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Effect of Textile Architecture on the Durability of Flax Textile-Reinforced Mortars

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Abstract

This paper presents the preliminary results of an experimental programme on the tensile performance of flax-TRM systems subjected to accelerated ageing. Two layers of flax textiles of different architecture were embedded in a lime-based mortar and were conditioned in water for 2000h (~83 days), 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. Both unconditioned and aged textiles and composites were subjected to direct tensile tests. The results show that the textile architecture affected primarily the short-term mechanical properties and the degree of composite action that can be achieved. Exposure to harsher environments resulted in similar strength retention rates for both textile types and equal to 60-70%, while the composite performance was found to be mainly affected by degradation mechanisms occurring at the textile reinforcement level, which may reduce the effective reinforcement ratio below critical values.

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Keywords: flax; TRM; durability; bio-composites; mechanical properties.

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1. Introduction

Natural fibre textiles have recently attracted the interest of both academia and industry as an alternative structural reinforcement in Textile-Reinforced Mortars (TRM), as they can offer the required mechanical performance while minimizing their environmental impact. Flax, sisal, cotton, hemp and jute textiles have been combined with lime-based mortar and have been studied under direct tension, with Flax-TRM showing the best performance and good mechanical properties, suitable for strengthening applications (e.g. Olivito et al., 2014; Trochoutsou et al., 2021a), followed by hemp- and jute-TRM (Codispoti et al. 2015). At a larger scale application, Flax-TRM systems have been shown to contribute effectively to the in-plane shear resistance and deformability of unreinforced masonry walls (Ferrara et al. 2020; Trochoutsou et al., 2022), and to outperform more advanced, PBO-based counterparts, in increasing the performance of masonry elements under eccentric loading (Cevallos et al., 2015).

Among key design parameters, the textile architecture plays a major role in determining the overall structural performance, affecting both the effective reinforcement ratio and the mechanical interlock at the fibre/mortar interface. Woven textiles can typically benefit from the strong anchoring effect resulting from the crimped yarn geometry (Peled and Bentur, 2003) and the additional mechanical anchorage offered by the presence of transverse yarns. Moreover, high linear density yarns may result in limited penetrability and promote telescopic failures (Cevallos and Olivito, 2014), while twisted yarns of smaller diameter can develop a better composite action with the mortar, resulting in composites with high utilisation of the textile strength and good bond with masonry substrates if applied in narrow TRM strips (Trochoutsou et al. 2021b).

A great challenge hindering the wider implementation of Flax-TRM systems, however, is their long-term durability, which still remains relatively unexplored even for already established, advanced TRM systems. The hydrophilic nature of natural fibres makes them highly susceptible to moisture absorption, which may induce volume changes inside the composite and the development of internal stresses and premature composite cracking (Célino et al., 2014). In addition, alkali hydrolysis of the main chemical components and precipitation of hydration products within the fibre cell wall can lead to fibre mineralization and degradation of the mechanical properties of natural fibres (Wei and Meyer, 2015). Although physical and structural modifications (e.g. coatings) could be implemented, the underlying degradation mechanisms occurring at the constituents (i.e. textile and mortar) and composite level need to be first elucidated in order to inform optimal modification strategies.

This paper aims to address this gap, by examining the tensile performance of flax textiles with different architectures and resulting Flax-TRM composites subjected to accelerated aging at controlled temperatures of 23°C and 40°C for 2000h.

2. Experimental Programme

2.1. Materials and Specimens

Two types of flax textiles were used as structural reinforcement, including: 1) a flax textile comprising single twist yarns (denoted as “K”) arranged in a 1.5-mm mesh with linear density equal to 100 TEX; 2) a flax textile comprising two-ply twist yarns arranged in pairs across a 4-mm mesh (denoted as “F”) with linear density equal to 324 TEX (Fig. 1). Both textiles were woven (i.e. warp and weft yarns are interlaced at 90° to each other), balanced bi-directional, with a bulk density equal to 1.5 g/cm^3. The yarn’s cross-sectional area was found equal to 0.07 mm^2 and 0.22 mm^2 for K and F textiles, respectively. It should be noted that the origin of the two types of flax fibres used in the textile production, and whether it was common to both textiles or not, is unknown.

