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Aging of lime-based TRM composites under natural environmental conditions

Ali Dalalbashi¹, Bahman Ghiassi², Daniel V. Oliveira³

5 ABSTRACT

6 Textile-reinforced mortar (TRM) composites, composed of textile fibers embedded in an 7 inorganic matrix, have been found to be a sustainable solution for strengthening of an existing 8 masonry or concrete structures. Despite the extensive recent attention in understanding the 9 mechanical performance of these composite, their long-term performance and durability 10 remain unknown. To address this gap, this paper presents a comprehensive experimental and 11 analytical study on the changes in the mechanical response of these composites across scales 12 (from material characterization to bond and tensile tests of TRM composites) under indoor 13 and outdoor conditions. For this purpose, steel and glass fibers with lime-based mortar are 14 used to investigate the pull-out response and the tensile behavior of TRM composites. The 15 results show that the long-term behavior of TRM composites is significantly dependent on the 16 mortar and fiber combination and, therefore, can change notably between different TRMs. It 17 is also observed that lime-based TRMs cannot reach their full mechanical properties under 18 indoor conditions even after 3 years. Outdoor conditions lead to better curing of the samples 19 and achieving significantly higher mechanical properties in these composites. However, it can 20 also lead to a significant deterioration at later ages.

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1	Keywords: TRM/FRCM, Fiber/matrix bond, Tensile behavior, Durability, Aging, Long-term
2	behavior.
3	Highlights:
4	1. A comprehensive experimental and analytical study on the changes in the mechanical
5	response of TRM composites under indoor and outdoor conditions is conducted.
6	2. 136 pull-out and tensile tests are performed on two steel and glass-based TRM
7	composite types.
8	<i>3. TRM mechanical characterizations are investigated for 920 days.</i>
9	4. Ageing effect on the bond behavior of steel-based TRM with two different mortar types
10	is investigated.
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1 **1 Introduction**

Textile Reinforced Mortar (TRM) composites, as an externally bonded reinforcement
technique, has received extensive attention as a sustainable solution for seismic strengthening
of masonry and historical monuments. TRMs, an attractive alternative to the Fiber Reinforced
Polymer (FRP) systems, are composed of continuous fabrics embedded in an inorganic matrix
[1]. Compared to FRPs, TRMs have some advantages, such as fire resistance and vapor
permeability [2,3].

The textile is usually made of glass, steel, basalt, carbon, or natural fibers (e.g., hemp, flax), and matrices are either cementitious or lime-based. Lime mortars are suitable for strengthening masonry and historical monuments because of the compatibility, sustainability issues, breathability, and capability of accommodating structural movements [4–9]. Meanwhile, cementitious matrices are usually used to strengthen strong and new masonry structures [10– 13].

14 TRM composites show a pseudo ductile response and multiple cracking by reaching their 15 maximum bond strength, making them suitable for seismic strengthening applications. This 16 multiple cracking behavior is owed to the fiber-to-mortar bond behavior [14–17]. 17 Understanding this mechanism and its effects on the short-term and long-term performance of 18 these composites is, therefore, of critical importance for having safe and resilient strengthening 19 solutions.

Although the mechanical behavior of lime-based TRMs has been the subject of a large number of recent studies [15,18–23], their long-term performance remains unaddressed and not understood. However, the durability performance of TRM composites has recently received attention from a few studies, in which the effect of freeze-thaw cycles, water attack, alkaline environment, salt crystallization on the tensile behavior, and TRM-to-substrate bond behavior
have been examined [24–29]. Aiming at a better understanding of this critical phenomenon,
this paper presents, for the first time, a comprehensive experimental and analytical study on
the effect of indoor and outdoor aging on the performance of these composites from the
material to composite scale.

6 2 Experiments

7 The experimental campaign investigates the changes in materials properties (compressive and 8 flexural strength), textile-to-mortar bond behavior, and the tensile response of TRM 9 composites with time under indoor and outdoor environmental conditions. The details of the 10 experimental plan are shown in Table 1. To address this aim, a set of samples (sample details 11 are presented in section 2.1 to 2.4) were placed in the laboratory conditions (20°C, 60 % RH) 12 for 920 days to replicate indoor conditions. Another set was placed outside under direct 13 exposure of rain and sun at the site of the University of Minho to simulate outdoor conditions. 14 The outdoor aged specimens, after initial curing of 90 days in the laboratory, were transported 15 to the outside of the laboratory since January 2017 for 830 days. Fig. 1 shows the changes in 16 mean temperature and humidity of air in the location of samples during the outdoor exposure. 17 A description of the materials, the specimens, and the test setups used are presented in the 18 following section.

19 2.1 Materials

20 Materials consisted of two commercially available lime-based mortars as the matrix, referred 21 to M1 and M2 throughout this paper, and the glass and the steel fabrics as reinforcing 22 materials. M1 mortar was a high-ductility hydraulic lime mortar composed of hydraulic lime 23 (NHL), Eco-Pozzolan, natural sand, special additives, synthetic polymers in water dispersion,

and short fibers [30]. M2 mortar was a pure natural NHL 3.5 lime and mineral geobinder base [31]. M1 mortar was prepared by mixing the powder with the liquid provided by the manufacturer (5:1 powder to liquid ratio according to the technical datasheets) in a low-speed mechanical mixer for four minutes to form a homogeneous paste. M2 mortar was prepared by mixing 1 kg powder with 0.212 kg water for seven minutes. According to the technical sheets provided by the manufacturer, the modulus of elasticity of the M1 and M2 mortars were 8 GPa and 9 GPa after 28 days, respectively.

The glass fabric (Fig. 2a) was a woven biaxial fabric mesh made of alkali-resistance fiberglass [32]. Its mesh size and area per unit length were equal to 25 mm×25 mm and 35.27 mm²/ m, respectively, according to the technical datasheets. The steel fiber (Fig. 2b) was a unidirectional ultra-high tensile steel sheet [33], with a density of 670 g/m², an effective area of one cord (five wires) equal to 0.538 mm², according to the technical datasheets. Each fiber was made by twisting five individual wires together, three straight filaments wrapped by two filaments at a high twist angle, forming a uniform cord.

