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Designing epoxy viscosity for optimal mechanical performance of coated Glass Textile Reinforced Mortar (GTRM) composites

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Abstract

Preliminary epoxy coating of the reinforcing fabric provides an effective approach for improving matrix-to-fabric strength in inorganic matrix composites. We investigate the effect of epoxy resin dilution in acetone on uni-axial tensile performance of coated alkali-resistant (AR) glass fabric embedded in a lime-based matrix. Remarkably, it is found that dilution has a mixed effect on performance and this trend is consistently retrieved for strength, ductility and energy dissipation. Indeed, performance initially decays and then it suddenly raises to a level close to or even exceeding that of the undiluted specimens. It is postulated that this behaviour is caused by resin viscosity, that falls off exponentially with the dilution degree. Once a viscosity threshold is breached, epoxy is capable of penetrating inside the yarn and thereby prevents telescopic failure, that is the sliding of the outer over the inner glass filaments. Furthermore, the interphase surface area increases dramatically and this enhances performance and narrows scattering. Besides, optimal viscosity is reached at an unexpectedly high dilution degree, whence material cost is significantly reduced. A cost-to-performance comparison of common strengthening technologies is presented, which shows that diluted epoxy composites score comparably to FRPs. It is

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concluded that epoxy coating optimization plays an important role in designing inorganic matrix composites.

Keywords: TRM, Epoxy coating, dilution, optimization, viscosity

1 **1. Introduction**

2 Inorganic matrix composites, such as Textile Reinforced Mortar/Concrete
3 (TRM/TRC), **Fibre Reinforced Cementitious Matrix (FRCM) and Inorganic**
4 **Matrix-Grid (IMG)** are being extensively investigated as promising alternatives
5 to the now traditional Fabric Reinforced Polymers (FRPs) [1]. Indeed, they
6 present well-known advantages over FRPs, such as thermal stability [2], en-
7 hanced durability [3, 4], reversibility of intervention and affinity to traditional
8 building materials [5, 6]. Besides, from an environmental standpoint, the in-
9 organic binder is certainly preferred over the organic matrix because it may
10 be easily repaired, strengthened or, eventually, recycled [7, 8]. On the other
11 hand, inorganic binders offer weaker mechanical response and, therefore, they
12 are unable to exploit the remarkable mechanical properties of the reinforcing
13 fabric. As a result, failure is fragile and inconsistent, for it mainly occurs by
14 internal delamination at the fabric-to-matrix interface [9]. On top of this, the
15 inorganic binder is coarse and viscous and therefore it is unable to penetrate
16 the small voids between the fabric filaments within the yarns. This leads to
17 the possibility of telescopic failure, that occurs when the outer filaments (the
18 so-called sleeve) adhere to the binder and yet they are capable of sliding over
19 the inner filaments (the core). Although this failure mode is more ductile, for
20 it is friction dominated, it still prevents the composite to reach its potential
21 performance [10, 8].

22 Several techniques have been proposed to address the limits inherent to
23 inorganic-based composites and, among these, fabric coating certainly appears
24 as one of the most promising [11, 12, 13, 14]. In particular, epoxy coating offers
25 obvious advantages for it draws on the vast body of knowledge gained with FRP
26 systems and, at the same time, minimizes the impact of the organic component.

27 Remarkably, very few contributions are available in the literature concerning the
28 actual role of epoxy resin at the fabric-to-matrix interface. Besides, for the most
29 part, they report on the effect of the coating, with little investigation on the
30 coating technique and formulation, nor on the action mechanisms. In [15], the
31 effect of epoxy coating on tensile, pull-out and water absorption performance of
32 TRC is presented. In [16], epoxy is applied at the lamination stage (wet coat-
33 ing) to create, together with sand, a thick intermediate layer between the carbon
34 fabric and the inorganic matrix. In [10], two formulations for the epoxy coat-
35 ing are adopted which produce different coating thickness and this is found to
36 strongly affect performance. In [2], epoxy coated TRM composites are exposed
37 to high temperatures and mechanical performance appears little impaired until
38 temperatures in excess of 200 °C are reached. In general, the details of the me-
39 chanical action of the epoxy coating on the interphase strength remain unclear
40 and likewise so for the optimal formulation and application strategies. Most
41 importantly, we still need to understand how much we can benefit from epoxy
42 coating in terms of mechanical performance and how well we fare in compar-
43 ison with competing technologies. In this paper, following a simplest possible
44 approach, we consider coating by a single epoxy resin with different degrees of
45 dilution in acetone. The aim is to resolve the effect of interphase strengthening
46 as opposed to yarn penetration. It is found that dilution weakens the inter-
47 phase until interpenetration suddenly takes place and undiluted performance
48 is restored or even surpassed. Finally, we present a simple cost effectiveness
49 analysis according to which the optimal epoxy dilution places coated G-TRM
50 alongside FRP in terms of cost-to-performance ratio.

51 **2. Materials and methods**

52 *2.1. Materials*

53 A commercially available premixed lime-based mortar (Kerakoll Spa, Geo-
54 calce Fino[®]) is considered as the embedding medium for the reinforcing fabric;
55 its nominal properties, as given by the manufacturer, are gathered in Table 1.

Table 1: Mortar properties (Kerakoll Spa, Geocalce Fino[®]), as given by the manufacturer

Characteristic	Unit	Value
Actual setting water content	%	22 ÷ 23
Final density	g/cm ³	1.58
Min. compression strength after 28 days	MPa	15.0
Min. flexural strength after 28 days (EN 196/1)	MPa	5.0
Min. support adhesion strength after 28 days	MPa	1.0
Aggregate maximum size	mm	1.4
Compression elastic modulus (EN 13412)	GPa	9.0

Table 2: AR-glass fabric properties.

Characteristic	Unit	Value
Yarn count	tex ^(*)	1200
Net specific weight per unit fabric area	g/mm ²	300
Fabric specific weight	g/cm ³	2.50
Grid spacing (square grid)	mm	12
Equivalent thickness, t_f	mm	0.06
Ultimate strength along warp (with epoxy)	MPa	1200
Ultimate elongation along warp	mstrain ^(**)	20
Elastic modulus	GPa	74

(*) tex = g/km; (**) 1 mstrain = 10^{-3} mm/mm.

56 Mortar characterization, through flexural and compression tests, is described in
 57 Section 3.1.

58 A thermo-welded balanced open-square grid AR-glass woven fabric (Fibre
 59 Net SpA) is employed as the reinforcing phase. The zirconium oxide (ZrO₂)
 60 sizing of the fibres ensures stability in the alkaline environment. The main
 61 geometrical and mechanical properties of this fabric, as declared by the manu-
 62 facturer, are reported in Table 2. We point out that, for better comparison, the
 63 same mortar and reinforcing fabric as in [10, 2] are considered.