The matrix was a commercial pre-mixed lime-based mortar, 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 to obtain optimal workability and fluidity and ensure penetration through the mesh openings of the textiles. The mechanical properties of the mortar were determined at 28 days following EN 1015-11 (1999b). The flexural and compressive strength were equal to 3.4 MPa (CoV: 10%) and 9.4 MPa (CoV: 6%), respectively.

In total, 30 FTRM composites comprising two layers of textile reinforcement were manufactured, measuring 500 x 50 x 10 mm (length x width x thickness). The casting procedure included the application of a 3-mm thick mortar overlay and the embedment of the textile alternately until the final composite thickness was achieved. Per layer, and

width-wise, K-TRM and F-TRM specimens comprised 30 and 20 yarns, respectively. 20 FTRM composites were conditioned in tap water for 2000h at controlled temperatures of 23±2ºC and 40±2ºC (five replicates per system and protocol), while ten FTRM composites (five per system) were conditioned in tap water for 21 days at 23±2ºC, and served as reference specimens. At the end of the conditioning period, specimens were removed from the conditioning chambers and stored in standard laboratory conditions for at least seven days before testing. It should be noted that, based on preliminary studies carried out by the authors, the use of a single layer of flax reinforcement, regardless of the textile architecture, was insufficient to develop strain hardening composites, hence two-layer FTRM systems are presented herein.

In addition, bare textiles were conditioned in a 0.16% w/w calcium hydroxide solution for the same duration and temperature conditions (five replicates per protocol) in order to simulate the environment provided by the lime-based mortar. At the end of the conditioning period, the textile specimens were left to dry for a couple of hours.

Prior to testing, the ends of both textile and composites specimens were fitted with 150-mm long aluminium tabs by means of epoxy, to ensure a uniform load application during the test.

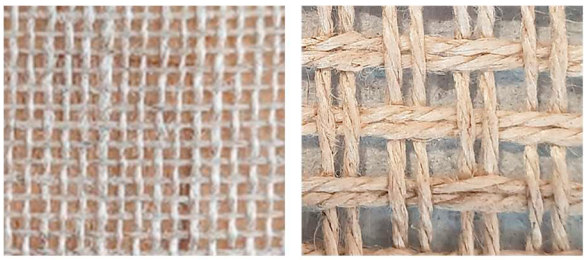


Fig. 1. Flax textile reinforcements adopted in the present study: (a) “K” and (b) “F” textiles.

2.2. Experimental Test Setup

Tensile tests were carried out using a universal testing machine equipped with a 10 kN load cell. The clamping system consisted of clevis-type grips, with the aluminium tabs connected to the testing frame by means of spherical joints, allowing for in- and out-of-plane rotation. Two LVDTs were mounted on either side of the specimens to record uniaxial deformation. Tests were carried out in displacement control at a rate of 0.5 mm/min for the bare textiles and 0.2 mm/min for the composites, following EAD 340275-00-0104 (2020).

3. Results and Discussion

The results are analysed in terms of tensile stress and strain. The former was calculated as the ratio of the applied load to the cross-sectional area of the textile. For “K” and “F textile specimens (i.e. one layer), this was equal to 2,00 mm^2 and 4,32 mm^2, respectively, while the cross-sectional area corresponding to two layers was considered in the case of the corresponding TRM composites resulting in a reinforcement ratio of 0,8% and 1,7% accordingly. Strain values were derived as the ratio of the average value recorded by the two LVDTs to the free length of the composite.

3.1. Bare Textiles

Table 1 summarises the average mechanical properties of the bare “K” and “F” textiles before and after exposure to accelerated ageing. Fig. 2a illustrates the effect of the conditioning protocol on the tensile strength, while Fig. 2b presents the tensile stress–strain curves obtained from representative textiles from each conditioning protocol.

