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Tensile behaviour and durability assessment of Flax Textile Reinforced Mortar composite systems

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ABSTRACT: The use of Textile Reinforced Mortar (TRM) composite systems is getting more and more common for enhancing shear and bending capacity masonry walls. In this context, employing natural fabrics deriving from vegetal fibres is a possible evolution in TRM technology, intended at enhancing the sustainability of the material. However, the organic nature of the aforementioned fibres raises new questions about the durability of the material.

Therefore, this paper investigates the tensile behaviour of Flax-TRM coupons also considering the effect of their being exposed to different environmental condition. Specifically, according to the acceptance criteria AC434 issued by the *ICC-Evaluation Service* (USA), the specimens have been immersed either in water or salt-water or alkali solution for a period of 3000h. The composite material components (namely, the mortar matrix and the flax fabric) have been subjected to the same treatments to quantify their influence in the global response. A series of specimens has been left in ambient condition to get a reference behaviour. The obtained results show that neither the composite system as a whole, nor its components have shown any significant decay in terms of mechanical behaviour with respect to the reference series. The results demonstrate that the investigated Flax-TRM system, exposed to the conventional protocols provided by AC434, complies with the acceptance criteria generally considered for qualifying composite materials.

1 INTRODUCTION

The use of Textile Reinforced Mortar (TRM) composite systems has gained a great attention in the last decade due to several properties such as vapour permeability, compatibility with the substrate, reversibility of retrofitting system, time and cost of installation (D'Ambrisi et al. 2013). Several studies have been carried out to define a qualification method to characterise the mechanical behaviour (RILEM TC-232-TDT 2016) of TRM systems by adopting as reinforcement different kind of fibres such as carbon, glass, steel, basalt, PBO (Caggegi et al. 2017). Once the mechanical effectiveness of TRMs has been proven the attention has focused on durability aspects in order to establish if any decay of the properties in the time, or in specific working environments may affect their reliability. Several aspects have been investigated such as: the mechanical behaviour of TRMs at high-temperature conditions (Donnini et al. 2017), the decay of strength of glass fabric exposed to alkaline environments reproducing the cementitious mortar conditions (Micelli et al. 2017), the tensile behaviour of TRMs coupons exposed to freeze-thaw cycles (Nobili et al 2017).

With the aim of improving the sustainability of the reinforcing systems several recent studies have focused the attention on the use of plant fibres, such as flax, curaua, sisal, jute, coir or hemp as reinforcement in TRM composite systems (Ferreira et al. 2017; Codispoti et al. 2015; Ferreira et al. 2018), by showing them as a promising alternative to the use of industrial fibres (Ferrara et al. 2019). However, it has been shown that plant fibres are characterised by significant degradation phenomena once immersed in cementitious matrices (Wei et al. 2016) and several studies have been devoted to increase the durability performance by modifying the matrix (Toledo Filho et al. 2003) or by treating the textile (Mohr et al. 2005).

As a consequence of a previous study in which the durability of flax fibres has been investigated by adopting aging protocol meant to reproduce the conditions of cement-based matrices (Ferrara^2 et al. 2019), this study focuses the attention directly on composite TRM systems characterised by flax fibres as reinforcement. The qualification procedure adopted, according to the acceptance criteria AC434, consists of the immersion of TRM coupons either in water or salt-water or alkaline solution for a period of 3000h. The durability performance is computed by comparing the tensile behaviour of the specimens tested after the period of exposure with the response of reference specimens stored in ambient conditions. The composite material components (namely, the mortar matrix and the flax fabric) have been subjected to the same treatments to quantify their influence in the global response. Some considerations about the mechanical response in tension on TRM composites reinforced by plant fibres are reported as well.

2 MATERIALS AND METHODS

The TRM adopted in the study is a composite characterised by flax textile embedded in hydraulic lime mortar whose mechanical properties are shown in a related study (Ferrara et al. 2019). TRM coupons, cast according to the guidelines reported in ACI 549 (2013), have been realised by spreading the first layer of mortar, placing on it the fabric making sure that the mortar completely fills the grid voids. A roll was used to apply a pressure on the flax fabric. After that, the second layer of mortar was poured. (Figure 1).

