tensile strength, $f_{t,max}$, strain at failure, $\varepsilon_{t,max}$, and Young’s modulus, E_t. The strength was calculated by dividing the maximum load by the textile area, while the Young’s modulus was calculated as the secant modulus of the linear part in the stress–strain response curve to allow the characterisation of the largest stiffness that can be developed. The tensile strengths developed in the textiles after each conditioning protocol, along with the associated standard deviation values, are compared in Figure 2a, while the tensile stress-strain response of representative textiles from each conditioning protocol is shown in Figure 2b.

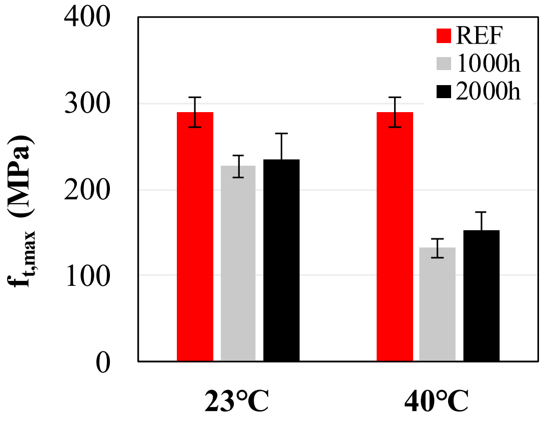
Table 2. Average mechanical properties of flax textiles (CoV in parentheses)

Textile ID	$f_{t,max}$ (MPa)	$\varepsilon_{t,max}$ (%)	E_t (GPa)
T-REF*	289.0 (6%)	3.80 (4%)	13.6 (7%)
T-23-1000	226.7 (6%)	4.96 (10%)	10.3 (19%)
T-23-2000	252.2 (6%)	4.96 (2%)	11.9 (15%)
T-40-1000	132.3 (8%)	4.00 (8%)	7.0 (10%)
T-40-2000	166.9 (10%)	3.15 (17%)	9.8 (24%)

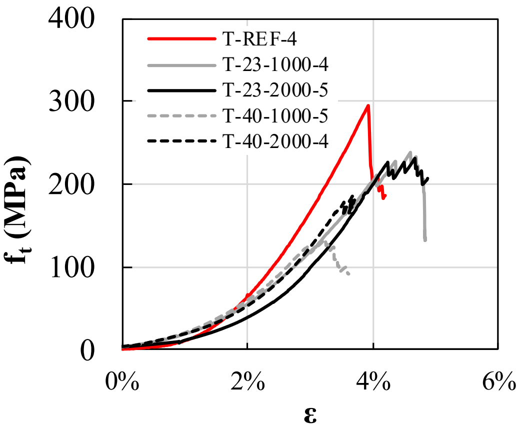
*experimentally determined in previous work (Trochoutsou et al. 2021a).

The response of the textiles was characterised by an initial inelastic branch followed by linear behaviour up to the peak stress and a softening stage resulting from the progressive failure of individual yarns. The unconditioned textiles developed strength values in good agreement with those reported in previous studies on similar flax textiles (Ferrara *et al.* 2019).

However, when subjected to 23ºC and 40ºC for 1000 h, flax textiles suffered a reduction in tensile strength and stiffness of about 22-24% and 50-54%, respectively. This is probably due to the combined effect of anisotropic swelling of the flax fibre multi-stack structure during immersion (Le Duigou *et al.* 2015), and the progressive alkaline hydrolysis of the chemical components of the fibre cell-walls (Wei and Meyer, 2015), which was accelerated under higher temperatures. Longer exposure durations did not seem to result in any further deterioration in the mechanical properties, taking into account the reported variability in Table 2 and illustrated in Figure 2a.



(a)



(b)

Figure 2. (a) Textile strength versus temperature and exposure duration; (b) typical tensile stress-strain of representative specimens from each conditioning protocol.