An initial inelastic behaviour followed by a linear elastic response up to the peak stress was consistently observed for both types of flax textiles. In all cases, failure occurred due to the progressive rupture of the individual yarns. Both types of unconditioned flax textiles attained similar values of strength (277 – 289 MPa) and ultimate strain (3.5-3.8%), in good agreement with those reported in previous studies (Ferrara et al., 2019).

Although exposure to 23°C for 2000h did not result in a significant change in the mechanical properties, given the observed variability, a decrease in tensile strength of up to 42% was recorded after exposure to 40°C, which accelerated the chemical reactions and the resulting degradation of the flax fibres.

Interestingly, the strength reduction was similar for both types of flax textiles. Typically, as higher linear density yarns contain more fibres, they also exhibit larger moisture absorption capacity (Alias et al., 2018). It can be surmised that the higher twist level and the presence of two-ply yarns in the "F" textile prevented the core yarns from being directly exposed to water molecules and hydration products, mitigating their overall degradation. Further work is needed to elucidate the moisture transport mechanism within the yarn cross-section as a function of its linear density.

Table 1. Average mechanical properties of flax textiles (CoV in parentheses).

Property\Specimen ID	"K" textiles			"F" textiles		
	REF	**23°C**	**40°C**	**REF[1]**	**23°C**	**40°C**
Tensile Strength (MPa)	276.9	281.2	162.2	289.0	252.2	166.9
	(4%)	*(5%)*	*(9%)*	*(6%)*	*(6%)*	*(10%)*
Ultimate strain (%)	3.50	2.03	2.22	3.80	4.96	3.15
	(6%)	*(22%)*	*(6%)*	*(4%)*	*(2%)*	*(17%)*
Young's modulus (GPa)	16.8	20.1	16.2	13.6	11.9	9.8
	(3%)	*(12%)*	*(19%)*	*(7%)*	*(15%)*	*(24%)*

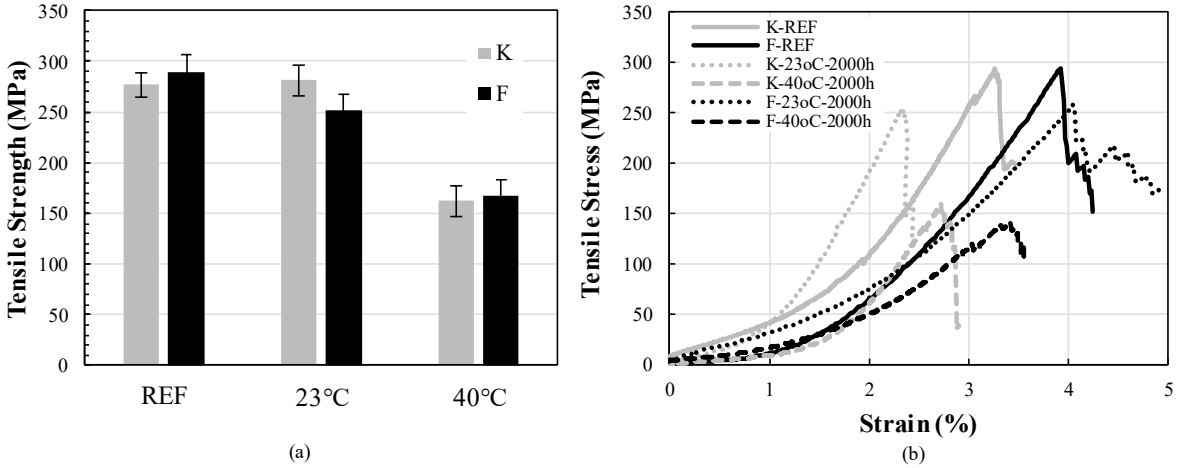


Fig. 2. (a) Tensile strength; (b) stress-strain curves of typical K and F bare textiles before and after exposure for 2000h.

3.2. Flax-TRM composites

Fig. 3a compares the average value of the tensile strength of TRM composites reinforced with two layers of "K" and "F" textiles, while Fig. 3b shows the tensile stress-strain response of representative TRM specimens from each system and ageing protocol. A summary of the average mechanical properties, their CoV, as well as the strength retention rate, calculated as the ratio of the ultimate strength of the TRM after exposure to that of the unconditioned TRM, are reported in Table 2.