These materials were used for the development of the steel-based and the glass-based TRM composite. The fabrics were used with their pair mortar provided by the same manufacturer (glass fibers with M1 mortar and steel fibers with M2 mortar). In addition, to investigate the effect of mortar type on the long-term bond behavior, the steel fiber was used with M1 mortar, too.

20 2.2 Material characterization tests

21 The compressive and flexural strength of the mortars was experimentally obtained at different

22 ages (3, 7, 14, 30, 60, 90, 180, and 920 days), according to ASTM C109 [34] and EN 1015-

23 11 [35], respectively. Five cubes $(50 \times 50 \times 50 \text{ mm}^3)$ and five prismatic $(40 \times 40 \times 160 \text{ mm}^3)$

specimens were prepared for each test at each age. Also, fifteen specimens were prepared to study the effect of real environmental exposure on the mechanical properties of the mortars. These specimens were cured in the lab environment for 90 days, stored outside, and then tested at the ages of 180 and 920 days (hence exposed to the real environmental conditions for 90 and 830 days, respectively).

6 The tests were performed by using a Lloyd testing machine under load-controlled conditions 7 at a rate of 150 N/s (for compressive tests) and 10 N/s (for flexural tests), as shown in Fig. 3. 8 In the compressive tests, for reducing the friction, a pair of Teflon sheets and oil was placed 9 between the specimen and the compression plates (Fig. 3a). The flexural tests were performed 10 in three-point bending test scheme with a 100 mm distance between the supports (Fig. 3b).

To obtain the tensile strength and elastic modulus of fabrics, a single roving was tested under direct tensile tests. A universal testing machine with a maximum load capacity of 10 kN was used for these tests. The tests were conducted under displacement-controlled conditions at a rate of 0.3 mm/min (Fig. 3c). The free length of the textile for all test specimens was equal to 300 mm. A 100 mm clip gauge located at the center of the specimens and the internal LVDT sensor of the machine measured the fiber deformation along with the tests, as shown in Fig. 3c.

18 2.3 Pull-out tests

The single-sided pull-out test setup developed and presented in [36] was used for examining the fiber-to-mortar bond performance. The specimens consisted of single fibers embedded in flat disk-shaped mortars with a cross-section of $125 \times 16 \text{ mm}^2$, as shown in Fig. 4a. The free length of the fiber was embedded in an epoxy resin block in 200 mm length and a rectangular cross-sectional area of $10 \times 16 \text{ mm}^2$ [36]. For preparing the pull-out specimens, first, one layer of mortar with 8 mm thickness was applied inside the wood molds, then fiber was placed on
it. Finally, the second layer of mortar with a thickness of 8 mm was applied. The specimens
were demolded after 24 hours of preparation and were placed in the lab environmental
conditions (20°C, 60 % RH) until testing.

For performing the pull-out tests, a U-shape steel support was used for supporting the specimens to a rigid frame, as shown in Fig. 4a and Fig. 5a. A mechanical clamp was used to grip the top of epoxy resin (thus the fiber) and to perform the tests. Two LVDTs with a 20 mm range and 2-µm sensibility were located at both sides of the epoxy block to record the slip. The averages of these LVDT measurements were presented as the slip in the experimental results. A servo-hydraulic system with a maximum capacity of 25 kN was used. The pull-out test procedure included the application of a constant displacement rate of 1.0 mm/min.

12 Pull-out tests were performed at 15, 30, 90, 180, 270, and 920 days of mortar age to study the 13 effect of mortar age on the textile-to-mortar bond behavior. The considered embedded lengths 14 were 150 mm and 50 mm for the steel and the glass fibers, respectively. These values were 15 equal to the effective bond length of the samples [37]. Four specimens were prepared and 16 tested for each testing age, resulting in 24 specimens for each the steel-based and the glass-17 based TRMs. Further, the effect of mortar type on the long-term bond behavior of textile-to-18 mortar was also examined by comparing the pull-out response of the steel fibers embedded in 19 M1 and M2 mortars at 90 and 920 days of aging.

Twelve samples from each TRM type were also prepared and placed outside the laboratory at the age of 90 days to be exposed to natural environmental conditions. These specimens were tested at the ages of 180, 270, and 920 days. Therefore, specimens were exposed to the natural environmental conditions for 90, 180, and 830 days, respectively

1 2.4 Tensile tests

2 Direct tensile tests were conducted on prismatic specimens with a length, width, and thickness 3 of 550 mm, 60 mm, and 10 mm, respectively, as shown in Fig. 4b. The samples consisted of 4 a 100 mm free fiber length at each side and a 350 mm central region in which the fabrics were 5 embedded in the mortar (Fig. 4b). The tensile specimens were prepared as follows: applying 6 the first layer of mortar inside the wood molds (5 mm thickness), placing the fabric mesh, and 7 finally applying the second layer of mortar with 5 mm thickness. The numbers of fibers 8 (parallel to tensile load) in each TRM system were 8 and 3 (with the area ratio of 0.0072 and 9 0.0044), respectively, for the steel and the glass-based TRM specimens (that was due to 10 specific geometrical properties of each mesh). Finally, samples were covered with plastic for 11 one day, then demolded and cured in the laboratory conditions (20°C, 60% RH) until the test 12 days.

13 One week before the test date, the free part of fibers was saturated and strengthened with resin 14 to avoid rupture of the fabric in the clamping area. Also, two steel plates $(100 \times 75 \times 10 \text{ mm}^3)$ 15 were glued to the free part of fibers to apply a uniform load to the fiber mesh.

16 For performing the tests, a mechanical clamp was used to grip the samples, see Fig. 5b. Two 17 LVDTs with a 20 mm range and 2-µm sensibility placed at both sides of the tensile specimen 18 and recorded the displacement. A servo-hydraulic jack with a maximum capacity of 25 kN 19 applied the direct tensile load to the specimens under a displacement control rate of 20 0.3 mm/min. The introduced stress was calculated by dividing the load by the cross-section area of the dry textile (steel and glass mesh area were equal to 4.3 mm² and 2.65 mm². 21 22 respectively). The strain was measured by dividing the mean value of the displacements 23 recorded from the two LVDTs by their base length (310 mm).