64 2.1.1. Fabric coating

65 As detailed in Messori et al. [10], AR-glass fabric is preliminarily treated
 66 with a coupling agent, to enhance chemical compatibility with the epoxy coat-
 67 ing. A 2% vol. aqueous solution of (3-Aminopropyl) triethoxysilane (99%,
 68 Sigma-Aldrich) is prepared in a covered beaker and mixed on a magnetic stir-
 69 rer for 15 min. Cut-to-size fabric sheets are immersed in this silane solution

Table 3: Epoxy coating compositions (normalized to 100 g of DER + acetone) and measurement of the actual polymer content (w_r) with respect to the matrix (w_m).

Dilution degree	D.E.R. [g]	Acetone [g]	DETA [g]	Resin [g]	w_r/w_m [%]
0%	100	0	11.9	111.9	4.68
10%	90	10	10.7	100.7	4.31
25%	75	25	8.9	84.9	3.50
50%	50	50	6.0	56.0	1.33
75%	25	75	3.0	28.0	0.62
90%	10	90	1.2	11.2	0.23

70 for 1 min and then left to dry naturally at ambient temperature. Successively,
71 the functionalized fabric is coated with epoxy resin obtained from high-purity
72 bisphenol A diglycidylether (D.E.R. 332, DOW Chemicals). The aliphatic hard-
73 ener diethylenetriamine (DETA 99%, Alfa-Aesar) is adopted as curing agent.
74 Alongside the undiluted epoxy, 6 dilution degrees are considered for the epoxy
75 precursor and, to this purpose, technical acetone ($(\text{CH}_3)_2\text{CO}$, Incofar Srl) is
76 adopted at 10, 25, 50, 75 and 90% weight ratios. To reduce the viscosity of
77 the solution, D.E.R. is mixed with acetone on a magnetic stirrer at 50 °C. The
78 solution is subjected to ultrasonication for 5 min to promote homogenization.
79 Finally, the curing agent is added and the solution is mixed for at least 15 min
80 or until complete homogenization is reached. Successively, fabric sheets are im-
81 mersed in the epoxy resin and than laid to harden for 7 days on a polypropylene
82 support at ambient temperature. All the fabric sheets are weighted before and
83 after coating in order to determine the polymer weight fraction in the finished
84 composite, as listed in Table 3, which also summarizes the dilution degrees in-
85 vestigated in the present work. It is noteworthy that the total polymer weight
86 does not exceed the threshold of 5%wt. defined by the most popular guidelines
87 [17] and sharply decay around a dilution degree of 50%, reaching a negligible
88 value ($< 1.5\%$). Besides, the polymer weight fraction does not correlate linearly
89 with the dilution degree. Such evidence is in accordance with what found out
90 in Section 4.

91 *2.1.2. Specimen manufacturing*

92 Following Annex A of ICC AC 434 [18], 1-ply rectangular coupons are cast
93 on an individual basis, to avoid cutting from a larger sheet. The manufacturing
94 process takes place through the following stages (see [4, 6, 13] for further details):

- 95 • Assembling of the dismantable formwork: the first set of equally-spaced
96 3-mm-thick constraining laths is placed onto a polyethylene support and
97 silicone oil is applied;
- 98 • A first layer of natural hydraulic lime (NHL) mortar is laid in between the
99 laths by manual wet lay-up and levelled on top with a scraper;
- 100 • Cut-to-size epoxy coated fabric sheets are laid and gently pressed onto the
101 fresh mortar, Fig.1(a);
- 102 • The second set of 3-mm-thick constraining laths is attached on top of the
103 first to provide guidance for the correct placing of the fabric as well as for
104 a second layer of mortar;
- 105 • Mortar is laid in between the laths and levelled up, Fig.1(b).

106 Specimens are left moist-curing in a polypropylene bag for 7 days and then
107 stripped from the formwork. Formwork disassembling facilitates the process of
108 stripping. Successively, curing takes place in the laboratory environment for
109 further 50 days. 7 days prior to mechanical testing, 100 mm-long G-FRP tabs
110 are glued at the specimen ends to accommodate the gripping system, Fig.1(c).

111 **3. Experimental investigation**

112 *3.1. Mortar characterization*

113 Three-point bending (3PB) tests are carried out on mortar prisms, according
114 to the guidelines UNI EN 1015-07 [19], to precisely assess the mechanical per-
115 formance of the lime-based mortar. Consequently, mortar specimens are cast in
116 a $40 \times 40 \times 160$ mm stainless steel mold and vibro-compacted. Specimen prisms
117 are subjected to 7 day moist-curing and then stored to cure in a Memmert HP10

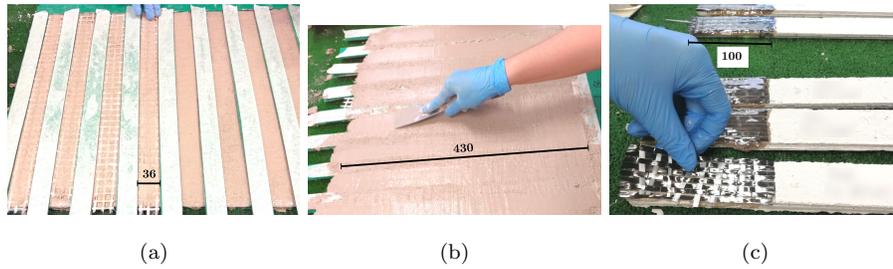


Figure 1: Specimen manufacturing protocol: (a) epoxy coated fabric sheets are placed onto the first layer of mortar, (b) application of the second layer of mortar, (c) C-FRP end tabs are glued to the specimens. *Quotes are in mm.*

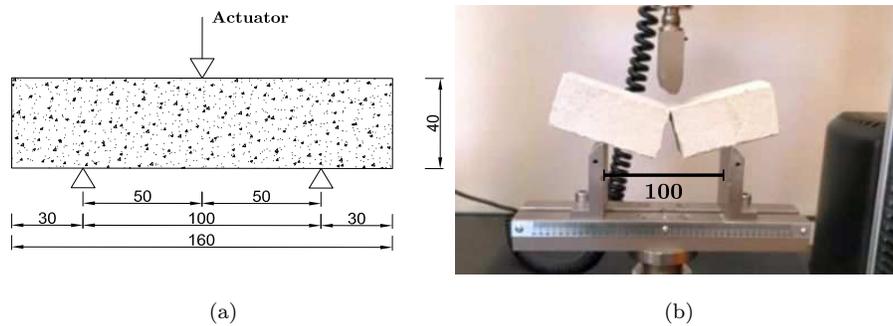


Figure 2: Three-point bending (3PB) test for mortar characterization: test geometry (a), test set-up and failed specimen (b). *Quotes are in mm.*

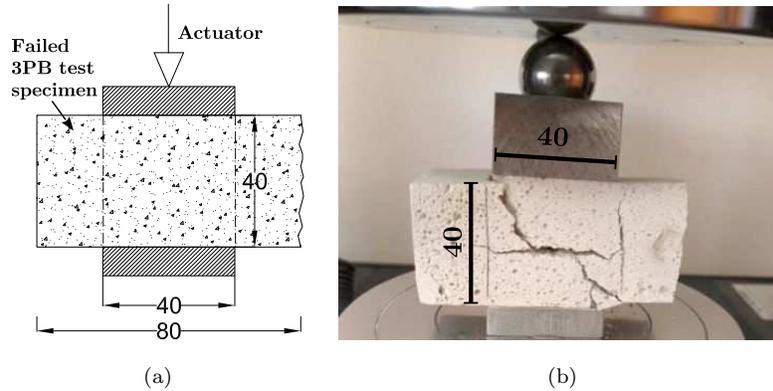


Figure 3: Compression test set-up (a) and failed specimen (b). *Quotes are in mm.*

118 climatic chamber at 65% relative humidity (RH) for further 21 days. Tests are
 119 performed through a Universal Testing Machine (UTM) at a nominal displace-
 120 ment rate of 1 mm/min (equivalent to $50 \div 100 \text{ Ns}^{-1}$). The test geometry and
 121 set-up are shown in Fig.2.