Overall, unconditioned flax-TRM composites developed ultimate strength values ranging from 190-310 MPa, with those reinforced with "K" textiles exhibiting higher cracking stress and ultimate strength values than their "F"-TRM counterparts at the expense of deformability and ductility.

[1] Previously determined by Trochoutsou et al. (2021).

Although both systems were produced using the same mortar mix design, it is assumed that the difference in the cracking stress, which primarily depends on the mortar tensile properties, is attributed to the different effective mortar cross-section subjected to tension. “F” textiles consisted of yarns of larger diameter than those in “K” textiles, which possibly influenced the homogenous distribution of the mortar around them as well as within the mesh openings. As a result, the effective cross-section of the mortar within the “F”-TRM composites was reduced, and cracking initiated at a relatively lower load level.

Table 2. Average mechanical properties and retention rates (CoV in parentheses).

Property\Specimen ID	**“K”TRM**			**“F”TRM**		
	REF	**23°C**	**40°C**	**REF**	**23°C**	**40°C**
Cracking stress (MPa)	392,5 *(10%)*	381,7 *(18%)*	445,1 *(9%)*	158,4 *(12%)*	156,8 *(7%)*	124,2 *(13%)*
Ultimate Strength (MPa)	310,0 *(6%)*	281,5 *(4%)*	214,9 *(12%)*	192,8 *(4%)*	177,5 *(3%)*	114,9 *(20%)*
Strain at cracking stress (%)	0,02 *(35%)*	0,03 *(27%)*	0,03 *(10%)*	0,03 *(14%)*	0,02 *(38%)*	0,02 *(32%)*
Strain at ultimate strength (%)	1,05 *(15%)*	1,18 *(8%)*	1,02 *(9%)*	7,56 *(10%)*	6,85 *(33%)*	4,26 *(59%)*
Retention Rate (%)	-	91	69	-	92	60

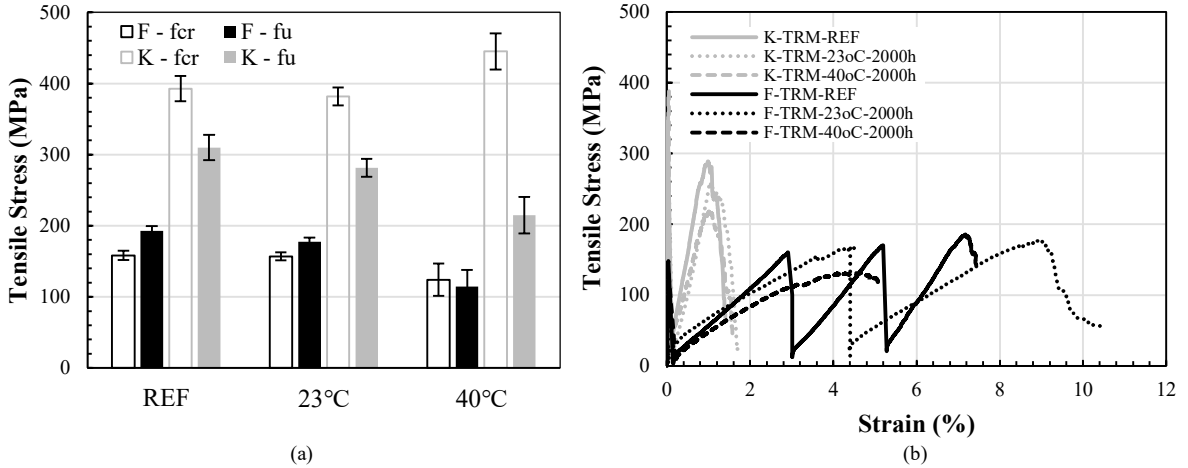


Fig. 3. (a) Cracking/ultimate strength; (b) stress-strain curves of typical K and F TRM composites textiles before and after exposure for 2000h.