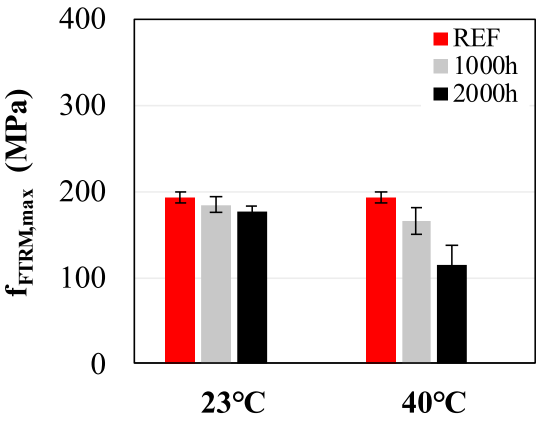
FTRM composites

The results of the tensile tests on the FTRM coupons are summarised in Table 3 in terms of average maximum strength at cracking, f_{cr}, and at failure, $f_{FTRM,max}$, corresponding strains, ε_{cr} and $\varepsilon_{FTRM,max}$, exploitation ratio of the textile, $\eta = f_{FTRM,max}/f_{t,max}$, and strength retention ($f_{FTRM,max}/f_{FTRM,max(REF)}$). The stress was calculated by dividing the load by the cross-sectional area of the textile (accounting for two layers of reinforcement), while the exploitation ratio was calculated as the ratio of the maximum strength developed by the FTRM composite to that developed by the bare textile exposed to the same environment. Figure 3a compares the average values of $f_{FTRM,max}$, while Figure 3b shows the tensile stress-strain response of representative composites subjected to the examined conditioning protocols.

Table 3. Average mechanical properties of FTRM composites (CoV in parentheses)

FTRM ID	f_{cr} (MPa)	ε_{cr} (%)	$f_{FTRM,max}$ (MPa)	$\varepsilon_{FTRM,max}$ (%)	η (%)	Retention (%)
C-REF	158.4 (12%)	0.03 (14%)	192.8 (4%)	7.56 (10%)	67	-
C-23-1000	116.0 (23%)	0.02 (20%)	184.5 (5%)	7.21 (14%)	81	96
C-23-2000	156.8 (7%)	0.02 (38%)	177.5 (3%)	6.85 (33%)	70	92
C-40-1000	155.6 (3%)	0.03 (20%)	165.6 (10%)	5.58 (47%)	125	86
C-40-2000	124.2 (13%)	0.02 (32%)	114.9 (20%)	4.26 (59%)	29	60

The three stages characterising the typical tensile response of TRM systems (Arboleda *et al.* 2016) were identified in all tested unconditioned FTRM composites, with failure following the formation of the last crack and occurring due to progressive yarn rupture, which triggered the initiation of a softening stage, as also observed in the tests on the textile specimens. Hence, the cracked stiffness could not be evaluated. The formation of large discrete cracks (typically three to four) was accompanied by a high energy release, and the absence of a clear stabilised cracking stage indicated that the provided reinforcement ratio (1.73%), although higher than the critical (Trochoutsou *et al.* 2021a), was still relatively low.



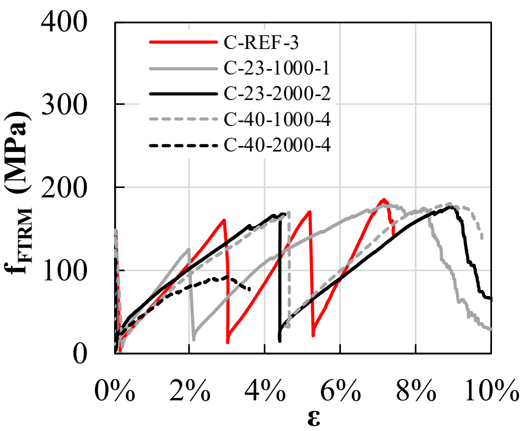


Figure 3. (a) Tensile strength of FTRM composites versus temperature and exposure duration; (b) typical tensile stress-strain of representative specimens from each conditioning protocol