122 Monotonic compression tests are performed on failed specimens after 3PB
 123 (Fig.3): either specimen end is compressed between two 40×40 mm plates at a
 124 fixed displacement rate of 1 mm/min (equivalent to $50 \div 500 \text{ Ns}^{-1}$). To rule out
 125 unwarranted bending effects which may arise owing to geometric irregularities
 126 in the specimen, a steel ball is placed right under the top steel plate of the UTM,
 127 see Fig.3. Flexural and compression ultimate strength and elastic moduli are
 128 obtained from the experimental curves. At least 6 specimens are tested both in
 129 compression and in flexure.

130 3.2. Uni-axial tensile tests

131 Uni-axial tensile tests are performed according to ICC AC434 [18] in a UTM
 132 equipped with a 30 kN load cell. Wedge grips act on the end tabs and loading is
 133 applied by means of friction; wedges ensure adequate lateral pressure to avoid
 134 slippage between the specimen and the clamp (see [20] for a discussion on the
 135 effect of different clamping systems). A spherical hinge allows for self-alignment
 136 of the specimen and minimizes bending effects. Tests are conducted at a fixed
 137 strain rate of 2 mstrain/min ($2 \cdot 10^{-3} \text{ min}^{-1}$), as prescribed in [21]. As in



Figure 4: Rheometer test set-up

138 standard practice, stress and strain obtained from the test are referred to the
 139 fabric cross-section, A_f , and to the gauge length, $L_g = 230$ mm,

$$\sigma = \frac{P}{A_f}, \quad \varepsilon = \frac{\delta}{L_g}. \quad (1)$$

140 Here, P and δ are the load and the corresponding displacement, as measured
 141 by the UTM and corrected by DIC to eliminate wedge grip elongation (see also
 142 [4]).

143 3.3. Digital Image Correlation data post-processing

144 Tensile tests are monitored by Digital Image Correlation (DIC) with a 3
 145 megapixel stereoscopic Dantec Dynamics optical system (Q-400). DIC allows
 146 to fine measure the actual displacement field of the specimen surface, that is
 147 previously sprayed with a fine black speckled pattern onto a white background.

148 3.4. Optical and electron scanning microscopy

149 Optical investigation at 35x magnification is performed in a Leica EZ4D
 150 stereo-microscope to qualitatively assess the coating distribution and its effect
 151 on interphase adhesion. A scanning electron microscope (SEM) Quanta-200 (Fei
 152 Company, The Netherlands) is also employed.

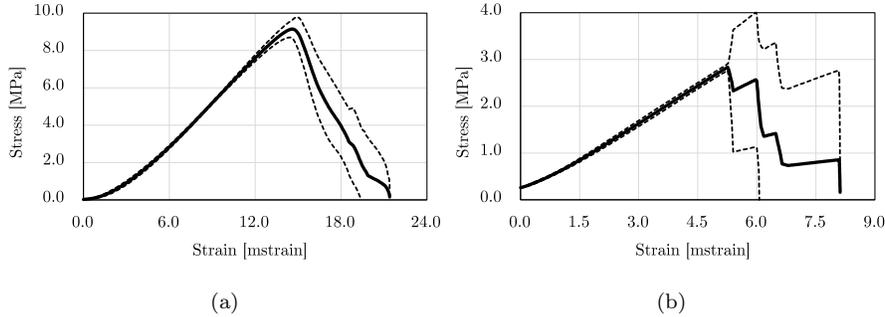


Figure 5: Mean stress-strain curve with ± 1 standard deviation bands for compression (a) and bending (b) of lime mortar prisms. (1 mstrain = 10^{-3} mm/mm)

153 3.5. Rheometer analysis

154 Resin viscosity is measured, for different dilution degrees, through a HAAKE
 155 RS100 Rheostress rheometer (Fig.4), that applies to the fluid a nominal tangen-
 156 tial stress, τ , at constant temperature (37 ± 1)°C. This temperature is chosen
 157 as to represent the actual conditions of fabric impregnation. The test program
 158 consists of an ascending ramp plus a descending ramp for the applied torque.

159 4. Results

160 4.1. Mortar characterization

161 The mean stress-strain curves for compression and bending of lime mortar
 162 prisms are reported in Figs.5(a) and (b), respectively. Data scattering is pro-
 163 vided by ± 1 standard deviation bands and it appears remarkably narrow for
 164 both compression and bending. Table 4 gathers the mean value of the mortar
 165 ultimate strength, $\mu(f)$, as well as of the secant modulus, $\mu(E)$, together with
 166 the relevant standard deviation, $\zeta(\cdot)$, and coefficient of variation, $CV(\cdot)$. The
 167 characteristic value $(\cdot)_k$ is evaluated as for a normal distribution (with the so-
 168 called "2-sigma-rule", used in the construction of approximate 95% confidence
 169 intervals [22])

$$(\cdot)_k = \mu(\cdot) - 1.96 \zeta(\cdot). \quad (2)$$

170 The elastic modulus is determined from the stress-strain curve as the slope
 171 of the secant line passing through $(\sigma_{0.6}, \varepsilon_{0.6})$ and $(\sigma_{0.9}, \varepsilon_{0.9})$, that are the stress-

Characteristic Unit	$\mu(\cdot)$ [MPa]	$\varsigma(\cdot)$ [MPa]	$CV(\cdot)$ [%]	$(\cdot)_k$ (Eq.(2)) [MPa]
Compressive strength, f_c	9.2	0.5	5.4	8.2
Young Modulus, $E_{c,s}$ (Eq.(3))	802	41	5.1	723
Flexural strength, f_f	3.4	0.6	17.6	2.3
Flexural modulus, $E_{f,s}$ (Eq.(3))	539	13	2.4	512

Table 4: Mechanical characterization of the lime mortar according to [19]. $\mu(f)$, $\varsigma(f)$ and $(f)_k$ are the mean, the standard deviation and the characteristic value of the (assumed normally distributed) stochastic variable f and they are connected through Eq.(2). $CV = \varsigma/\mu$ is the coefficient of variation

172 strain points at 60% and 90% of the ultimate strength [23]

$$E = \frac{\sigma_{0.9} - \sigma_{0.6}}{\varepsilon_{0.9} - \varepsilon_{0.6}}. \quad (3)$$

173 4.2. Uni-axial tensile tests

174 Fig.6 presents the mean stress-strain curve for each coating group alongside
175 two reference curves expressing the mean performance in the uncoated and in
176 the undiluted (alias 0% diluted) epoxy group (the latter is taken from [10]).
177 Remarkably, it appears that epoxy dilution in acetone little impairs the mean
178 mechanical performance, which remains way superior to that of the uncoated
179 group, particularly in terms of ductility. Further, most unexpectedly, perfor-
180 mance is not a monotonic decreasing function of the dilution degree and, after
181 an initial descending trend, it raises again and it reaches or even exceeds the
182 undiluted performance.