The tensile tests were performed at the mortar ages of 90, 180, 270, and 920 days. Five specimens were tested at each age resulting in 20 specimens for each steel and glass-based TRM type. In addition, 15 specimens from each TRM type were stored in natural environmental conditions and tested at the age of 180, 270, and 920 days (storing outside 90, 180, and 830 days, respectively).

6 **3** Experimental results and discussion

7 3.1 Material properties

8 Table 2 and Table 3 summarize the variation of compressive and flexural strength of both 9 mortar types aged under indoor and outdoor conditions. Although the peak compressive 10 strength of both mortars is similar, this value is reached at different ages showing governance 11 of different hydration rates in these two mortars. Also, it can be observed, as opposed to cementitious mortars reaching to the maximum strength after 28 days, the peak compressive 12 13 and flexural strength is not be reached at a specific age in these lime-based mortars. The peak 14 compressive strength of M1 mortar under indoor conditions is at 60 days (8.3 MPa), while its 15 peak flexural strength only at 180 days (6.0 MPa). Interestingly, a slightly higher compressive 16 strength, but lower flexural strength is obtained under outdoor conditions.

In contrast, the peak compressive strength in M2 mortar (stored indoor) is at 30 days (9.5 MPa), and the peak flexural strength at 920 days (3.1 MPa). In this mortar, under outdoor conditions, both flexural and compressive strength is slightly lower (except for compressive strength at 180 days). Overall, M1 mortar has a higher flexural strength than M2 mortar despite having a lower compressive strength, which indicates a more ductile response of this mortar due to the existence of short fibers in the mortar mix.

1 It can be indicated that outdoor condition causes both M1 and M2 mortar to reach to higher 2 compressive strength compared to the indoor aged specimens. This observation can be due to 3 the presence of more moisture and more hydration of mortars. In contrast, indoor aged 4 specimens dry faster, and the hydration processes stop. As for the fabrics, direct tensile tests 5 are on single yarns showed average tensile stress, Young's modulus, and rupture strain of 6 2972 MPa (coefficient of variation: COV=8%), 189.3 GPa (COV=8%), and 7 0.0188 mm/mm (COV= 9 %), for the steel cords, as well as 875 MPa (COV= 13 %), 65.9 GPa 8 (COV=5 %), and 0.0177 mm/mm (COV=10 %) for the glass yarn.

9 3.2 Pull-out behavior

10 For the analysis of the pull-out tests, the main characteristics of the load-slip curves are 11 obtained with age and presented and discussed in sections 3.21 and 3.2.2. These include the 12 peak load, its corresponding slip, initial stiffness, debonding energy, pull-out energy, and 13 chemical bond energy, as reported by [36,38,39]. Debonding energy expresses the energy 14 dissipated during the complete fiber debonding and is measured as the area under the load-slip 15 curve until the peak load [39,40]. The pull-out energy is the energy dissipated by the fiber-to-16 mortar frictional interface during the dynamic stage. It is measured as the area under the load-17 slip curve from the peak load until the end [39,41]. Material deformation and new surfaces by 18 cracking characterize the debonding energy [41]. Additionally, the pull-out energy attributes 19 the post-peak behavior of the fiber-to-mortar bond, which is significant in the pseud-ductility 20 behavior of TRM composites. Meanwhile, the chemical bond energy (G_d) is expressed as 21 follows: [42–44]:

22
$$G_{d} = \frac{2P_{\Delta}^{2}}{\pi^{2}E_{f}d_{f}^{3}}, N/mm$$
 (1)

In which P_∆ is the magnitude of the load drop at the peak load, E_f is the fiber elastic modulus,
 and d_f is the fiber diameter.

3 The load-slip curves are also used to extract the bond-slip laws following the stress-based 4 analytical model (shear-lag model) proposed by Naaman et al. [45]. A modified bond-slip law 5 is considered for simulating the slip hardening effect observed in experimental tests, see Fig. 6 6, [36]. The proposed bond-slip law model is characterized by the bond shear strength (τ_{max}), 7 the elastic bond modulus (κ), the frictional stress (τ_f), and the slip hardening coefficient (β). 8 In addition, in Fig. 6, d_f and L are the yarn diameter and bond length, respectively. η reflects 9 the changes in the slope of the pull-out curve and v is the rigid body displacement of the varn 10 after full debonding. The bond-slip laws parameters are obtained with the aim of the analytical 11 model, and its accuracy is evaluated by predicting the pull-out curves as followed. The 12 analytical pull-out modeling consists of two primary and secondary problems [45]. The output 13 of the primary problem is the bond-slip law parameters (τ_{max} , τ_{f} , and κ). In the secondary 14 problem, the load-slip curve is predicted from the obtained bond-slip law. For more details of 15 how to calibrate the bond-slip laws parameter and the modeled pull-out response, the reader 16 is referred to [36].

17 3.2.1 Steel-based TRM

The failure mode for all the specimens is fiber slipping/pull-out from the mortar. The pull-out curves at all ages show the typical linear, nonlinear, and dynamic stages with a drop of the load after the peak load (see, for example, the results obtained from samples tested at 15 days in Fig. 7a). This sudden drop load shows the transition from chemical/frictional bond to frictional bond and indicates that the frictional bond is smaller than the adhesive bond in this system [39,42,44,46,47]. After this load drop, a slip hardening behavior (forming a second peak load) and then a softening response until the end of the tests is observed [39,44,47–50].
Comparing the load-slip curves of the samples tested at different ages under indoor conditions,
Fig. 7b, shows that in general, the bond behavior is improved with time even until 920 days,
a slight decrement of bond performance is also observed at some ages. This behavior is
because of the increase in the M2 mortar strength.

