Comparing durability of steel reinforced grout (SRG) and textile reinforced mortar (TRM) for structural retrofitting

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Abstract We assess tensile performance of Steel Reinforced Grout (SRG) and Fabric Reinforced Cementitious Matrix/Textile Reinforced Mortar, upon exposure to aggressive environments. Galvanized and brass-coated Ultra High Tensile Strength Steel fabrics are considered for SRG, while carbon, AR-glass, basalt and PBO fabrics are investigated for TRM, in a common cement mortar. Exposure to the aggressive environments is realized by specimen immersion for 1000 h (41.6 days) at controlled temperature in distilled water as well as alkaline, saline and acid solutions. Mechanical performance of rectangular 1-ply coupons is assessed in uni-axial traction: Ultimate strength and elongation, dissipated energy at failure and environmental conversion factors for design values are calculated and compared. It is found that significant performance difference exists in dependence of the aggressive environment under consideration. As a result, careful selection of the reinforcing fabric leads to substantial advantage in terms of durability, that should be capitalized upon at the design stage. A simple material selection matrix is presented which suggests the best reinforcing textile/aggressive environment combination for design purposes.

Keywords TRM · SRG · Durability · Environmental conversion factors

1 Introduction

Inorganic matrix composite materials, such as Fabric Reinforced Cementitious Matrix (FRCM) or Textile Reinforced Mortar (TRM), are a new class of composite systems that is gaining grounds for structural rehabilitation and retrofitting [1–3]. Over the wide class of organic matrix composites, among which we mention the established group of Fabric Reinforced Polymers (FRP), TRM offer several important advantages, such as affinity with traditional building materials (fire clay, cement, masonry) and intervention reversibility, in the sense that externally bonded (EB) reinforcement may be removed with limited damage to the support (which is a crucial asset when dealing with cultural heritage retrofitting [4, 5]), resistance to high temperature [6] and UV exposure, applicability in the presence of water and on wet
When High Tensile Strength Steel (HTSS) is used as the reinforcing fabric, the composite goes under the name of S-FRCM or Steel Reinforced Grout (SRG) [8, 9]. After two decades of extensive research, the role of TRM as strengthening systems is currently shifting from R&D to the application stage. This evolution is supported by the appearance of new code guidelines, such as the recently approved Italian specifications [10] and acceptance criteria [11], which follow upon the already established guidelines by ICC [12] and ACI [7]. One important issue, that is discussed in these guidelines, concerns the performance decay associated with exposure to aggressive environments. In fact, following Mobasher [13], "a major challenge is in incorporating durability test methods into a standard acceptance test protocol". Although ACI and Italian guidelines agree on the conditioning regimes to be considered for durability assessment (see Donnini [14]), they take a different stance on how to move from test data to design values. Beside experimentation, ACI does not provide specific prescriptions for taking into account performance reduction as a result of aggressive environment exposure. In contrast, the Italian regulation introduces an environmental conversion factor $\eta_a$ for reducing design values [15, Sect. 3.5.1]. In fact, in the lack of specific tests, it provides the one-fits-them-all coefficient $\eta_a = 70\%$, common to all aggressive environments. Interestingly, this is precisely the factor attached to exposure to aggressive environments of aramid/epoxy FRP and should be confronted with $\eta_a = 85\%$ assumed for carbon/epoxy FRP [15, Tables 2, 3]. Consequently, according to the Italian regulation, TRM are no better performing than FRPs in aggressive environments in general. This is particularly remarkable if one considers that "better long-term durability" is credited among the major assets of TRM systems [16]. In this work, we show that this stance is not always justified in terms of design values. Only a small number of papers have appeared in the literature discussing the performance decay of TRM systems associated with exposure to aggressive environments and to humidity and gas penetration in the reinforcing system. Indeed, according to the recent review by Koutas et al. [2], "Future work in this field should be directed at [...] understanding the durability of the strengthening system". Furthermore, opposing results are sometimes encountered. In her interesting dissertation, Arboleda [17] investigates the tensile strength of PBO and carbon FRCM 1-ply coupons after immersion in alkaline and saline solutions, and after exposure to water vapour and freeze-thaw cycles. Unexpectedly, performance appears consistently unaffected by exposure, if not enhanced. In fact, Arboleda et al. [18] write "Results indicate there are no significant degradation concerns for the environments cited. On the contrary, strength improvements are noted on most exposures probably due to continued hydration after 28 days". Nobili [19] considers tensile performance of AR-glass FRCM coupons after immersion in a saline or alkaline solution. Consideration of the effect on the isolated components, namely dry fabric and lime mortar, shows that exposure little affects AR-glass. Indeed, this result parallels the findings of Purnell et al. [20, 21], for glass reinforced cement (GRC), of De Santis and De Felice [22] and Micelli and Aiello [23] for dry fabric in alkaline environment. In fact, exposure mainly impairs the lime mortar and this, in turn, promotes delamination failure and large data scattering. Exposed specimens present a residual strength that is roughly 75% of that pertaining to the control group, in the mean. Although this appears in line with the conversion factor given by the Italian regulation, consideration of design values offers a different perspective. In the paper by Signorini et al. [24], a detailed investigation is presented for carbon FRCM that considers the role of curing time of the lime mortar as well as the impact of exposure on design values. For these, reductions in excess of 60% of the control group are easily encountered (residual strength <40%), although long curing time effectively mitigates the decay. A careful study is performed to correlate the crack pattern evolution against the performance decay. It is found that the average crack spacing provides a reliable measure of matrix/fabric bond degradation at all test stages, as pointed out also by Tekieli et al. [25], using the technique of Digital Image Correlation (DIC) too. Recently, Donnini [14] presented a durability analysis of AR-glass FRCM after immersion for 1000hours in a saline solution or in water at 60°C. Single shear-bond tests show that adhesion to a fire clay support is reduced by more than 20% (surprisingly, relative data scattering is decreased in the exposed groups) and the hydraulic mortar is little affected by exposure. In contrast to the findings of Nobili and Signorini [26], dry glass fabric performance is reduced by more than
30% in the mean. A likely explanation of this result may be traced to the exposure temperature, that is sensibly higher than that suggested by the guidelines (namely 23°C). In fact, Micelli and Aiello [23] point out that “a maximum temperature should be individuated in conditioning protocols, otherwise unreal detrimental effects could be produced”. In their work, they assess the tensile strength of E- and AR-glass, carbon, basalt, PBO and steel strands extracted from dry fabrics after exposure to different alkaline environments at various temperatures, the latter designed as to simulate different service life spans. They find that "E-glass fibres and basalt fibres confirmed to be highly sensitive to the alkaline environments”, while "carbon and steel fibres did not exhibit a chemical vulnerability”. The protective role of a polymeric coating is also investigated. De Santis and De Felice [27] consider immersion for 15, 30 and 41.6 days of dry steel textiles in Substitute Ocean Water (SOW), presumably at laboratory temperature. They report that exposure produces negligible effect on the stress-strain curves and therefore propose $\eta_a = 95.5\%$ for the longest immersion. From this literature review, it clearly appears that durability is a complex function of fabric coating, matrix composition and curing time. We also observe that, to the best of our knowledge, no all-around durability investigation is available concerning SRG. In this paper, we investigate durability of TRM systems reinforced with different fabrics, including HTSS, embedded in a common cement mortar. In fact, although each system usually comes with a dedicated matrix, we prefer to adopt a single cementitious mortar throughout, in order to reduce variability and focus on the role of different fabrics. In this sense, this work may be considered as a preliminary step to establish a lower performance limit for each system. Spotlight is set on the determination of environmental conversion factors, which provide easy and accessible guidance at the design stage for the best selection of the reinforcing fabric in dependence of the aggressive environment under consideration.