183 To take a better insight into this unexpected behaviour, Fig.7 presents the
184 mean ultimate tensile strength (UTS) and strain for all groups alongside ± 1
185 standard deviation bars. Looking at this figure, two interesting observations
186 can be made:

- 187 1. the mean ultimate performance is a decreasing/increasing/decreasing func-
188 tion of epoxy dilution, which attains a local minimum at 10 ÷ 25%-dilution
189 and then raises up to a local maximum that occurs at 75% for strength
190 and at 50% for strain;

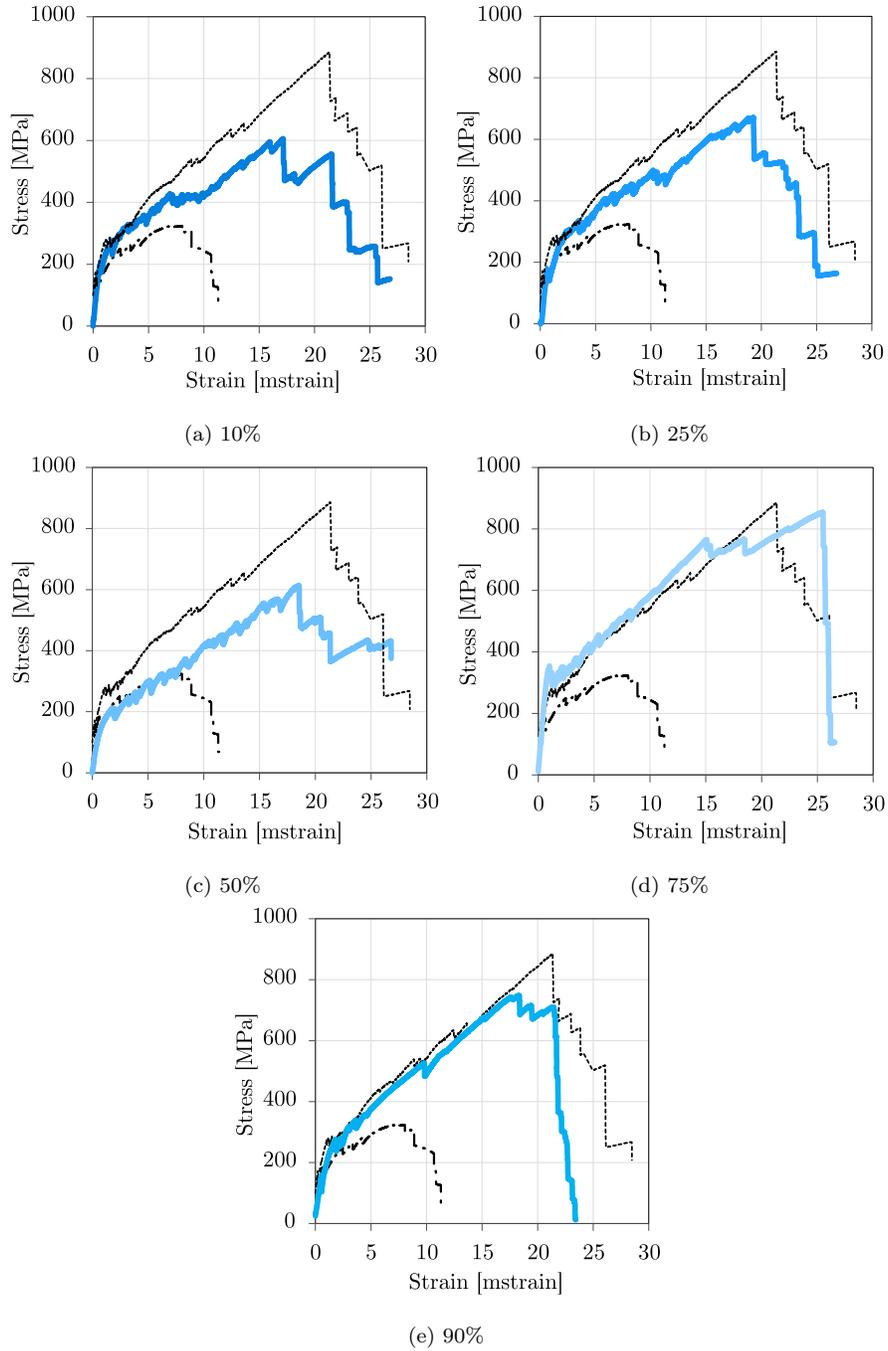


Figure 6: Mean stress-strain curves obtained in uni-axial tension of epoxy-coated G-TRM coupons for different dilution degrees (blue, solid lines), compared to the uncoated (black, dash-dotted lines) and to the undiluted (black, fine dashed lines) groups [24]. (1 mstrain = 10^{-3} mm/mm)

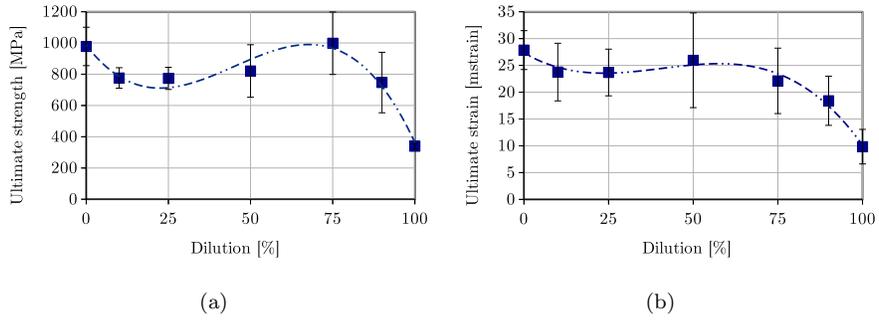


Figure 7: Mean ultimate strength (a) and strain (b) as a function of the dilution degree. ± 1 standard deviation bars and cubic curve-fits are also plotted. ($1 \text{ mstrain} = 10^{-3} \text{ mm/mm}$)

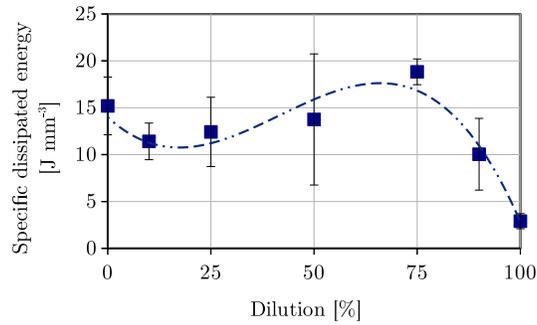


Figure 8: Mean energy dissipation per unit volume with ± 1 standard deviation bars and cubic curve fitting