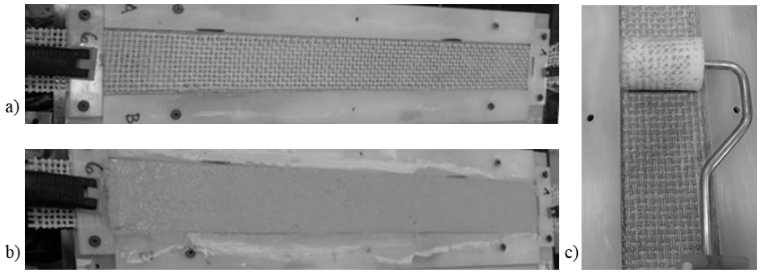

Figure 1. TRM coupons implementation: a) application of the textile; b) application of the second layer of mortar; c) pressure application on the textile.

The aging protocols adopted in this study are defined in accordance to the AC434-1011-R1 (2011) and described below:

- *Ambient*: the specimens are stored in ambient conditions for 3000 h (125 days) and are used as reference.
- *Water*: the specimens are immersed in deionised water for a period of 3000h (125 days).
- *Salt-water*: the specimens are immersed for a period of 3000 h (125 days) in a saline environment consisting of 3.5% in weight of sodium chloride (NaCl) aqueous solution, that is meant to reproduce the world’s ocean seawater average salinity.

- *Alkaline solution*: the specimens are immersed for a period of 3000 h (125 days) in an alkaline environment with 9.5 PH level, reproduced by adding sodium hydroxide (NaOH) to the deionised water.

In order to investigate the durability performance of both the composite material and its components, for each conditioning environment the follow specimens have been considered:

- 3 mortar prisms (40x40x160 mm^3) to be tested in bending and compression in accordance to the EN 196-1 (1994) (Figure 2a);
- 14 flax threads to be tested in tension with a free length of 100 mm (Figure 2b);
- 5 TRM coupons 5 mm thick, 60 mm large and 500 mm long (of which 300 mm of free length) (figure 2c).

Tensile tests on the fibres were performed by means of a Universal Testing Machine by using a 1 kN load cell, with a displacement rate of 4mm/min. TRM tensile tests were carried out by means of a Zwick Roell Schenck Hydropuls S56, with a maximum capacity of 630 kN in displacement control with a charging rate of 0.25 mm/min. A gripping system specifically studied for TRM tensile tests was adopted to clamp the coupons at the two charged edges for a length of 100 mm (Figure 2d).

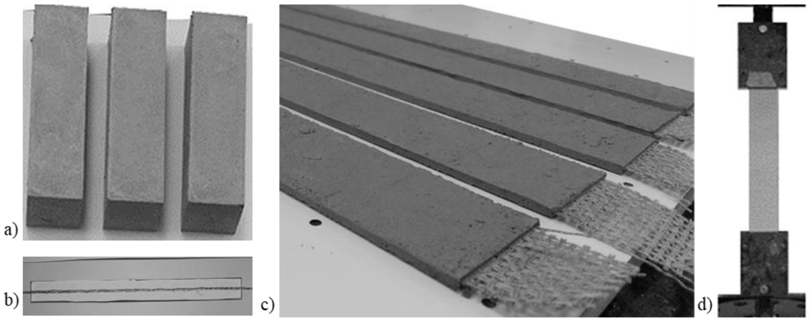

Figure 2. a) prismatic mortar specimens; b) textile specimen; c) TRM specimens; d) TRM coupon tensile test set up.

Figure 3a shows the clamping system adopted to perform tensile tests of TRM composite coupons.

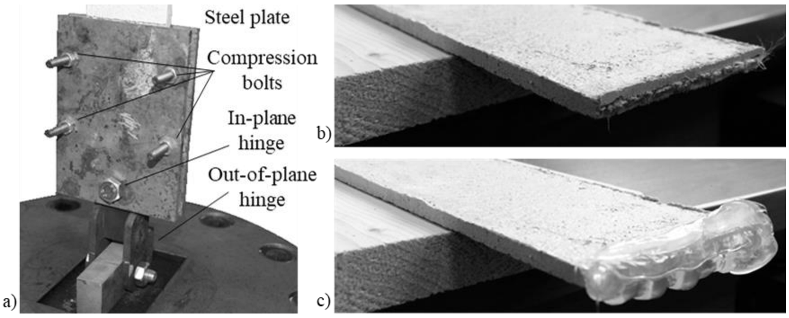

Figure 3. a) TRM tensile test clamping system; b) TRM coupon edge before the sealing; c) sealing of TRM coupon edges.