2 Materials and methods

2.1 Materials

Four commonly used reinforcing textiles, namely carbon, Alkali-Resistant (AR) glass, basalt and poly-parafenilenbenzobisoxazolo (PBO), are considered in the TRM class, see Fig. 1a–d. Similarly, two Ultra-High Strength Steel (UHSS) fabrics are employed as reinforcement for SRG, namely zinc-coated and brass-coated, which differ by the surface treatment that is applied to prevent chemical corrosion, see Fig. 1e–f. The main mechanical and physical properties of the fabrics are reported in Table 1 for both TRM and SRG reinforcing systems. Mechanical properties of SRG are well in line with those given in the paper by De Santis and De Felice [27] concerning steel cord tensile strength, elastic modulus and the fabric density.

A commercially available cement mortar with structural capabilities (Monotop X2, Sika Spa) is adopted as the embedding matrix, common to all specimens. Mortar properties, as given by the manufacturer, are reported in Table 2 together with flexural performance data. These are assessed, as detailed in Sect. 3.1, through three-point bending (3PB) tests. The main aim of this paper is to assess performance degradation of the considered strengthening systems, with respect to the aging protocols described in Sect. 2.3.

2.2 Specimen manufacturing

Six $(b \times h \times L_f) = 40 \times 40 \times 160$ cm prismatic specimens for mortar characterization are manufactured, according to UNI-EN 1015-11 [28], in a standard rectified steel formwork and then vibro-compacted. Specimens undergo moist-curing in a polypropylene bag for 7 days and then curing at 20°C and 65% relative humidity (RH) for further 21 days in a climatic chamber (HPP110, Memmert GmbH + Co. KG).