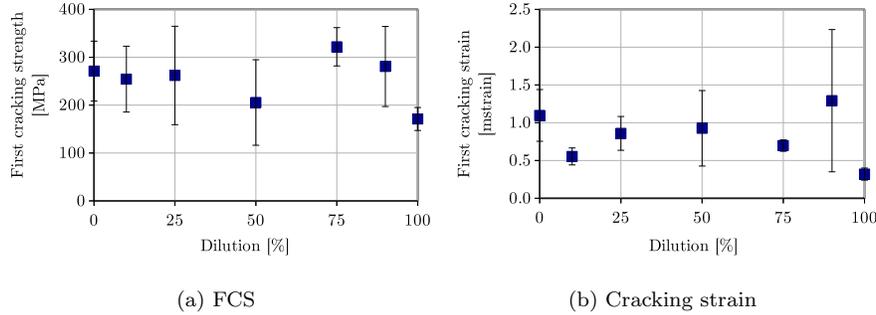


Figure 9: Mean first cracking strength (a) and strain (b) as a function of the dilution degree, with ± 1 standard deviation bars. (1 mstrain = 10^{-3} mm/mm)

- 191 2. strikingly, this maximum strength appears best performing (i.e. it is an
- 192 absolute maximum), although it occurs in the presence of wider scattering
- 193 when compared to the undiluted group;
- 194 3. data scattering is not monotonic increasing either and it is relatively stable
- 195 across the groups.

196 It is important to emphasize that dilution affects strength and strain in a similar
 197 manner, which fact is a good indication that an underlying phenomenon is
 198 consistently being captured. Indeed, the same trend is confirmed by looking at
 199 the dissipated energy at failure, that is evaluated as the mean, within each group,
 200 of the area under the stress-strain curve. In this respect, Fig.8 is even more
 201 surprising, for best performance is again associated with 75% dilution and yet
 202 it now exceeds by more than 30% that of the undiluted group, while possessing
 203 remarkably narrow data scattering. This behaviour seems to suggest that a
 204 threshold dilution exists which triggers a beneficial effect on performance and
 205 scattering. This effect competes against and eventually overcomes the expected
 206 degradation of the epoxy coating associated with resin dilution.

207 Fig.9 plots the first cracking strength (FCS) and strain and once more it
 208 supports the assumption that dilution has a mixed bearing on mechanical per-
 209 formance. Here, however, the picture is less clear cut, owing to the uncertainty
 210 that is associated with the identification of the transition point. Indeed, tran-

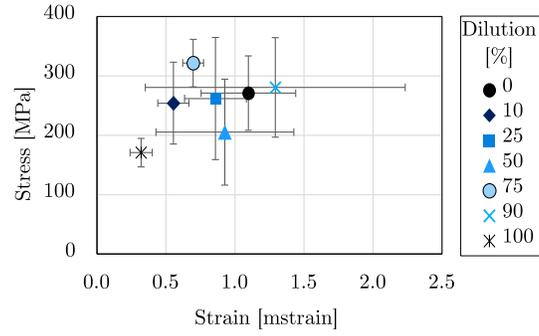


Figure 10: Transition points (TP) location as a function of the dilution degree with ± 1 standard deviation bars. (1 mstrain = 10^{-3} mm/mm)

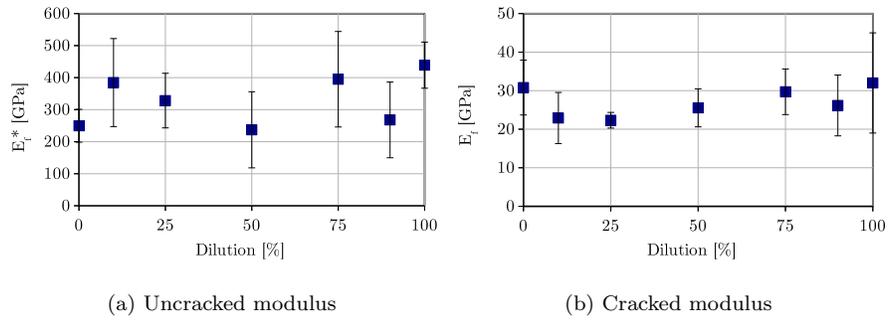


Figure 11: Mean uncracked (a) and cracked (b) moduli as a function of the dilution degree with ± 1 standard deviation bars

211 sition point location is charted in Fig.(10) and it is interesting to observe that
212 the highest stress and the least scattering again occurs at 75% dilution. Fig.11
213 shows the uncracked and the cracked elastic moduli, which reflects the matrix
214 (see Tab.4) and the fabric moduli, respectively. As expected, little dependence
215 on the dilution grade is demonstrated and yet the underlying trend can still be
216 appreciated.

217 *4.3. Optical and Scanning Electron Microscopy*

218 Fig.12 presents the outcome of optical investigation of failed specimens at
219 35x. The effect of dilution emerges with great clarity in that individual fibres
220 within the fabric yarn can only be appreciated at high dilution degrees, and
221 to these fibres large mortar patches adhere. In contrast, at low dilution, fibres
222 are deeply embedded in a sizeable lump of epoxy resin (that traps several air
223 bubbles) to which only small mortar patches can adhere. Evidently, mortar
224 adhesion occurs mainly at 50% and 75% dilution.

225 Along the same line and yet with greater detail, Fig.13 displays the outcome
226 of SEM microscopy at 1000x. Indeed, at low dilution, scanty fibres emerge from
227 the resin block which mainly surrounds the external filaments of the yarn, the
228 so-called sleeve. To this block, scattered mortar patches adhere. In contrast,
229 dilution reveals the glass fibres within the yarn, that the epoxy is eventually
230 capable of penetrating. The coating thickness is substantially reduced to a
231 thin layer to which mortar patches are diffusely attached. This adhesion is
232 perhaps of poorer quality, yet it extends well inside the core of the fabric yarn
233 and the surface area involved is greatly enlarged (Fig.14). Besides, telescopic
234 failure, that is failure by sleeve filaments sliding over the core, is prevented. The
235 dilution degree that triggers filaments penetration is the threshold level that
236 significantly enhances mechanical response. Competing with this positive effect
237 is the reduction of the epoxy content due to dilution, that weakens interphase
238 adhesion and negatively affects performance. Of course, a mixed response is
239 exhibited for intermediate dilution degrees.