6 The role of the mortar type seems to be significant for the bond performance of indoor aged 7 samples, as shown in Fig. 7c. Specimens prepared with M1 mortar show a better bond 8 performance at 90 days but a worse one at 920 days than specimens prepared with M2 mortar. 9 It seems that although pull-out samples prepared with M1 mortar gain higher strengths in early 10 ages, bond deterioration or mortar shrinkage in longer ages governs their performance at later 11 ages. Also, a comparison between the pull-out response of M1 mortar at 90 and 920 days 12 shows (Fig. 7c) that the transition from the progressive debonding stage to the dynamic stage 13 has changed from a smooth and upward trend to a sudden drop in the pull-out load.

14 Comparing the pull-out curves of indoor and outdoor aged samples (made of M2 mortar), Fig. 15 7d, shows that generally, outdoor aged samples have a better bond performance. This 16 observation can be due to a higher hydration degree achieved in the samples aged under 17 outdoor conditions. Clearly, hydraulic lime-based mortars aged under indoor conditions have 18 a considerably slower hydration degree and thus the bond performance. The peak load of 19 samples aged (at 920 days) under outdoor conditions is 1125.9 N, which is 1.19 times that of 20 samples aged under indoor conditions. It should also be noted that samples aged under outdoor 21 conditions reached a peak load of 1550.3 N at 270 days showing a deterioration mechanism 22 afterward until 920 days.

1 To better understand the role of environmental conditions, the changes in the key 2 characteristics of the pull-out curves with time is presented in Fig. 8. Here, the individual 3 sample results are all presented together with a nonlinear regression line showing the general 4 trend of the results with time. The mean values of pull-out parameters of indoor and outdoor 5 specimens are presented in Table A1 and Table A2 in the appendix section. It can be observed 6 that the peak load, the initial stiffness, the deboning energy, the chemical bond energy, and the pull-out energy show, in general, an incremental trend up until 270 days, and then the 7 8 values have decreased until the end of the tests in outdoor aged samples. Meanwhile, in indoor 9 aged samples, these properties reached their peak value at an early age and, after that, do not 10 show a significant change with time except for the chemical bond energy and initial stiffness, 11 which are slightly decreased in the initial stage of exposure. As expected, the variation of the 12 experimental results is also higher in the samples aged under outdoor conditions.

13 The average bond-slip laws are also presented in Fig. 9. Again, the bond strength, τ_{max} , (Fig. 14 9a), and the frictional strength, τ_f , (Fig. 9b) show an incremental trend in outdoor aged samples 15 (bond strength decreases from 270 days to 920 days), while no significant changes can be 16 observed in indoor aged samples. The bond modulus (κ), however, seems to be increasing 17 significantly in outdoor aged samples, but slightly decreasing in the early ages in indoor aged 18 samples (note a high variation is observed in the results for this parameter), Fig. 9c. At the 19 same time, the slip hardening coefficient (β) shows an increasing trend for both indoor and 20 outdoor aged samples (Fig. 9d); nevertheless, the indoor aged specimens show higher values 21 in contrast to the outdoor aged specimens. A comparison between τ_f and β shows the higher 22 frictional stress, the lower slip hardening coefficient. The mean values of the bond-slip laws

for indoor and outdoor specimens are also presented in Table A3 and Table A4 for interested
 readers.

3 3.2.2 Glass-based TRM

4 The pull-out curves of the individual samples, the experimental average, and the analytical 5 curves of the glass-based TRM are presented in Fig. 10. These specimens, in contrast to steel-6 based TRMs, do not show a sudden load drop after the peak load; thus, the transition from the 7 progressive debonding to the dynamic stage is smooth. This behavior can be due to the 8 insufficient curing condition of the M1 mortar, followed by the weak bond at the fiber-to-9 mortar interface. Comparing the pull-out curves tested at different ages and under indoor 10 conditions (Fig. 10b) shows that at early and late ages (until 30 days and after 270 days), the 11 slip hardening is followed by a softening in the pull-out curves. However, at 90 and 180 days, 12 the slip hardening is followed by a second slip hardening effect leading to significant 13 absorption of energy. This change of final slip softening at early ages to slip hardening seems 14 to be a result of further hydration of the mortar. Nevertheless, at later ages, it seems that a sort 15 of bond deterioration or mortar shrinkage by forming micro-cracks at the bond interface has 16 occurred, which led to a slip softening behavior.

17 Comparison of the indoor and outdoor aged samples indicates again that generally, outdoor 18 aged samples show a better bond performance compared to indoor aged samples, see Fig. 10c. 19 This behavior is in line with what is observed for the M1 mortar changes at indoor and outdoor 20 conditions. As also observed in indoor aged samples, a degradation of the bond performance 21 can also be observed in the samples aged under outdoor conditions at later ages.

The key characteristics of the pull-out response, when compared in Fig. 11, show that the peak load and debonding energy of outdoor samples are slightly higher than the corresponding

1 specimens tested in the indoor condition. However, both the peak load and debonding energy 2 show a decline behavior from 270 days to 920 days in outdoor aged samples. The initial 3 stiffness of the outdoor aged samples is significantly higher than the indoor aged samples 4 becoming more than three times at 920 days, owing to better curing conditions or higher 5 hydration of the M1 mortar. Moreover, both the debonding energy and the pull-out energy 6 show an increase trend for indoor aged samples, energy desorption is always smaller than that of outdoor aged samples up until the end of the tests where they become close. Increasing the 7 8 energy desorption at the early ages of outdoor exposure can be due to improving the bond of 9 fiber-to-mortar. By increasing the exposure ages, the bond declined due to deterioration, 10 shrinkage, or micro-cracks. Again, the experimental mean values are presented in Table A5 11 and Table A6.