In general, accelerated ageing resulted in a loss of tensile strength, which was minimal after exposure to 23°C (≤ - 10% after 2000 h) and more significant after exposure to 40°C, (-40% after 2000 h). Regardless of the conditioning protocol, all specimens failed due to fibre rupture after distinct large cracks were formed in the composites. However, the different exposure conditions affected the crack development stage, with conditioned specimens being characterised by the development of two major cracks, typically close to the gripping tabs, which widened significantly during the test. Exposure to harsher environments (40ºC, 2000 h) led to a composite performance with no strain hardening and absence of the crack development stage, indicating that the significant degradation occurring in the fibres, also evidenced by the reduction in the ultimate tensile strength of the composite, resulted in a further reduction of the actual reinforcement ratio.

The average stress developed at first cracking in the mortar of unconditioned specimens was 2.7 MPa, corresponding to a stress of 158.4 MPa in the textile. This stress was not significantly affected by accelerated ageing, considering the high scatter of results, thus indicating that the composite performance was primarily a result of the degradation of the textile. This, in turn, resulted in: a) a loss of bond stress transfer ability and loss of composite action, and b) a possible reduction in the effective cross-section of the textile, and thus reinforcement ratio, due to fibre embrittlement arising from water absorption and alkaline hydrolysis. In fact, this was also reflected by the low exploitation of the associated textile strength within the composite (29% - Table 3). Although accurate monitoring of yarns' dimensional changes in humid environments requires the implementation of advanced spectroscopic techniques, SEM analyses are currently underway to provide additional information on the microstructural surface characteristics of yarns and composites, as well as on the degree of adhesion between textile and mortar. Overall, the reduction in the strength of the textile embedded in the composites was lower than that recorded for the associated bare textiles immersed in lime solution, highlighting the ability of the mortar to protect to a certain extent the textile.

According to the Acceptance Criteria issued by the ICC-Evaluation Service (AC434, 2011), a tensile capacity retention rate of 85% and 80% should be ensured after immersion in water in 38ºC for 1000 h and 3000 h, respectively. Based on the preliminary results of this study, the two-layer FTRM systems comply with the criteria for qualifying TRM systems at 1000 h (retention rate equal to 86%), however they are unlikely to comply with the criteria set for 3000 h, as already at 2000 h a retention rate of only 60% was achieved. Further work should focus on examining different environments and exposure conditions, which will help gain a deeper understanding of the degradation mechanisms and will allow the optimal design of flax-TRM systems for strengthening applications.

CONCLUSIONS

This experimental study examined the tensile performance of flax-TRM systems before and after water immersion for 1000 h and 2000 h at controlled temperatures of 23°C and 40°C, with a view of investigating their long term properties. The following conclusions can be made:

- Conditioning at 23 ºC did not significantly influence the mechanical properties of the bare textiles or the FTRM composites for all examined exposure durations.
- Conditioning at 40 ºC resulted in a significant reduction in tensile strength of textiles and composites, by 50% and 40%, respectively.
- The failure mode of the flax-TRM composites was not affected by the environmental conditioning, with all composites failing due to fibre rupture and typically high exploitation of the textile strength. However, harsher environments affected the crack development stage, indicating a reduction in the effective reinforcement ratio, and thus composite action.
- Key degradation mechanisms seem to mainly involve the textile reinforcement, as the mortar matrix did not show to be sensitive to accelerated ageing.
- Flax-TRM systems were able to satisfy currently established durability performance criteria after 1000 h but not after longer exposure limits.

Although the investigation of the mechanical performance of flax-TRM is still in its infancy, these results highlight the potential of achieving durable flax-TRM systems. Given that ageing primarily leads to the degradation of the textile properties, rather than those of the mortar matrix, it is believed that the bond of these flax-TRM systems to masonry substrates under similar environments will be dominated by the fibre/matrix rather than the matrix/substrate interface. More work is needed towards not only the investigation of different conditioning protocols but also of the durability performance of flax-TRM systems with different textile architectures and alternative mortars of lower alkalinity and porosity, yet providing good vapour permeability to allow the underlying masonry substrate to breathe.