The different ultimate strength attained by the two TRM systems can be explained upon the analysis of the associated stress-strain response (Fig. 3b). All “K”-TRM composites achieved a cracking load value higher than that of the maximum load attained during the cracked stage, with no strain hardening behaviour, exhibiting only one single crack during the test. This behaviour was observed in both unconditioned and aged composites, indicating that the reinforcement ratio in “K”-TRM composites (0,8%) was insufficient to enable stress redistribution. Failure occurred due to slippage of the yarns within the mortar in the proximity of the crack, followed by yarn rupture. For unconditioned coupons, the ultimate strength was similar to that attained by the corresponding bare “K” textiles. On the contrary, reference and conditioned “F”-TRM specimens at ambient temperature for 2000h presented the typical stages generally observed in TRM systems: i) stage I, where the stress increases linearly with the first crack formation, ii) stage II, crack development attributed to the degree of bond at the textile/mortar interface, iii) stage III, crack saturation and linear increase in stress until the peak load. The ultimate strength was immediately followed by the progressive failure of individual yarns, with unconditioned specimens showing typically more cracks than specimens conditioned at 20°C for 2000h. Stages II and III were not always distinguishable, with crack formation being accompanied by large energy release. This resulted in the limited contribution of the “F” reinforcement to the overall composite performance, and a lower exploitation of the textile strength (~67-70%) for both unconditioned and

conditioned "F"-TRM, indicating that the reinforcement ratio (1,7%) was still relatively low. This was also reported by Trochoutsou et al. (2021a) when examining flax-TRM composites of similar architecture and reinforcement ratios.

In general, and accounting for the observed variability in the cracking stress values in Table 2, accelerated ageing affected mainly the textile due the combination of moisture absorption as well as alkaline hydrolysis. Conditioning at ambient temperatures, as in the case of the bare textiles, did not affect significantly the ultimate strength (≤ 10% after 2000h). However, a significant decrease was recorded after exposure to 40°C for 2000h, resulting in a strength retention rate similar for both TRM systems and ranging between 60-70% (Table 2). These exposure conditions also affected the crack development stage in "F"-TRM systems, and led to a composite performance with no strain hardening and absence of the crack development stage. This indicates that the significant degradation occurring in the textile resulted in a loss of stress transfer between the textile and the mortar and a further reduction of the actual reinforcement ratio, compromising the composite action. Overall, the reduction in the strength of the textile embedded in the composites as a function of the accelerated ageing was similar to that recorded for the associated bare textiles immersed in lime solution (approximately 10% for 23°C and 30-40% for 40°C), indicating the suitability of the alkaline solution to simulate the environment surrounding the textile within the composite.

4. Conclusions

This study assessed the effect of the textile architecture on the long-term mechanical performance of flax-TRM composites. The main conclusions are listed as follows:

- Unconditioned flax textiles exhibited strength values ranging from 277-289 MPa, with textiles with twisted yarns positioned at larger spacing showing higher elongation capacity (3,8%).
- Despite their larger diameter, two-ply twisted yarns exhibited a similar degradation to the smaller diameter yarn textiles, possibly indicating that their morphology provided a degree of "protection" and did not result in higher moisture absorption.
- The low reinforcement ratio of the stiffer "K" textiles resulted in TRM composites with no strain-hardening behaviour.
- The textile architecture critically affected the degree of stress redistribution that could be achieved within the composite, but did not seem to affect the development of the main degradation mechanisms. Both textiles and resulting composites exhibited similar strength retention rates.
- Conditioning at 23 ºC did not significantly influence the mechanical properties of the bare textiles or the flax-TRM composites after 2000h.
- Conditioning at 40 ºC for 2000h resulted in a significant reduction in the tensile strength of textiles and composites, by approximately 40%.
- The effective reinforcement ratio can be reduced after exposure to harsher environments and fall below critical values, compromising the composite action.
- Reinforcement ratios higher than 1,8% should be employed to ensure flax-TRM systems with good composite action.

More work is needed towards the investigation of textiles with different architectures under different accelerated ageing protocols, which will help elucidating the water absorption and alkaline hydrolysis mechanisms as a function of the nature of the constituent materials.

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