12 The changes in the bond-slip law parameters are shown in Fig. 12, Table A7, and Table A8. 13 The bond strength, τ_{max} , is always higher in outdoor aged samples than indoor samples (almost 14 twice at 920 days), as shown in Fig. 12a. On the other hand, the frictional stress, τ_f , shows an 15 incremental trend (initially with higher rates and then lower rates) in samples under indoor 16 conditions, in contrast to the outdoor aged samples in which a significant deterioration can be 17 observed from 270 to 920 days. By contrast, the bond modulus, κ , and slip hardening 18 coefficient, β , do not show a significant change in indoor aged samples but increase 19 significantly with time in outdoor aged samples. These observations can show the effect of 20 higher hydration of the M1 mortar on the parameters of the bond-slip law

21 3.3 Tensile behavior

Fig. 13 shows the schematic tensile behavior of TRM composites [1,18,19,21,51–53], in which the tensile load was applied to TRM composites. While in this study, the load is applied 1 directly to the fiber meshes. Three stages are usually identified in the tensile response: (stage 2 I) a linear stage which presents the behavior of uncracked composite material [51–53]; (stage 3 II) a crack development stage in which multiple cracks are formed in the specimens. The 4 distance, the width, and the number of cracks are strictly dependent on the fiber-to-mortar 5 bond behavior in this stage [51–53]. Finally, (stage III), no further cracking occurs, and the 6 load is only resisted by the bundles/yarns. The peak tensile stress (σ), the strain corresponding 7 to the peak stress (ϵ) and tensile modulus (E) in each stage, and the saturated crack spacing 8 are the key characteristics of the tensile response of these composites and therefore will be 9 discussed in the next sections for each aging condition and TRM type.

10 3.3.1 Steel-based TRM

11 The typical tensile stress-strain response of individual steel-based TRMs at 90 days, together 12 with their experimental average curves, are presented in Fig. 14a. In all the specimens, fiber 13 rupture was the governing failure mode. In addition to the three typical stages of the tensile 14 response, explained previously, a final softening stage can be observed in the stress-strain 15 curves. This final softening is probably due to the non-uniform distribution of the stresses 16 among the cords or the step-by-step failure of wires. Cracking of the mortar can be clearly 17 observed in the samples Fig. 14b. Many cracks have formed, showing the balance between the 18 bond and mortar strength and suitable textile-to-mortar bond behavior in these samples.

At first glance, no significant change is observed in the tensile response of samples aged under indoor conditions, Fig. 14c, or the samples aged under outdoor conditions (despite the final tension strength), Fig. 14d, with time. However, looking at the changes in the main characteristics of the tensile response, Fig. 15, shows interesting trends. Only a slight increase can be observed in the first cracking stress, σ_1 , with time in indoor aged samples. However,

1 the cracking strength is increased until 270 days and then decreased until the end of the tests 2 in the outdoor aged samples. At all times, however, outdoor samples show higher cracking 3 stress than the indoor samples, which can be again attributed to a higher hydration degree of 4 the mortar. These observations are in line with the observed changes in the mechanical 5 properties of the mortars reported in previous sections. The stress corresponding to the end of 6 stage II, σ_2 , increases notably with time in both indoor and outdoor aged samples. Again, 7 outdoor aged samples show a higher σ_2 than indoor aged samples. In contrast, σ_3 , shows an 8 initial decrease and then an increase in both cases. As for stiffness, E₁ is increased initially and 9 then decreased, E₂, increases, and E₃ does not show any significant changes with time. The 10 saturation crack spacing of the samples gradually decreases over time, Fig. 16a. The mean 11 values are also explicitly presented in Table A9 and Table A10.

12 3.3.2 Glass-based TRM

The typical tensile stress-strain response of individual glass-based TRMs (at 90 days), together with their experimental average curves, are presented in Fig. 17a. In all the specimens, again, fiber rupture was the governing failure mode. Although the three stages of the tensile response are identified in the curves, no fluctuation in the crack developing stage can be observed, which is due to the small number of cracks formed in these samples and/ or the low tensile strength of the glass fibers (Fig. 17b).

19 No significant change is observed in the tensile response of samples aged under indoor 20 conditions, Fig. 17c, though the samples aged under outdoor conditions, show the tensile 21 behavior declines by increasing the exposure, as presented in Fig. 17d. However, an in-depth 22 look at the changes in the main characteristics of the tensile response (Fig. 18) shows some 23 differences between the samples aged under indoor and outdoor conditions. As opposed to

1 steel-based TRM, the first cracking stress, σ_1 , decreases with time. This decrease is 2 significantly higher in outdoor aged specimens in the first 270 days, which is then recovered 3 to some extent until the end of the tests. The stress corresponding to the end of stage II, σ_2 , 4 increases with time in indoor aged samples but decreases in outdoor aged samples. σ_3 , shows 5 a slight decrease in indoor aged samples and a significant one in outdoor aged samples. This 6 observation shows the sensitivity of the glass yarns to outdoor environmental conditions, 7 which has led to their mechanical degradation. As for stiffness, E₁ increases with time for 8 indoor aged samples and decreases for outdoor aged samples, E2 increases in indoor aged 9 samples but shows a decrease after 270 days in outdoor aged samples and E₃ decreases in both 10 cases. In contrast to Steel-based TRM, the crack spacing is decreased in indoor aged but 11 decreases in outdoor aged samples, Fig. 16b. The mean values are also explicitly presented in 12 Table A11 and Table A12.

13 **4** Conclusions

14 The effect of indoor and outdoor aging on the micro- and macro-mechanical behavior of two 15 lime-based TRMs were examined in this paper. A comprehensive experimental and analytical 16 study was performed to investigate the changes of the mortar mechanical properties, the 17 textile-to-mortar bond behavior, and the TRM tensile response was characterized until 920 18 days of aging. From the results obtained in this study, the following conclusions can be drawn: 19 In lime-based TRMs, special attention needs to be given to the hydration degree of the • 20 mortar and its effects on the short-term and long-term performance of those 21 composites. 30 days curing age testing, as usually used for cementitious matrices, does 22 not seem to be particularly a good reference for hydraulic lime-based TRMs. With the 23 large variety of the characteristics of the existing lime-based mortars, it is also difficult

to propose a specific time that is representative of the long-term behavior of those
composites. The experimental results showed a good correlation between the changes
in the textile-to-mortar bond behavior and the flexural strength of the mortar. Flexural
strength is, therefore, proposed to be used as an indication for evaluating the changes
in the response of lime-based TRMs in the lack of more detailed results.

As expected, the mortar type was found to have a significant influence on the shortterm and long-term bond performance and therefore cracking behavior of TRMs.