Specimens for tensile testing consist of 1-ply rectangular coupons, manufactured on a one-by-one basis in a suitably designed polyethylene formwork. Coupon geometry is shown in Fig. 2c. The gauge length is $L_g = 250$ mm. The specimen width, $w_d$, is reported in Table 3 and it varies across different
reinforcing fabrics. Indeed, it is designed so as to accommodate an integer number of yarns (i.e. it is a multiple of the mesh spacing) in the warp direction.

The manufacturing protocol follows closely the procedure already described in previous works [19, 26, 29–31] and hereinafter summarised. A first layer of cement mortar is applied on the lubricated formwork in between pairs of 3-mm-thick spacers, Fig. 2a. These spacers confine the mortar around and provide reference for scraping the excess of material on top. Successively, the reinforcing fabric is gently pressed onto the fresh cement, Fig. 2b. A second layer of spacers is placed on top of the first to provide reference for the next mortar layer and to constrain the fabric in place. This procedure ensures standardized fabric placing at the coupon mid-plane and avoids cutting from a larger sheet. This is especially important in consideration of the role that cutting-induced-cracks play in conveying the aggressive agent inside the specimen. Following the guidelines issued by ICC [12], 7-day moist-curing in the formwork is followed by stripping and then by 21-day curing at laboratory conditions. 100-mm long AR-glass tabs are epoxy-glued at the specimen ends to accommodate for the clamping grips at the testing stage. Each test group consists of six specimens.

### 2.3 Aging protocols

Specimens are immersed for 1000 h (41.6 days) at constant temperature in the aggressive environments listed in Table 4 along with the relevant guidelines, see also the paper by Nobili and Signorini [26] and
Arboleda [17]. For the sake of comparison, control specimens (CC) undergo extra curing at laboratory conditions for the same amount of time. The alkaline environment (AK) is a caustic soda (NaOH) aqueous solution with pH 10. This solution is comparable to Environment D discussed by Micelli and Aiello [23] which, however, is pH 14. In fact, Environment D “may appear too severe in order to reproduce service conditions in buildings” [23]. The saline environment (SW) is a 3.5% weight sodium chloride (NaCl) aqueous solution, which, according to ASTM D 1141 [34], simulates the world’s oceans average salinity (substitute ocean water, SOW). This is the artificial aging protocol considered by De Santis and De Felice [27] at 15, 30 and 41 days. Following the procedure suggested by Kajorncheappunngam et al. [32], immersion in a 1M hydrogen chloride acid solution (HA), pH 2.5, diluted from hydrochloric acid (HCl 37% RPE Carlo Erba Reagents Srl), is also considered. Together, AK and HA provide double-end insight into the effects of extreme pH conditions. Finally, to single out the role of specimen immersion, distilled water (DW) is also investigated for comparison with SW and AK [12]. As such, this test is not fully compliant with the specifications given in ASTM

**Table 3** Geometrical data of specimens for tensile testing

| Fabric | Grid spacing (warp) (mm) | $w_d$ (mm) | Strands (–) | $A_f$ (mm²) |
|--------|--------------------------|------------|-------------|-------------|
| C      | 5                        | 35         | 7           | 3.10        |
| P      | 10                       | 30         | 3           | 1.37        |
| G      | 12                       | 36         | 3           | 2.16        |
| B      | 8                        | 32         | 4           | 3.58        |
| ZS     | 6                        | 36         | 6           | 3.23        |
| BS     | 6                        | 36         | 6           | 3.23        |

**Table 4** Aggressive environments under testing: CC—control, SW—salt water, AK—alkaline solution, HA—hydrochloric acid, DW—distilled water

| Environment | Curing (days) | Time of exposure | Temp. °C | Ref. |
|-------------|---------------|------------------|----------|-----|
| CC          | 28            | –                | Room     | –   |
| SW          | 28            | 1000 h           | 23 ± 1   | [12, Table 2], [11] |
| AK          | 28            | 1000 h           | 23 ± 1   | [12, Table 2], [11] |
| HA          | 28            | 1000 h           | Room     | [26, 32] |
| DW          | 28            | 1000 h           | Room     | [26, 33] |

Room temperature is $[21 ± 2]°C$ ($[70 ± 3.6]°F$)

Fig. 2 TRM specimens: manufacturing (a), dimensions [in mm] (b) and tensile test set-up (c)
2.4 Three-point bending tests

Three-point bending (3PB) tests are performed on plain mortar prisms according to the guidelines UNI EN 1015-11 [28], directed at mortar characterisation, to assess mechanical performance in flexure. Tests are carried out in an electro-mechanic Universal Testing Machine (UTM), equipped with a two-point support and a floating knife connected to a 5kN load cell (Instron 5567). Supports are placed 100mm apart (distance $L_s$) and the floating knife moves at the nominal displacement rate of 1mm/min (equivalent to $50 \div 100 \text{Ns}^{-1}$).