Two high stiff steel plates are glued at the edges of the specimens by means of epoxy resin, with a bond length of 100 mm, so that the tensile load is transferred by shear stresses. 4 bolts are placed in order to apply a compression stress, when needed. A further bolt is placed in the middle with the aim to realise a rotational release in the specimen plane. The latter is connected to a metallic system that constitutes a hinge allowing the rotations out of the plane. The hinge system was specifically studied to prevent bending and twisting moments to be transferred to the specimens in tension. If needed the two hinges bolts may be tightened to create a perfectly clamped configuration (Figure 3a). In the present study no compression was applied to the plates and both the rotations were permitted. To prevent the direct absorption of the water through flax textile, the two edges of the specimens were sealed by means of silicon before the immersion in the water solutions (Figure 3b,c).

3 RESULTS AND DISCUSSION

The TRMs response is shown in terms of stress-strain curves for each series of specimens (Figure 4). The responses of the specimens of the same series are overlapped in the same graph.

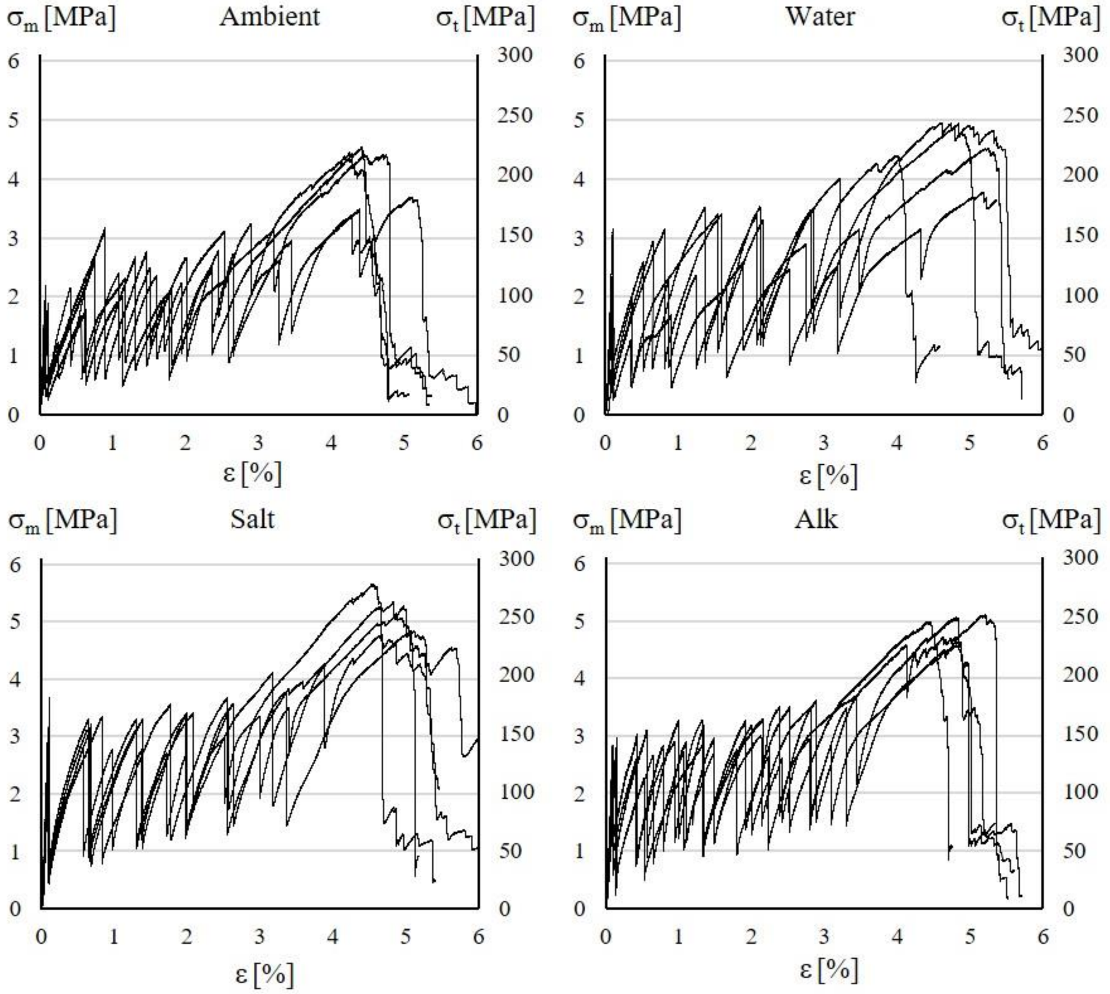

Figure4. Stress-strain curves of the series: a) TRM-Amb; b) TRM-W; 3) TRM-S; 4) TRM-Alk.

As expected in TRM systems, the response of all specimens is characterised by three stages:

- the first one represents the elastic response up to the occurrence of the mortar first crack;
- the second shows a transition phase characterised by the development of several cracks;
- the third one is mainly governed by the textile mechanical behaviour.