8 In both systems studied here, TRMs did not reach their highest performance under 9 indoor conditions even after 920 days. This means that under indoor conditions the 10 hydration of the mortar is still in progress. This was more noticeable in the steel-based 11 TRM, which showed a much lower bond strength when cured under indoor conditions 12 than outdoor conditions. Advanced curing conditions may be useful for accelerating 13 hydration such as autoclave, steam, and strength achievement. Outdoor conditions in 14 both systems lead to better mechanical performance in both systems and led to the 15 deterioration in the long-term. The degree of this deterioration, which was significant 16 in some cases) was observed to be dependent on the TRM type (fiber-mortar 17 combination).

• The difference between the tensile response and cracking behavior of the TRM 19 composites under indoor and outdoor conditions was also noticeable and was observed 20 to be dependent on the TRM type. In the steel-based TRM, aging led to the decrement 21 of the crack spacing and no specific change in the final tensile strength. Meanwhile, in 22 the glass-based TRM, the effect of outdoor exposure was significant in terms of crack 23 spacing (increased) and tensile strength (decreased).

Due to the high humidity and rain, the hydration rate of the hydraulic lime-based
 mortars was high, which increased the strength of the specimens. In contrast, owing to
 the constant humidity inside the laboratory, the mortars showed low hydration rates,
 and their strength gradually increased over 920 days.

5

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Exposing time [days] Fig. 1. Changes of the temperature and humidity of air at Guimarães region during outdoor exposure conditions.



Fig. 2. Fiber configuration: (a) glass mesh; (b) steel mesh.



(a) (b) (c) Fig. 3. Mechanical characterization tests: (a) compressive mortar test; (b) flexural mortar test; (c) fiber direct tensile test.



(b)

Fig. 4. Specimens' configurations and corresponding test setups: (a) pull-out test; (b) tensile test.

1 2



(a) (b) Fig. 5. Test setups and instrumentation used: (a) pull-out test; (b) tensile test.





Fig. 7. Pull-out behavior of the steel-based TRM: (a) typical pull-out behavior; (b) effect of the mortar age; (c) effect of the mortar type; (d) effect of environmental condition.



Fig. 8. Pull-out behavior parameters of the steel-based TRM: (a) peak load; (b) initial stiffness; (c) debonding energy; (d) pull-out energy; (e) chemical bond energy.



Fig. 9. Bond-slip law parameters of the steel-based TRM: (a) bond shear strength; (b) friction stress; (c) bond modulus; (d) slip hardening coefficient.



Fig. 10. Pull-out behavior of the glass-based TRM: (a) typical pull-out behavior; (b) effect of the mortar age; (c) effect of environmental conditions.



Fig. 11. Pull-out behavior parameters of the glass-based TRM: (a) peak load; (b) initial stiffness; (c) debonding energy; (d) pull-out energy.



Fig. 12. Bond-slip law parameters of the glass-based TRM: (a) bond shear strength; (b) friction stress; (c) bond modulus; (d) slip hardening coefficient.



Fig. 13. Typical tensile stress-strain behavior of TRMs.





Fig. 14. Tensile response of the steel-based TRM: (a) typical tensile behavior; (b) saturated cracking stage at 90 days (indoor aged); (c) effect of the mortar age under indoor conditions; (d) effect of mortar age under outdoor conditions.











Fig. 17. Tensile response of the glass-based TRM: (a) typical tensile behavior; (b) saturated cracking stage at 90 days (indoor aged); (c) effect of the mortar age under indoor conditions; (d) effect of mortar age under outdoor conditions.





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Table 1. Overview of the experimental tests.

Test type	Objective	Mortar	Fiber	Bond length [mm]	Age [days]
Mortar strength	effect of the mortar age on its strength	M1-M2	-	-	15 30 60 90 180 920
	effect of the real environmental condition on the mortar strength	M1-M2	-	-	180 920
	effect of the mortar age on the textile-to-mortar bond	M1- M2	glass- steel	50- 150	15 30 90 180 270 920
pull-out	effect of the real environmental condition on the textile-to-mortar bond	M1- M2	glass- steel	50- 150	180 270 920
	effect of mortar type	M- M2	steel	150	90 920
toncila	effect of the mortar age on the tensile behavior of TRM composites	M1- M2	glass- steel	350	90 180 270 920
tensile	effect of the real environmental condition on the tensile behavior of TRM composites	M1- M2	glass- steel	350	180 270 920

3 4

Table 2. Mechanical properties of mortars aged under indoor conditions.*

Mortar	Test	3 davs	7 davs	14 days	30 days	60 days	90 days	180 days	920 days
	Compressive strength (f _c) [MPa]	0.9 (4)	3.8 (5)	5.9 (8)	7.1 (9)	8.3 (11)	7.8 (4)	7.5 (10)	5.7 (12)
MI	f _c / f _{c-30 days} [%]	13	53	84	100	117	111	106	81
	Flexural strength (fft)		2.5	4.0	4.7	5.1	5.6	6.0	5.2
	[MPa]	-	(7)	(3)	(7)	(3)	(10)	(10)	(11)
	f _{ft} / f _{ft-30 days} [%]	-	53	86	100	108	109	118	102
	Compressive strength (f _c) [MPa]	3.9 (7)	6.5 (7)	8.8 (7)	9.5 (10)	8.8 (12)	8.9 (5)	7.5 (9)	7.9 (5)
M2	f _c / f _{c-30 days} [%]	41	68	92	100	92	93	79	83
	Flexural strength (f _{ft})	1.4	1.5	1.8	2.5	2.1	2.3	2.6	3.1
	[MPa]	(3)	(3)	(12)	(9)	(7)	(9)	(13)	(12)
	f _{ft} / f _{ft-30 days} [%]	55	60	71	100	82	92	103	123

*Coefficients of variation in percentage terms are provided inside parentheses.

Mortar	Test	90 days	180 days	920 days
	Compressive strength (f _c)	7.8	9.7	6.6
M1	[MPa]	(4)	(16)	(8)
	Flexural strength (f _{ft})	5.6	5.3	4.1
	[MPa]	(10)	(7)	(11)
	Compressive strength (f _c)	8.9	10.9	6.3
MO	[MPa]	(5)	(12)	(5)
IVIZ	Flexural strength (f _{ft})	2.3	2.3	2.3
	[MPa]	(9)	(12)	(3)

Table 3. Mechanical properties of mortars aged under outdoor conditions.*

*Coefficients of variation in percentage terms are provided inside parentheses.