2.5 Uni-axial tensile tests

Monotonic uni-axial tensile tests are performed on the composite coupons in the same UTM, now equipped with two self-aligning wedge grips. The test procedure is compliant with the Italian qualification guidelines [11], which make no specific provision on a particular gripping system, provided it warrants adequate lateral pressure. The upper grip is connected to a 30 kN load cell and to the moving crosshead through a double hinge. Elongation occurs at the nominal displacement rate $\dot{\varepsilon} = 0.5 \text{mm/min}$, that is a little slower (17%) than the nominal rate 0.01 mm s$^{-1}$ considered in the paper by De Santis and De Felice [27]. This displacement rate, normalized to the gauge length, corresponds to the strain rate $\dot{\varepsilon} = 2 \text{mstrain/min}$ and it is compliant with RILEM’s TC232 guidelines [35].

The actual elongation rate of the specimen during tensile testing is measured through a stereoscopic 3 MPixel Digital Imaging Correlation (DIC) system (Q-400, Dantec Dynamics A/S, Denmark) operated at 5Hz. Displacement rate is obtained by linear (in time) fitting of DIC displacement data concerning a small region close to either wedge clamp; it slightly differs from the nominal rate as a consequence of wedge elongation. As observed by Nobili [19], consideration of the actual displacement, as opposed to the rate imposed by the testing machine, strongly affects the ultimate tensile elongation (UTE) as well as of the cracked modulus. Data comparing nominal and actual displacement rates for a typical specimen are available in the supplementary material.

3 Results

3.1 Mortar characterization

The average stress-strain curve in flexure, taken over six mortar prisms, together with ±1 standard deviation bands is available as supplementary material. Data scattering is remarkably narrow. As in standard practice, the stress $\sigma$ and the strain $\varepsilon$ are obtained, respectively, from the load, $P$, applied at the floating anvil and from the mid-span displacement, $\delta$, according to the classical strength of material relations

$$\sigma = \frac{3}{2} \frac{L_s}{bh^2} P, \quad \varepsilon = \frac{6h}{L_s^2} \delta.$$  

The mean secant elastic modulus in flexure, $E_f$, is evaluated as the mean slope of the secant lines going through two reference points in each strength curve [17, Eq. (3) p. 51].

$$\mu(E_f) = \frac{\sigma_{@00\%UFS} - \sigma_{@60\%UFS}}{\varepsilon_{@90\%UFS} - \varepsilon_{@60\%UFS}},$$

being UFS the ultimate flexural strength of the mortar. For the mortar under investigation we have

$$E_f = (629 \pm 5) \text{MPa}, \quad \text{and} \quad UFS = (2.9 \pm 0.3) \text{MPa},$$

respectively for the mean secant modulus and for the mean ultimate flexural strength.

3.2 Monotonic tensile tests

3.2.1 Multifilament TRM

Figure 3 compares the mean strength curves, for each TRM specimen group, across all tested environments. Mean curves are obtained by averaging over six specimens within a group. As detailed in the Italian qualification guidelines [11, §2.1.1], stress is conventionally scaled over the dry reinforcement cross-sectional area, $A_f$, reported in Table 3. Given the wide range of ultimate tensile strength (UTS) levels that are attained by different reinforcements (e.g. PBO...
provides more than twice the strength of carbon in the control group and twice the ductility in the distilled water group, the same axis scale could not be adopted for all groups.

For better comparison, Fig. 4 presents a bar-chart illustration of UTS for the reinforcing textiles across all environments. The same confrontation, both in terms of ultimate tensile elongation (UTE) and of dissipated energy ($W$), is provided, for the sake of completeness, in the supplementary material. Mechanical energy dissipated at failure is conventionally evaluated as the area under the stress-deformation curve: It provides an established performance index describing the quality of the strengthening system,
given that it combines strength and ductility capabilities. Table 5 gathers the main performance indices for the TRM systems under investigation. The following observations can be made:

- Surprisingly, carbon performs poorly when immersed in DW, where it fails the acceptance condition [11], demanding that UTS after exposure rests above 85% of the control group performance. This outcome contrasts with the results presented by Arboleda [17, Fig. 5]. Interestingly, carbon marginally benefits from HA exposure and this progress carries over to energy dissipation. Performance improvements due to exposure are not uncommon in the literature, see, for example, Arboleda et al. [18]. In SW and AK solutions, carbon suffers a mild performance loss and stands on the boundary of acceptance. It is worth observing that Micelli and Aiello [23] find zero tensile strength loss for carbon under any (alkaline) aggressive environment for all exposure times.