The gauge length to get the strain values corresponds to the entire free length of the specimens and it is equal to 300 mm. Concerning the normal stress within the composite two configurations have to be considered. In the case of the *uncracked* configuration the stress can be assumed to be constant throughout the entire surface of the composite, therefore the normal stress, σ_m, can be assessed by assuming the cross section of the entire composite (matrix and textile) A_m, that is equal to 300 mm^2. In the case of the *cracked* configuration we can assume, in proximity to the cracks, the entire load to be borne by the textile and therefore the maximum value of the normal stress, σ_t, can be evaluated by assuming the cross section of the textile alone, A_t, being equal to 6.12 mm^2. Both the values of the normal stress are reported in Figure 4. As regards the distribution of the normal stress between textile and matrix in the zone located between two consecutive cracks reference should be done to specific studies focused on the constitutive law at the mortar-to-fibre interface surface.

Table 1 shows the main parameters deriving from the tensile tests: the maximum load, $Load_{max}$; the displacement, s_{max}, the tensile stress, σ_{max}, and the strain, ε_{max}, corresponding to the maximum load; the stiffness at the first, E_I, the second, E_{II}, and the third stage, E_{III} (evaluated with respect to the mortar cross-section). Since the transition between the first and the second stages is not immediately ap-parent, a simplified procedure was applied to estimate the stiffness in the second stage by linking the end point of the elastic phase with the starting point of the third stage. By comparing the graphs and the relevant values of the mechanical parameters of the four series of specimens, it is clear that no significant decay of the mechanical behaviour occurred after the immersion of specimens in the various water solutions considered in the present study. Table 1 shows the main values of the mechanical parameters concerning the flax threads and the mortar prisms as well: flax threads tensile strength, $\sigma_{t,max}$, flax strain corresponding to the tensile strength, ε_{max}, fibres Young Modulus, E, hydraulic lime mortar tensile strength in flexion, $\sigma_{f,max}$, and compression strength, $\sigma_{c,max}$. As expected from the experimental evidences from the tensile tests on the TRM coupons, the same trend was observed in the behaviour of both the components of the composite material where no significant changing in strength were observed after the exposure to the ageing protocol.

Table1. Mean values of mechanical parameters of tensile tests (coefficient of variation in brackets, %)

	Flax TRM								Textile			Mortar	
Env.	$Load_{max}$ N	s_{max} mm	σ_{max} MPa	ε_{max} %	E_I GPa	E_{II} GPa	E_{III} GPa	τ MPa	$\sigma_{t,max}$ MPa	ε_{max} %	E GPa	$\sigma_{f,max}$ MPa	$\sigma_{c,max}$ MPa
Ambient	1224.22	13.65	4.08	4.55	2.01	0.03	0.12	0.24	283.67	3.32	9.07	4.81	11.79
	(13)	(8)	(13)	(8)	(32)	(33)	(10)	(18)	(15)	(12)	(12)	(3)	(4)
Water	1379.87	15.03	4.60	5.01	2.75	0.04	0.12	0.17	309.38	3.45	9.13	4.05	13.73
	(7)	(16)	(7)	(16)	(35)	(36)	(15)	(18)	(12)	(13)	(7)	(5)	(5)
Salt	1540.20	14.40	5.13	4.80	3.56	0.02	0.14	0.21	294.02	3.64	7.98	4.54	12.21
	(7)	(4)	(7)	(4)	(9)	(20)	(12)	(32)	(12)	(7)	(9)	(7)	(7)
Alkaline	1468.34	14.45	4.89	4.82	2.84	0.03	0.13	0.23	267.74	3.73	7.09	4.39	14.10
	(5)	(6)	(5)	(6)	(19)	(60)	(7)	(18)	(9)	(8)	(11)	(16)	(7)

The typical failure mode of the specimens is characterised by a sequence of sudden drops of the load, corresponding to the mortar cracks, up to the rupture of the textile in one of the cracked sections (Figure 5a). More generally, Figure 5 (b-e) shows the failure modes observed in a representative specimen for each series. It can be observed that in all the specimens the distance between two consecutive cracks is roughly the same. Consequently, being the amount of textile, and the specimen size, the same for all the samples, it can be said that also the interface behaviour at the fibres-to-matrix interface remains unchanged after the application of the aging protocol.