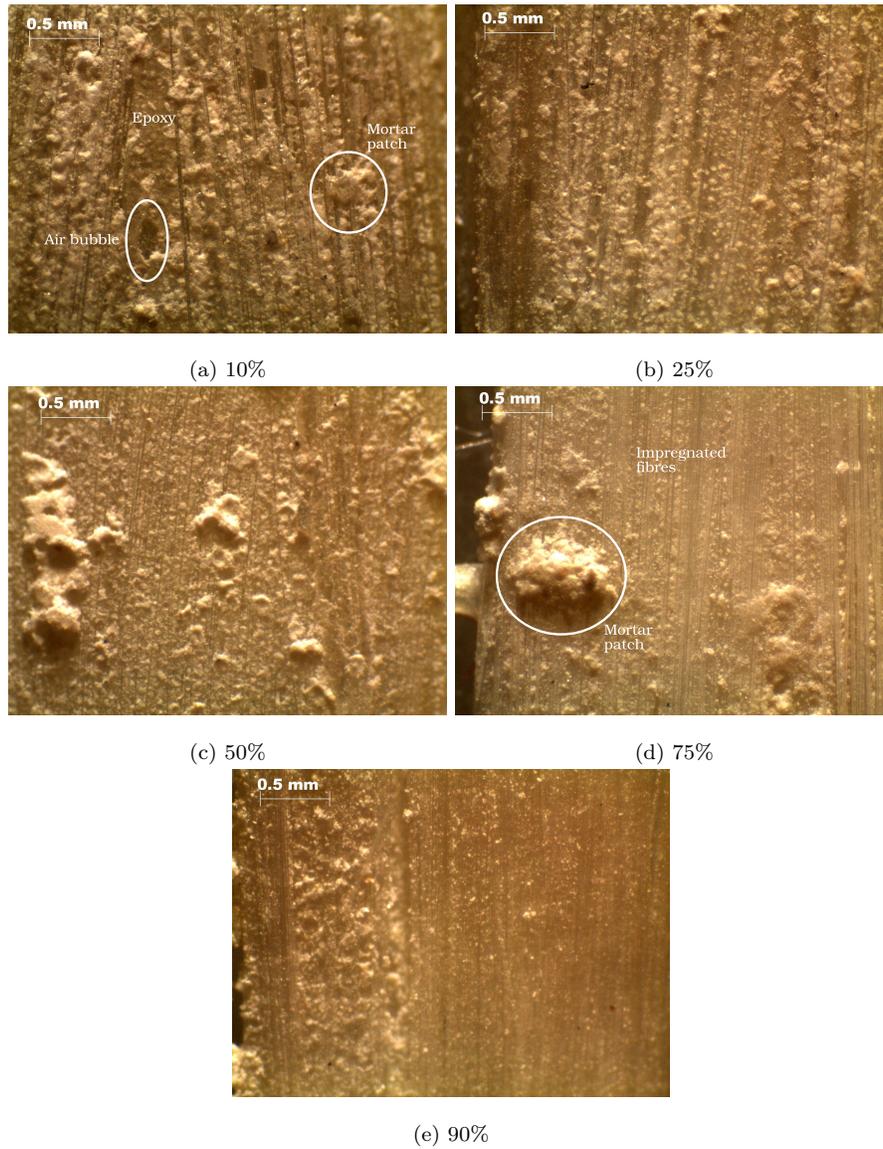
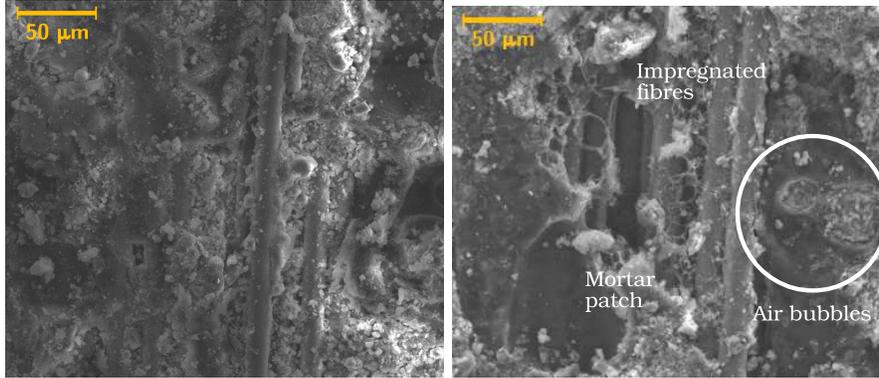
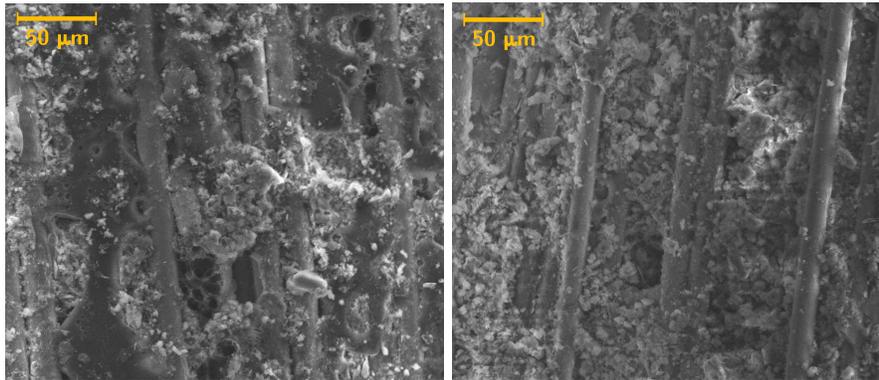


Figure 12: Optical microscopy of the fabric after failure at 35x magnification



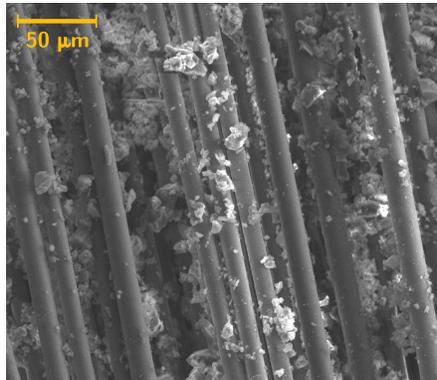
(a) 10%

(b) 25%



(c) 50%

(d) 75%



(e) 90%

Figure 13: SEM of the fabric after failure at 1000x magnification

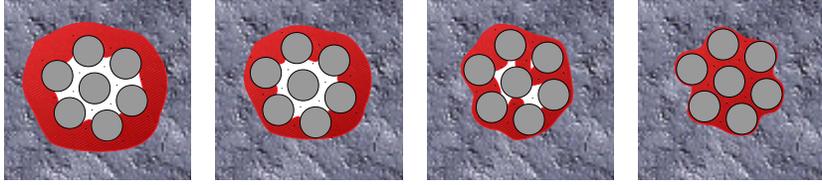


Figure 14: Penetration of the epoxy resin (red) in the voids between the filaments (gray) within the fabric yarn: dilution decreases viscosity and favours deep penetration