- PBO is exceptionally well performing in all aggressive environments and never fails acceptance. Indeed, this behaviour is compatible with the findings presented by Arboleda [17, Fig. 5]. Interestingly, UTS benefits from exposure to DW and HA and this pattern carries over to energy dissipation. Excellent performance extends to UTE, although AK and SW exposure reduce ductility by 16% and 26%, respectively; yet such losses are compensated by strength gains and therefore energy dissipation remains as in the control group.

- AR-glass is really sensitive to SW exposure only, where the composite fails acceptance and ductility is almost halved. Other aggressive environments produce little effect, see also the paper by Nobili [19]. Energy dissipation and UTE capability behave similarly: they are unaltered in AK and HA, suffer a mild loss in DW and strongly decay in SW.

- Performance of basalt reinforced TRM is strongly impaired by all aggressive environments: in fact, basalt always fails acceptance. In the AK solution, the outcome is compatible with the findings reported by Micelli and Aiello [23, Table 6] for

|   | F | CC | SW | AK | DW | HA |
|---|---|----|----|----|----|----|
|   | μ(f) [MPa] | CoV [%] | μ(f) [MPa] | CoV [%] | Δf [%] | μ(f) [MPa] | CoV [%] | Δf [%] | μ(f) [MPa] | CoV [%] | Δf [%] | μ(f) [MPa] | CoV [%] | Δf [%] |
| Strength | C | 433 | 26.4 | 376 | 31.4 | 13.2 | 362 | 30.7 | 16.6 | 271 | 25.9 | 37.4 | 505 | 22.7 | 16.6 |
|   | P | 888 | 19.6 | 915 | 22.4 | 3.0 | 925 | 8.1 | 4.1 | 1240 | 9.0 | 39.7 | 1280 | 20.6 | 44.1 |
|   | G | 335 | 10.0 | 254 | 15.7 | 24.0 | 333 | 6.1 | 0.6 | 328 | 8.0 | 2.1 | 374 | 13.5 | 11.8 |
|   | B | 246 | 9.1 | 152 | 14.1 | 38.4 | 202 | 15.6 | 18.1 | 145 | 18.4 | 37.4 | 168 | 11.5 | 31.9 |
|   | F | 3.40 | 28.9 | 3.05 | 10.4 | 3.23 | 19.6 | 5.3 | 4.85 | 17.5 | 42.3 | 5.15 | 34.3 | 51.4 |

|   | μ(ε) [10^-3] | CoV [%] | μ(ε) [10^-3] | CoV [%] | Δε [%] | μ(ε) [10^-3] | CoV [%] | Δε [%] | μ(ε) [10^-3] | CoV [%] | Δε [%] | μ(ε) [10^-3] | CoV [%] | Δε [%] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Strain | C | 10.6 | 23.2 | 9.0 | 50.8 | 14.7 | 11.6 | 58.2 | 9.2 | 7.9 | 36.7 | 25.8 | 11.1 | 18.0 | 4.2 |
|   | P | 14.6 | 13.3 | 11.2 | 49.2 | 19.8 | 10.7 | 14.4 | 23.5 | 16.4 | 7.9 | 17.4 | 16.1 | 21.7 | 14.8 |
|   | G | 10.1 | 8.9 | 6.7 | 44.4 | 33.6 | 11.0 | 39.2 | 8.7 | 8.7 | 20.3 | 14.4 | 10.9 | 33.2 | 8.2 |
|   | B | 10.4 | 19.0 | 3.8 | 54.6 | 64.0 | 7.4 | 32.3 | 28.9 | 3.6 | 26.1 | 65.0 | 3.4 | 38.8 | 67.1 |
|   | F | 2.51 | 33.5 | 1.84 | 45.6 | 26.7 | 2.28 | 52.0 | 9.0 | 1.18 | 55.6 | 52.7 | 2.94 | 28.2 | 17.4 |
|  } | 3.40 | 28.9 | 3.05 | 10.4 | 3.23 | 19.6 | 5.3 | 4.85 | 17.5 | 42.3 | 5.15 | 34.3 | 51.4 |
|   | G | 1.92 | 11.2 | 1.20 | 33.4 | 37.9 | 2.01 | 23.7 | 4.6 | 1.62 | 17.7 | 15.9 | 2.08 | 37.3 | 8.0 |
|   | B | 2.22 | 23.1 | 0.69 | 33.3 | 69.2 | 1.40 | 33.0 | 37.0 | 0.64 | 37.9 | 71.4 | 0.55 | 41.9 | 75.3 |
dry yarns. Performance loss in terms of UTE and energy dissipation capability is remarkable.

- Data scattering is generally acceptable and comparable with the uncertainty usually encountered in durability tests, which fact suggests good reproducibility of the results. One notable exception is carbon, whose data scattering is high, albeit consistently. This outcome stems from the adoption of a dense fabric, indeed the densest among all tested fabrics, which provides poor interlocking capability with the matrix. Therefore, failure is mainly driven by friction and thereby inherently inconsistent.