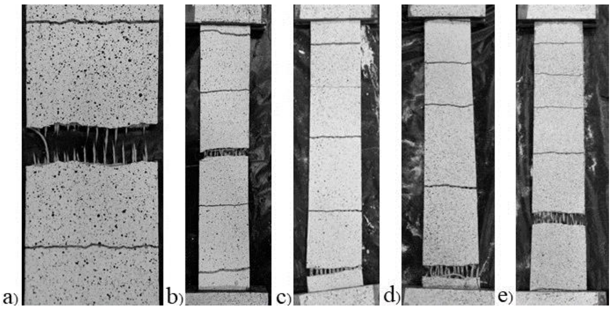

Figure5. a) textile rupture; failure mode of the specimens: b) TRM-Amb-5; c) TRM-W-5; d) TRM-S-3; e) TRM-Alk-3.

As a matter of fact, the results demonstrate that the investigated Flax-TRM system, exposed to the conventional protocols provided by AC434, complies with the acceptance criteria generally considered for qualifying composite materials.

4 INSIGHTS INTO THE MECHANICAL BEHAVIOUR

This section aims to provide an approximated value of the shear stress at the matrix-to-fibre interface. We can assume in each section the applied force, F, to be equal to the sum of a contribution borne by the textile and a contribution borne by the matrix, obtaining the Equation1:

$$F = \sigma_m(z)A_m + \sigma_t(z)A_t \tag{1}$$

where σ_m and σ_t represent the normal stress in the matrix and the textile, A_m and A_t are the cross section area of the matrix and the textile. By assuming the shear stress τ to be constant along the z and the normal stress in the mortar σ_m to be equal to zero in the cracked section, we obtain a stress distribution in proximity to the cracked section as shown in Figure 6.

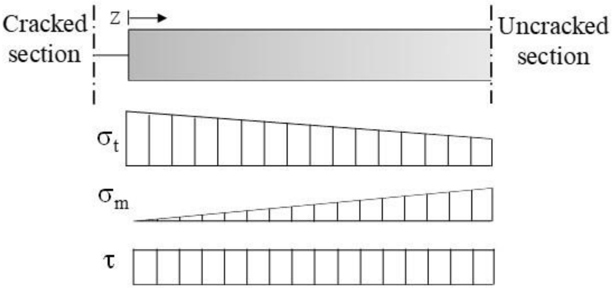

Figure6. Normal and shear stress distributions in proximity of a cracked section.

Therefore, we can assume that by moving along z the contribution to the applied force of the textile starts with a value equal to F in the cracked section, and decreases of the quantity that is transferred to the matrix equal to the integral of the shear stress τ along the z. Having assumed the τ constant, we obtain the Equation2:

$$\sigma_t(z)A_t = F - \tau \cdot p \cdot z \tag{2}$$

where p represents the lateral surface of the fibres per unit length (117.41mm^2/mm, Ferrara[3] et al. 2019). By substituting the Equation1 in the first member of the Equation2, and by assuming the section $z=\delta_0$ in which the crack occurs, and so by assuming the $\sigma_m=f_{t,m}$, being f_t the tensile strength of the mortar, we obtain a relationship between the shear stress τ and the distance between two consecutive cracks δ_o (Equation 3).

$$\tau = \frac{f_{t,m} A_m}{p \delta_0} \tag{3}$$

By measuring the average value of the distance between two consecutive cracks, a mean value of the shear stress τ has been computed for each specimens and reported in Table1. It is clear that no significant differences are observed by comparing each other the values of the different series.

5 CONCLUSION

The present work summarises the results of an experimental study aimed to investigate the mechanical response of Textile Reinforced Mortar (TRM) composite systems reinforced by Flax fabric exposed to different aging environments. The experimental campaign has led to the following conclusions:

- the tensile behaviour of Flax-TRM composites is characterised by a first elastic stage, then by development of several cracks in the matrix until the response is mainly governed to the textile up to the rupture of the flax threads;
- the clamping arrangement adopted during the Flax-TRM tensile test, specifically designed for this type of test, has proven to be an effective and handy system to correctly carry out the test;
- no significant decay of the mechanical properties occurred after the exposure of both the TRM and its components to any of the conditioning environments considered;
- insights into the mechanical behaviour of TRMs in tension provided an estimation of the maximum value of the mean shear stress at the fibre-to-matrix interface that lies in the range of 0.17-0.24 MPa.

The experimental investigation carried out in this study shows that the Flax-TRM composite material exposed to a conventional aging protocol complies with the acceptance criteria. However, further investigations are needed in order to get information about the aging process of mortar based composite systems reinforced by plant fibres, perhaps by adopting more severe conditioning environment or by increasing the period of exposure.

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