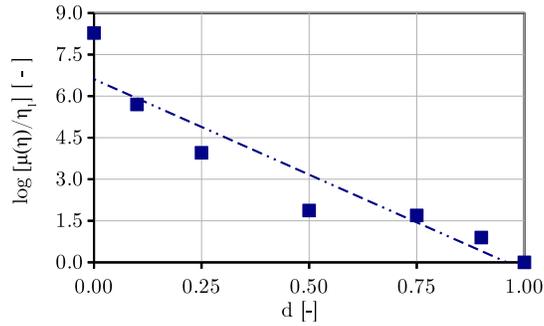


Figure 15: Viscosity measurement in logarithmic scale at 37 °C as a function of the dilution degree. An exponential curve-fit is also proposed ($R^2 = 0.95$)

240 4.4. Viscosity curve

241 It is most striking that the beneficial effect of epoxy resin penetration in the
 242 yarn core occurs almost suddenly and at an unexpectedly large dilution degree.
 243 Indeed, the dilution threshold is located around 3 : 1 acetone to epoxy weight
 244 ratio. This outcome may be traced back to the exponential decay of epoxy
 245 viscosity as a function of acetone dilution d . Fig.15 plots the mean viscosity,
 246 $\mu(\eta)$, normalized to acetone viscosity η_1 , superposed onto the exponential fit
 247 (logarithmic scale)

$$\mu(\eta) = \eta_1 \exp[-6.613(d - 1)], \quad (4)$$

248 where $0 \leq d \leq 1$ is the dilution degree. The viscosity at $d = 1$ (i.e. the uncoated
 249 group) is let equal to acetone viscosity, namely $\eta_1 = 0.28 \text{ mPa} \cdot \text{s}$ [25]. The fit
 250 shows good correlation ($R^2 = 0.9518$).

Dilution 100d [%]	probability of exceedence [%]		
	UTS	Strain	Energy
10	1.0	7.8	1.8
25	0.4	9.8	8.4
50	8.2	30.6	31.2
75	53.6	46.2	89.2
100	4.0	0	4.2

Table 5: Permutation test results

251 5. Resampling analysis

252 We begin by considering the question whether the different behaviour that
253 we see across the test groups is due to sampling or rather reflects some intrinsic
254 variance. For this, we carry out a permutation test on the total count [26] and
255 results are given in Tab.5. The permutation test works as follows: we compare
256 two dilution groups, namely 0%, that is the reference group, and $y\%$ and for this
257 we bring them together in the set A_y . Then, we form $N = 500$ permutations
258 with repetition of 5 elements of A_y and, for each of these, we compute the
259 total count (sum of the elements) s_k , $k = 1, \dots, 500$. We count the number
260 of permutations whose total count exceeds that of the reference group 0% and
261 divide by N . We expect that, when difference is due to sampling, the total
262 count of any permutation is located above/below the reference count 50% of
263 the times. We see that this is never really the case for any group, although it
264 may occasionally occur for a single characteristic. For instance, considering UTS
265 and ultimate strain, we see that the reference group and $y = 75\%$ dilution are
266 statistically equivalent, yet the latter still dissipates significantly more energy
267 than the former. We conclude that results are statistically meaningful and an
268 underlying process is being captured.

269 Next, we carry out a resampling analysis for each dilution group and consider
270 the statistics of 5000 permutations with repetition of the original dataset. Fig.16
271 plot the mean UTS and ultimate elongation, normalized to the corresponding
272 mean of the original sampling in the undiluted group, respectively f_0 and ε_0 ,

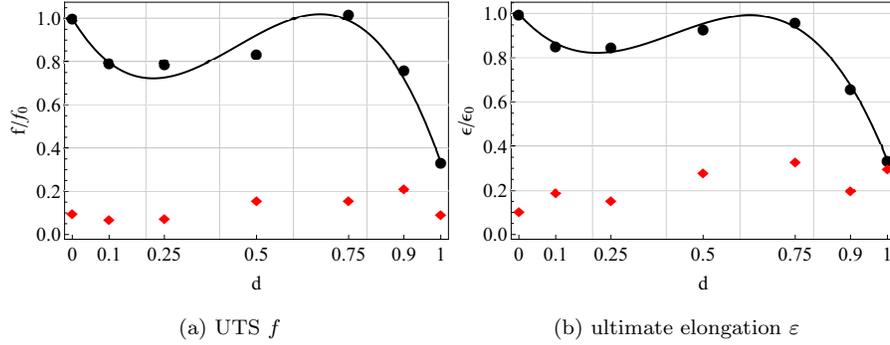


Figure 16: Resampled mean tensile ultimate strength and elongation (black, circles) with mean CV (red, diamonds) as a function of the dilution degree d , normalized to the corresponding mean of the original sample for the undiluted group, respectively f_0 and ε_0 . The cubic curve fit (5) is also shown

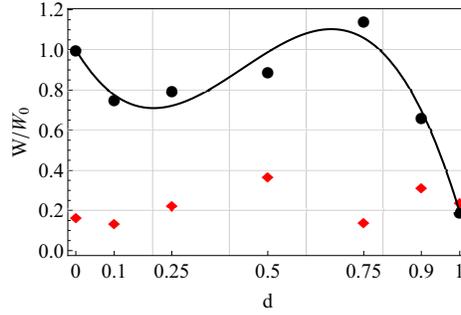


Figure 17: Resampled mean dissipated energy at failure W (black, circles) and mean CV (red, diamonds) as a function of the dilution degree, normalized to the original sample mean dissipated energy of the undiluted group, W_0

273 superposed onto a cubic curve fit of the form (likewise for strain)

$$\mu(f) = f_0 [1 + (f_1 - 1)x + a_2x(x - 1) - a_3x(x^2 - 1)], \quad (5)$$

274 where f_1 is the mean of the resampled uncoated group. A cubic curve-fit
 275 chosen because $d \leq 1$ and any curve-fit turns into a polynomial in a Taylor sense.
 276 Remarkably, upon normalization, strength and elongation follow a very similar
 277 trend, whose resemblance supports the fact that a physical process is being
 278 portrayed. Besides, unless a very large dilution degree is adopted, performance
 279 rests above 80% of the uncoated group, before falling off steeply beyond 75%
 280 dilution.

281 Figs.17 presents the resampled dissipated energy at failure W , normalized

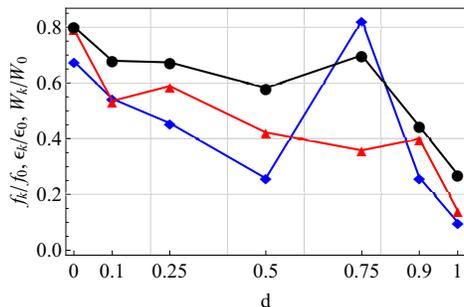


Figure 18: Resampled characteristic ultimate strength (black, circles), strain (red, triangles) and dissipated energy (blue, diamonds) as a function of the dilution degree, normalized to the corresponding mean values in the undiluted group

282 to the mean dissipated energy W_0 in the original undiluted sampling, and it
 283 shows that a 14% performance gain over the undiluted group is achieved at 75%
 284 dilution, that is accompanied by a very small CV. This behaviour, that seems
 285 to contrast that observed for strength and strain, may be explained noting that
 286 these are contravariant statistical variables, in the sense that when one increases,
 287 the other decreases and yet their "product" (i.e. the energy) remains the same.