- TRM samples consistently fail by fabric pull-out (i.e. sliding of the fabric yarns in the matrix), which mechanism stems from poor adhesion at the interphase. This holds true also in the case of control specimens.

- Very exceptionally, exposed specimens may behave better than controls. This surprising outcome is likely related to additional curing of the cementitious matrix in the aggressive solution (that

![Fig. 5 Mean stress-strain curves for SRG in all tested environments: CC, control, (black, dotted); DW, distilled water, (green, thick solid); HA, hydrochloric acid, (violet, thin solid); AK, alkaline solution, (light-blue, solid) and SW, salt-water, (red, solid). (Color figure online)](image)

### Table 6  Mean UTS, UTE and $W_{\mu(f)}$, coefficients of variance, CoV, and percent variation with respect to control group, $\Delta f$.

|     | CC   | SW   | AK   | DW   | HA   |
|-----|------|------|------|------|------|
| F   | $\mu(f)$ [MPa] | CoV [%] | $\mu(f)$ [MPa] | CoV [%] | $\Delta f$ [%] | $\mu(f)$ [MPa] | CoV [%] | $\Delta f$ [%] | $\mu(f)$ [MPa] | CoV [%] | $\Delta f$ [%] | $\mu(f)$ [MPa] | CoV [%] | $\Delta f$ [%] |
|     | ZS   | 2496 | 18.6 | 1602 | 14.9 | -34.0 | 1829 | 25.5 | -24.7 | 2086 | 15.4 | -14.1 | 1772 | 11.0 | -27.0 |
|     | BS   | 2109 | 13.3 | 2467 | 16.6 | 17.0 | 2292 | 25.0 | 8.7  | 2213 | 28.6 | 4.9  | 1565 | 27.8 | -25.8 |
| F   | $\mu(\varepsilon)$ [10^{-3}] | [10^{-3}] | $\mu(\varepsilon)$ [10^{-3}] | [10^{-3}] | $\mu(\varepsilon)$ [10^{-3}] | [10^{-3}] | $\mu(\varepsilon)$ [10^{-3}] | [10^{-3}] | $\mu(\varepsilon)$ [10^{-3}] | [10^{-3}] | $\mu(\varepsilon)$ [10^{-3}] | [10^{-3}] |
| Strength | ZS   | 20.6 | 5.3  | 14.3 | 23.3 | -30.7 | 9.7  | 41.5 | -52.9 | 13.9 | 33.3 | -32.7 | 8.1  | 19.2 | -60.6 |
|     | BS   | 21.1 | 16.7 | 26.5 | 42.1 | 25.6 | 22.5 | 35.9 | 6.3  | 19.3 | 16.7 | -8.5  | 16.1 | 21.6 | -23.9 |
| F   | $\mu(W)$ [J] | [10^{-3}] | $\mu(W)$ [J] | [10^{-3}] | $\mu(W)$ [J] | [10^{-3}] | $\mu(W)$ [J] | [10^{-3}] | $\mu(W)$ [J] | [10^{-3}] | $\mu(W)$ [J] | [10^{-3}] |
|     | ZS   | 25.7 | 19.1 | 13.7 | 25.6 | -46.7 | 11.9 | 45.9 | -53.8 | 17.3 | 37.7 | -32.6 | 9.8  | 38.6 | -62.0 |
|     | BS   | 31.3 | 23.6 | 35.3 | 41.1 | 12.7 | 31.2 | 48.0 | -0.3 | 29.0 | 39.7 | -7.4  | 17.8 | 34.0 | -43.3 |
is mostly water). As pointed out by Ramezanian-pour and Malhotra [36] and Nobili and Signorini [26], matrix curing is a leading factor in determining resistance to aggressive environments. On the other hand, in the case of highly durable fabrics (like carbon, glass, and PBO in particular) performance decays are mainly associated with matrix and especially matrix-to-fabric damage. This interpretation is supported by the observation that curing, which involves only the matrix, is a driving factor in preventing damage from environmental exposure, as illustrated in previous studies by Nobili et al. [26] and Signorini et al [24].