5 7 APPENDIX

6 7

2 3 4

Table A1. Pull-out properties of the steel-based TRM aged under indoor conditions.* Chemical Slip Pull-out Peak Debonding Initial corresponding bond Age Number of energy Mortar load energy stiffness to peak load specimens [days] energy [N] [N.mm] [N.mm] [N/mm] $[J/mm^2]$ [mm] 711.1 376.0 1902.6 0.8 0.06 6030.6 4 15 (20)(37) (19) (16)(7) (7)871.9 529.2 0.09 8132.8 2076.1 0.9 4 30 (9) (9) (20)(57) (9) (23) 0.8 740.6 364.5 0.07 6763.9 1277.4 90 4 (3)(9) (10)(16)(10)(10)M2 0.9 730.9 436.8 0.04 7253.0 1360.3 180 4 (16)(17)(32)(54)(16)(14)0.8 747.9 408.4 0.09 6373.3 1865 4 270 (29)(21)(17)(43)(55)(2)1.02 945.3 614.8 0.06 8691.6 1889.2 920 3 (11)(14)(6)(50)(8)(25)1.0 916.6 599 12514.4 2657.8 90 4 _ (8) (18)(12)(14)(16)M1 537.0 0.01 1.1 769.2 7358.8 1202.7 920 4 (19)(8) (28) (91) (13)(6)

*Coefficients of variation in percentage terms are provided inside parentheses.

8 9 10

Table A2. Pull-out properties of the steel-based TRM aged under outdoor conditions*.

Age [days]	Slip corresponding to peak load [mm]	Peak load [N]	Debonding energy [N.mm]	Chemical bond energy [N.mm]	Pull-out energy [N.mm]	Initial stiffness [N/mm]	Number of specimens
180	1.3 (5)	1121.5 (4)	1045.0 (11)	0.08 (35)	10139.3 (5)	2871 (27)	3
270	1.7 (6)	1550.3 (2)	1839.2 (5)	0.12 (56)	12262.0 (1)	3222.3 (13)	3
920	1.3 (36)	1125.9 (16)	971.0 (43)	0.03 (25)	9243.7 (12)	2058.5 (40)	4



*Coefficients of variation in percentage terms are provided inside parentheses.

Table A3. Bond-slip laws of the steel-based TRM aged under indoor conditions.*

Mortar	Age [days]	τ _{max.} [MPa]	τ_{f} [MPa]	к [Mpa/mm]	β
	15	3.97	1.34	17.72	0.0001
	15	(18)	(6)	(45)	(0)
	20	5.10	1.69	22.06	0.0004
	50	(28)	(6)	(53)	(29)
	90	3.05	1.42	4.93	0.0003
MO		(15)	(10)	(45)	(0)
1012	180	3.01	1.51	6.52	0.0005
		(27)	(16)	(55)	(33)
	270	4.32	1.39	17.56	0.0003
		(38)	(14)	(66)	(33)
	020	4.73	1.94	17.92	0.0006
	920	(30)	(8)	(62)	(14)
	00	4.53	2.09	38.73	0.0020
M1	90	(20)	(14)	(35)	(41)
111	020	2.55	1.77	4.34	0.0001
	920	(13)	(10)	(30)	(19)

*Coefficients of variation in percentage terms are provided inside parentheses.

Table A4. Bond-slip laws of the steel-based TRM aged under outdoor conditions.*

Age [days] τ_{max} [MPa] τ_{f} [MPa] K [MPa/mm] p	
6.64 2.32 41.36 0.000	5
(6) (7) (47) (44)	
10.01 3.17 45.34 0.000	4
(7) (0) (16) (43)	
4.92 2.91 22.00 0.000	3
(28) (11) (100) (60)	

4 5 6 *Coefficients of variation in percentage terms are provided inside parentheses.

Table A5. Pull-out properties of the glass-based TRM aged under indoor conditions.*

Age [days]	Slip corresponding to peak load [mm]	Peak load [N]	Debonding energy [N.mm]	Pull-out energy [N.mm]	Initial stiffness [N/mm]	Number of specimens
15	2.6 (12)	284.6 (10)	542.9 (16)	2279.0 (8)	456.1 (4)	4
30	1.9 (31)	250.5 (30)	380.2 (49)	2166.9 (38)	815 (22)	4
90	2.3 (13)	378.8 (16)	656.4 (8)	4554.6 (19)	857.8 (22)	4
180	2.3 (27)	390.8 (12)	648.4 (32)	5133.8 (10)	909.1 (35)	4
270	3.1 (13)	339.5 (17)	792.7 (24)	2775.7 (28)	917.3 (38)	4
920	1.9 (22)	410.9 (10)	607.6 (13)	2569.8 (28)	785.5 (43)	4

*Coefficients of variation in percentage terms are provided inside parentheses.

Table A0. I un-out properties of the glass-based TKW aged under outdoor conditions.							
Ago	Slip corresponding to	Dook	Debonding	Pull-out	Initial	Number	
[days]	nosk load [mm]	I cak	energy	energy	stiffness	of	
[uays]	peak load [mm]	IOau [IN]	[N.mm]	[N.mm]	[N/mm]	specimens	
100	1.8	459.7	622.8	4878.2	1012.7	4	
160	(18)	(4)	(23)	(19)	(18)	4	
270	2.2	437.6	801.0	4461.3	1423.0	4	
	(11)	(15)	(21)	(18)	(48)	4	
920	2.1	403.2	695.9	3542.4	3069.2	4	
	(20)	(12)	(18)	(24)	(2)	4	

Table A6. Pull-out properties of the glass-based TRM aged under outdoor conditions.*

*Coefficients of variation in percentage terms are provided inside parentheses.