288 With the resampling size $N = 5000$, the population distribution is close to
 289 normality and we may safely consider characteristic values according to Eq.(2).
 290 Fig.18 presents the characteristic ultimate strength, strain and dissipated en-
 291 ergy, normalized with respect to the corresponding *mean* value in the original
 292 sample of the undiluted group. We see that dilution has a significant negative
 293 effect on the characteristic ultimate strain, which drops in monotonic fashion.
 294 This is due to increasing standard deviation, see Fig.16(b). Conversely, strength
 295 and energy recover significantly at 75% dilution to the point that they behave
 296 almost as or better than the undiluted group. Such results support the idea
 297 that optimizing epoxy dilution and epoxy viscosity conveys remarkable benefit
 298 in terms of performance-to-cost efficiency.

299 6. A simple cost-effectiveness analysis

300 Fig.19(a) shows the total cost of raw materials per unit dissipated energy
 301 at failure. The material cost is a decreasing function of dilution, for acetone is

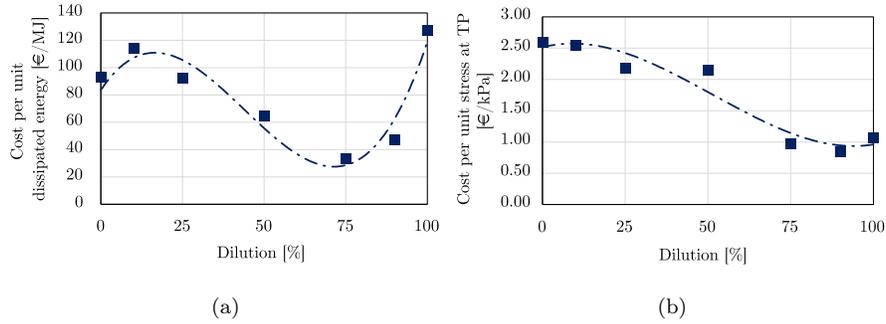


Figure 19: Mean cost per unit dissipated energy at failure (a) and per FCS (b) as a function of the dilution degree. A third-order polynomial curve-fit is also proposed.

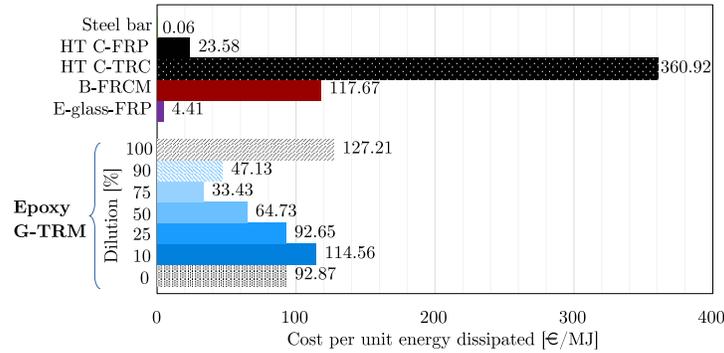


Figure 20: Comparison among strengthening and retrofiting technologies in terms of cost per unit dissipated energy (HT : high-tenacity, C : carbon, B : basalt, FRCM : fabric reinforced cementitious mortar)

302 far cheaper than epoxy, yet performance loss produces a competing trend. As
 303 expected, an absolute optimal point is met in correspondence of 75% dilution,
 304 where a 64% (74%) reduction in the cost-to-performance ratio is achieved, with
 305 respect to the undiluted (uncoated) group. Within this comparison, the undi-
 306 luted group is only 37% better performing than the uncoated group, despite the
 307 vastly superior mechanical performance, see Fig.17. Unexpectedly, cost normal-
 308 ization in terms of FCS leads to a monotonic decreasing function, i.e. the cost
 309 reduction associated with dilution outweighs the performance decay in terms
 310 of FCS, see Fig.19(b). This result, among others, may justify the marginal
 311 diffusion of epoxy coating in the current TRM technology landscape.

312 Fig.20 presents an all-around cost-to-performance comparison among differ-

ent strengthening and retrofitting technologies, in terms of mean material cost per unit dissipated energy. Costs for FRP and steel mesh are taken from 2018 data officially provided in [27]. FRP dissipated energy is obtained referring to the mean ultimate stress-strain values, as given by [28], and restricting the analysis to the linear regime. Mechanical response of steel is assumed to follow a bilinear model, with an initial elastic response until yield, followed by a linear hardening plastic phase until failure. Data for high-tenacity (HT) carbon (C) and basalt (B)-TRC are taken from Signorini and Nobili [29]. According to Fig.20, strengthening technologies may be ranked as follows. First, steel appears to be the best performing by far, mainly in consideration of its marginal cost. This obvious result, which accounts for the large adoption of reinforced concrete, should be weighed against other design constraints, such as durability and feasibility. Then, FRP follows, in light of its low cost compared to the outstanding mechanical performance. Glass TRM comes third and we see that dilution is capable of dramatically reducing the cost-to-performance ratio to an extent that is comparable with high tenacity carbon FRP. In fact, 75% dilution produces an outstanding three-fold reduction in the cost-to-performance index compared to the undiluted group. Of course, different performance indices may be considered and costs greatly vary across countries, but the general idea that diluted epoxy coating may significantly increase the interest in TRM composites still holds. Basalt and carbon FRCM come last, although they score similarly to epoxy coated TRM. However, mechanical performance is generally little reliable in the absence of interphase strengthening [6].

7. Conclusions

We present the results of mechanical uni-axial traction tests on epoxy coated AR-glass Textile Reinforced Mortar (TRM) specimens. Spotlight is set on the role of the epoxy coating and its ability to penetrate the glass filaments within the yarn. To this aim, epoxy is diluted with acetone at 10, 25, 50, 75 and 90% weight ratios and performance is compared to that of undiluted and uncoated fabric. It is found that the effect of dilution is two-fold: on the one hand it de-

343 creases the interphase strength and yet, on the other hand, it decreases viscosity
344 exponentially and therefore enhances the epoxy penetration capability. These
345 two effects are competing and, as a result, an optimal formulation is defined.
346 Most remarkably, filament penetration occurs at a unexpectedly high dilution
347 degree and it takes place through a rapid surge of mechanical performance.
348 This burst is so intense that it compensates interphase weakening, to the extent
349 that performance gets close to or even exceeds that of the undiluted specimens.
350 This trend consistently emerges in the first cracking strength and strain, in the
351 energy dissipation capability, in the cracked and uncracked moduli and in the
352 turning point location alike. Besides, a simple cost-effectiveness analysis shows
353 that dilution leads to a very substantial material cost reduction, which places
354 this technology on an efficiency level comparable to that of FRPs. It is con-
355 cluded that careful engineering of the epoxy coating can significantly contribute
356 to the improvement of the overall performance of glass TRM composites.

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363 **Declarations of interest**

364 None.

365 **Data availability**

366 The raw data required to reproduce these findings are available to download
367 from <http://dx.doi.org/10.17632/kgb7dz3yhx.1>

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