3.2.2 SRG

Figure 5 illustrates the mean stress-strain curves for zinc-coated (ZS) and brass-coated (BS) SRG coupons, with the same scaling for both axes. As expected, strength curves for SRG are almost perfectly bi-linear, reflecting uncracked and cracked performance, the latter extending until sudden failure occurs. This behaviour stems from the enhanced mortar-to-fabric bond formation capability of steel. Comparison of Fig. 5 with De Santis and De Felice [27, Fig. 6] reveals a great difference in terms of UTS, while UTE is comparable. This outcome is most likely due to a different test setup and, in particular, to the confining pressure at the grips. Indeed, in our setup, the applied pressure is purposely not large enough as to prevent fabric slippage from occurring eventually inside the specimen. As a result, fabric-to-mortar adhesion determines the onset of failure prior to fabric failure. This is desirable because fabric-to-mortar adhesion is very sensitive to aggressive environment exposure and the determination of this sensitivity is precisely among the aims of our tests. Conversely, for the setup considered by De Santis and De Felice [27], the stress-strain curves for the dry fabric and for the composite specimen almost coincide, i.e. fabric slippage is prevented altogether. It is therefore little surprising that negligible data scattering appears in the paper by De Santis and De Felice [27, Table 4] (better than 6% CoV for all groups) and that SW immersion brings little harm. This explanation is supported by similar findings presented by De Santis et al. in an extensive round-robin test [37] where, in some tests, ”the specimens where gripped on the dry textile out of the matrix”. Of course different gripping mechanisms are possible and yet, along with Arboleda [17, p.38], we observe that ”gripping mechanisms that apply transversal loading (clamping) to ensure the specimen does not slip are effectively […] producing results that are unrealistically high”. Furthermore, specifically for steel cords, the Italian guidelines impose an upper limit for the UTS equal to the yield stress of the reinforcement, on the grounds that “post-elastic behaviour should be excluded for strengthening purposes” [11, §2.1.1]. We conclude that, as long as a reasonable confining pressure is consistently applied across all specimens, comparative tests are meaningful, while absolute performance remains questionable. From a durability standpoint, it appears that zinc-coated SRG is definitely more sensitive to aggressive environment exposure than brass-coated SRG, despite displaying better performance in the control group.

The bar-charts of Fig. 6 for UTS, alongside the ones for UTE and $W$ available as supplementary material, combined with the corresponding Table 6, better illustrate the point. We observe that

- brass-coated SRG behaves remarkably well in AK, SW and DW, while it greatly suffers from acid attack (HA) where it fails acceptance.
Accordingly, brass-coated SRG appears an attractive candidate for seafront interventions, although large data scattering penalizes design values, see §4.

- In contrast, zinc-coated SRG behaves poorly in all environments, where it fails acceptance, with the possible exception of DW. In any environment, ductility is strongly impaired and so is energy dissipation capability.
- Data scattering is in line with TRM.
- SRG samples consistently fail near the end tabs. This outcome is likely a consequence of the strong adhesion between the steel fabric and the cementitious matrix, which prevents failure by delamination, that is the typical failure mode of TRM. Failure by rupture occurs instead, which demands a considerable tensile force applied by the clamping system, whence the carbon fabric end tabs are incapable of dealing with the entailing clamping pressure.
- Looking at failed specimens reveals that the fabric embedded in the matrix is very well preserved from the detrimental action of the aggressive environments, providing further evidence that performance decay is mainly due to matrix, and especially matrix-to-fabric, decay (see the Supplementary Material).

4 Environmental conversion factors and design considerations

As discussed out in the paper by Nobili and Signorini [26], data scattering plays a crucial role in the determination of design values, to the point that material A, that is less performing in the mean than material B with respect to the performance index \( f \), namely \( \mu(f_A) < \mu(f_B) \), may still be better performing in terms of design value,

\[
f_{dA} > f_{dB},
\]

where subscript \( d \) stands for design and \( f_d \) incorporates data scattering in some form. For instance, according to the verification by the partial factor method described in the Eurocode - Basis of Structural Design [38, §6.3.3], we may adopt

\[
f_d = \frac{\eta}{\gamma_m} f_k,
\]

where \( f_k \) is the characteristic value for a normal distribution (i.e. 95% quintile), \( \gamma_m = 1 \div 1.5 \) is the material partial factor and \( \eta \) takes into account special conditions. In the case of environmental exposure, it is \( \eta = \eta_a \), the latter being the environmental conversion factor. Accurate determination of this factor is essential to correctly design externally-bonded reinforcements by taking in due account the long-term performance of the strengthening system. This, in turn, depends on the specific constituent materials and on the type of environmental aggression. The specific nature of the inorganic binder advises against borrowing conversion factors from the well-established literature on FRP systems. This serious deficiency extends to the current guidelines and it is aggravated by the lack of established artificial aging protocols, capable of simulating real environmental exposure conditions [39]. The connection between artificial aging protocols and real-life exposure is particularly delicate. It is also emphasized that aging extends to the bonding capacity of the strengthening system, which, in the so-called bond critical applications, is the limiting design parameter. It follows that investigation on environmental conversion factors should extend to the matrix/support pair. Italian regulations issued by the National Research Council (CNR) determine design values according to Eq. (2) for FRP [15, Eq. (3.2)] and for FRCM [10, Eq.(3.1)]. Alternatively, the use of the “three-sigma-rule” with no partial factor

\[
f_d = \mu(f) - 3 \text{SD}(f),
\]

is the design strategy advocated in ICC AC434 [12, §8.1]. However, this choice puts strong emphasis on data scattering and therefore heavily favours materials which may be less performing and yet fail consistently [26].