ACKNOWLEDGMENTS

This work was supported by the 2023 Go Fund grant awarded to the first and last author by the Grantham Centre for Sustainable Future. The lime-based mortar was kindly provided by KIMIA S.p.A.

REFERENCES

Arboleda, D., et al. (2016). “Testing procedures for the uniaxial tensile characterization of fabric-reinforced cementitious matrix composites.” *J. Compos. Constr.* 20, 04015063.

Askouni, P. D. and Papanicolaou, C. G. (2017). “Experimental investigation of bond between glass textile reinforced mortar overlays and masonry: The effect of bond length.” *Mater. Struct.,* 50 (2): 164.

European Committee for Standardization (CEN). (1999b). *EN 1015-11:1999: Methods of test for mortar for masonry.* Brussels: CEN.

European Organisation for Technical Assessment (EOTA). (2020). *EAD 340275-00-0104: Externally-bonded composite systems with inorganic matrix for strengthening of concrete and masonry structures.* Brussels: EOTA.

Ferrara, G. et al. (2019). “Tensile behaviour and durability assessment of Flax Textile Reinforced Mortar composite systems.” *Proceedings of 5th conference on Smart Monitoring Assessment and Rehabilitation of Civil Structures, SMAR, 2019*. Potsdam, Germany. e-Journal of Nondestructive Testing, 25(1).

Ferrara, G. et al. (2019). “Tensile strength of flax fabrics to be used as reinforcement in cement-based composites: experimental tests under different environmental exposures.” *Compos. Part B*, 168, 511-523.

ICC-Evaluation Service (ICC-ES). (2011). *AC 434: Acceptance criteria for masonry and concrete strengthening using fiber-reinforced cementitious matrix (FRCM) and steel reinforced grout (SRG) composite systems.* Birmingham, AL: ICC-ES.

Joshi, S.V. et al. (2004). “Are natural fiber composites environmentally superior to glass fiber reinforced composites”. *Compos. Part A Appl. Sci. Manuf.,* 35(3): 371-376.

Kouris, L.A.S. and Triantafillou, T.C. (2018). “State-of-the-art on strengthening of masonry structures with textile reinforced mortar (TRM)”. *Constr. Build. Mater.*, 188, 1221-1233.

Le Duigou, A., Bourmaud, A. and Baley, C. (2015). “In-situ evaluation of flax fibre degradation during water ageing”. *Ind. Crops Prod.*, 70, 204-210.

Monaco, A. et al. (2023). “Effectiveness of Flax-TRM composites under traction.” *Procedia Struct. Integr.,* 44, 2278-2285.

Olivito, R.S., Cevallos, O.A. and Carrozzini, A. (2014). “Development of durable cementitious composites using sisal and flax fabrics for reinforcement of masonry structures.” *Mater. Des.*, 57, 258-268.

Trochoutsou, N. et al. (2021a). “Mechanical characterisation of flax and jute textile-reinforced mortars.” *Constr. Build. Mater.*, 271, 121564.

Trochoutsou, N. et al. (2022). “In-Plane Cyclic Performance of Masonry Walls Retrofitted with Flax Textile–Reinforced Mortar Overlays.” *J. Compos. Constr.,* 2022, 26(5), 04022049.

Wei, J. and Meyer, C. (2015). “Degradation mechanisms of natural fiber in the matrix of cement composites.” *Cem. Concr. Res.,* 73, 1-16.

Yan, L., Kasal, B. and Huang, L. (2016). “A review of recent research on the use of cellulosic fibres, their fibre fabric reinforced cementitious, geo-polymer and polymer composites in civil engineering.” *Compos. Part B Eng.,* 92, 94-132.