Table A7. Bond-slip laws of the glass-based TRM aged under indoor conditions.*

Age [days]	τ _{max.} [MPa]	τ_{f} [MPa]	κ [MPa/mm]	β
15	1.97	1.03	6.46	0.009
15	(16)	(22)	(35)	(34)
20	2.92	0.65	14.04	0.017
50	(28)	(34)	(49)	(51)
00	5.38	0.86	18.57	0.028
90	(24)	(28)	(28)	(29)
190	2.73	1.25	10.35	0.009
180	(24)	(11)	(69)	(76)
270	2.88	0.91	11.70	0.014
270	(45)	(34)	(92)	(111)
020	5.43	1.64	15.51	0.013
920	(37)	(12)	(63)	(58)

*Coefficients of variation in percentage terms are provided inside parentheses.

Table A8.	Bond-slip lav	vs of the glass	-based TRM	A aged under	outdoor co	onditions.*

Age [days]	τ _{max.} [MPa]	$\tau_{\rm f} [{ m MPa}]$	κ [MPa/mm]	β
180	6.62	1.6	26.20	0.007
180	(32)	(12)	(48)	(38)
270	8.94	1.37	51.17	0.013
	(9)	(14)	(50)	(28)
920	8.81	0.49	101.06	0.056
	(6)	(14)	(3)	(21)

*Coefficients of variation in percentage terms are provided inside parentheses.

	Table A9. Tensile parameters of the steel-based TRM aged under indoor conditions.*													
Age [days]	E ₁ [GPa]	E ₂ [GPa]	E ₃ [Gpa]	ε ₁ [%]	ε ₂ [%]	ε ₃ [%]	σ ₁ [MPa]	σ ₂ [MPa]	σ ₃ [MPa]	Number of cracks	Distance between cracks [mm]	Number of specimens		
90	1266.3 (62)	37.5 (53)	163.9 (10)	0.03 (69)	0.15 (21)	1.40 (13)	226.2 (15)	277.8 (17)	2318.4 (9)	8	39	5		
180	3094.3 (25)	63.4 (31)	162.8 (5)	0.01 (17)	0.19 (8)	1.14 (8)	227.1 (22)	339.0 (21)	1887.8 (6)	9	36.7	4		
270	1464.7 (29)	56.7 (66)	149.4 (10)	0.02 (19)	0.21 (19)	1.49 (10)	229.9 (25)	332.0 (12)	2223.8 (6)	11	30.8	4		
920	986.8 (37)	85.6 (16)	181.0 (22)	0.03 (37)	0.22 (4)	1.51 (25)	244.1 (12)	411.4 (6)	2582.8 (8)	13	26.1	3		



2 3 4

Table A10. Tensile behavior of the steel-based TRM aged under outdoor conditions. *

*Coefficients of variation in percentage terms are provided inside parentheses.

	Table 7110. Tensile benavior of the steel based TRW aged under buddoor conditions.													
Age [days]	E1 [GPa]	E ₂ [GPa]	E ₃ [GPa]	ε ₁ [%]	ε ₂ [%]	ε ₃ [%]	σ ₁ [MPa]	σ ₂ [MPa]	σ ₃ [MPa]	Number of cracks	Distance between cracks [mm]	Number of specimens		
180	1159.6 (41)	61.6 (37)	184.8 (4)	0.03 (32)	0.20 (4)	1.29 (5)	291.7 (9)	399.8 (5)	2411.7 (3)	11	29.6	4		
270	1057.1 (10)	56.7 (47)	150.6 (8)	0.03 (22)	0.23 (10)	1.18 (20)	303.9 (14)	416.3 (4)	1877.5 (26)	15	20	3		
920	400.4 (32)	92.4 (26)	173.1 (8)	0.08	0.24	1.37 (6)	245.1 (22)	390.2 (11)	2340.9 (4)	14	25	3		



*Coefficients of variation in percentage terms are provided inside parentheses.

Table A11. Tensile behavior of the glass-based TRM aged under indoor conditions.*

Age [days]	E ₁ [GPa]	E ₂ [GPa]	E ₃ [GPa]	ε ₁ [%]	ε ₂ [%]	ε ₃ [%]	σ ₁ [MPa]	σ ₂ [MPa]	σ ₃ [MPa]	Number of cracks	Distance between cracks [mm]	Number of specimens
90	408.1 (44)	12.2 (46)	49.3 (13)	0.10 (40)	0.47 (25)	1.83 (18)	353.1 (15)	395.6 (12)	1054.0 (2)	4	63.8	5
180	323.3 (43)	34.5 (29)	60.7 (18)	0.14 (38)	0.46 (32)	1.68 (8)	397.4 (14)	472.6 (18)	932.5 (2)	3	102.8	4
270	491.3 (25)	19.0 (24)	42.2 (7)	0.07 (12)	0.52 (33)	1.68 (12)	358.2 (17)	440.8 (16)	934.4 (8)	4	78.2	5
920	735.3	25.6 (23)	41.6	0.05	0.77	1.98	339.6 (10)	528.8 (20)	1006.9 (17)	6	46.9	4

8 9 10

*Coefficients of variation in percentage terms are provided inside parentheses.

Table A12. Tensile behavior of the glass-based TRM aged under outdoor conditions.*

Age [days]	E ₁ [GPa]	E ₂ [GPa]	E ₃ [GPa]	ε ₁ [%]	ε ₂ [%]	ε ₃ [%]	σ ₁ [MPa]	σ ₂ [MPa]	σ ₃ [MPa]	Number of cracks	Distance between cracks [mm]	Number of specimens
180	670.7 (29)	34.5 (23)	51.5 (27)	0.06 (13)	0.44 (18)	1.07 (18)	365.1 (22)	497.6 (15)	804.7 (10)	2	115	3
270	509.9 (46)	59.0 (43)	30.5 (30)	0.02 (42)	0.45 (33)	0.82 (24)	71.4 (15)	292.1 (15)	406.5 (11)	4	88	4
920	384.0 (22)	27.2 (44)	38.9 (22)	0.05 (32)	0.55 (21)	1.10 (21)	193.8 (16)	320.9 (15)	528.0 (11)	2	119	4

*Coefficients of variation in percentage terms are provided inside parentheses.

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