The effect of exposure to the aggressive environment \( a \) on the performance index \( f \) may be described calculating the corresponding environmental conversion factor \( \eta_a \)

\[
\eta_a = \frac{f}{\bar{f}};
\]

which expresses the fraction of the original performance \( \bar{f} \) (obtained in the control group) that remains after exposure. When multiple specimens are dealt
with, we have a set of performance values after exposure, \( \{ f_i \}, i = 1, \ldots, N \), to be compared with a set of control values \( \{ f_j \}, j = 1, \ldots, N' \). Then, we may treat \( \eta_a \) as a random variable

\[
\{ \eta_a \} = \{ f_i / f_j \}
\]

where the ratio is computed for all possible choices of the numerator and of the denominator, respectively in the exposed and in the control group. This is method (b) described in the paper by Nobili and Signorini [26]. Then, we may compute the sample mean \( \mu(\eta_a) \), which is illustrated in Figs. 7 and 8 for UTS and UTE, respectively. An analogous analysis is carried out for dissipated energy \( W \), which relevant conversion factors are graphically reported as supplementary material. In general, the provision \( \eta_a = 70\% \) works out surprisingly well as a lower design limit for strength and elongation, with the partial exception of basalt (B) and zinc-coated steel (ZS), which fare significantly below. Consideration of energy dissipation is more demanding and yet the 70% lower limit still stands, although now also carbon in DW and BS in HA score below. The following considerations may be put forward:

- B is generally worst performing in all environments in terms of UTS, UTE and dissipated energy \( W \), with the exception of AK, where it scores better than ZS. In general, it substantially underperforms the 70% lower design limit.
- Conversely, PBO is generally best performing in every respect, for it shows little performance decay after exposure, if not improvement. In particular, it displays impressive performance gains in DW and HA.
- G, similarly to C, fares rather well in all environments in every respect: it might slightly underperform 70% UTE in SW, where C is preferable, yet it is the best choice in AK, even superior to P. Unexpectedly, C performs poorly in DW.
- BS performs exceedingly well in SW, and very well in AK and DW, while it scores rather poorly in HA.
- ZS is hardly a good option in any environment and underperforms the 70% lower design limit in terms of UTE in AK and HA.

In the previous analysis no consideration has been given to the uncertainty connected to the evaluation of the environmental conversion factor. To remediate this shortcoming, we consider a 95% confidence interval for the mean and assume it is normally distributed,

\[
\eta_{ad} = \mu(\eta_a) - 1.96 \frac{\text{SD}(\eta_a)}{\sqrt{N_p}}.
\]

Fig. 7 Mean environmental conversion factors for UTS, \( \eta_a(f) \) for different reinforcing fabrics: G (glass, grey), B (basalt, amaranth), P (PBO, orange) and C (black, carbon), BS (ochre, brass-coated steel) and ZS (blue, zinc-coated steel). The acceptance limit is also shown (red, dash-dot). (Color figure online)
where \( N_p = N \bar{N} \) is the entity of the statistical population of the random variable \( \eta_{\text{ad}} \), as defined by Eq. (4). We thus obtain the material selection table of Fig. 9.

### 5 Conclusions

Figure 9 ranks the reinforcing fabrics in terms of residual performance after exposure to different aggressive environments, with respect to the corresponding unexposed (control) specimen. It reports the environmental conversion factor lower limits in a 95% confidence interval, according to Eq. (5). As such, it provides a convenient first-glance material selection table for scientists and practitioners. From it, we see that

- the 70% lower limit performance advocated in the Italian guidelines [10] is generally sound but may be significantly breached downwards. In fact, this occurs 7 times for UTS and 11 for UTE out of 24 combinations, although mainly owing to basalt (B) and zinc-coated steel (ZS).
- brass-coated steel (BS) and PBO (P) are, almost always, the optimal choice, but the advantage over the second best, mainly AR-glass (G), is not large. Noticeably poor performance is attained by BS in acid conditions and P in salt water;
- carbon (C) and glass (G) perform similarly, with a significant margin in favour of the latter. In fact, the former appears preferable only in marine
conditions. Conversely, carbon exhibits a surprisingly poor performance in distilled water.

- zinc-coated (galvanized) steel (ZS) and basalt (B) are never really an option in light of their performance that often scores two or even three times less than the best candidate.

We conclude that careful selection of the reinforcing fabric plays a significant role in the determination of the durability of the composite. In this respect, the common-to-all-fabric environmental conversion factor given by the Italian guidelines conceals large performance differences, which should be capitalized at the design stage. Finally, best design options, in terms of durability, are available both in the SRG and in the TRM groups.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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