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Tensile Behavior of a Glass FRCM System after Different Environmental Exposures

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Abstract: The use of Fabric-Reinforced Cementitious Matrix (FRCM) systems as externally bonded reinforcement for concrete or masonry structures is, nowadays, a common practice in civil engineering. However, FRCM durability against aggressive environmental conditions is still an open issue. In this paper, the mechanical behavior of a glass FRCM system, after being subjected to saline, alkaline and freeze–thaw cycles, has been investigated. The experimental campaign includes tensile tests on the fabric yarns, compression and flexural tests on the matrix and tensile tests (according to AC434) on FRCM prismatic coupons. The effects of the different environmental exposures on the mechanical properties of both the constituent materials and the composite system have been investigated and discussed. Ion chromatography analysis has also been performed to better understand the damage mechanisms induced by environmental exposures and to evaluate the ions' penetration within the inorganic matrix. Alkaline exposure was shown to be the most detrimental for Alkali-Resistant (AR) glass fiber yarns, causing a reduction in tensile strength of about 25%. However, mechanical properties of the FRCM composite seemed not to be particularly affected by any of the artificial aging environments.

Keywords: Fabric-Reinforced Cementitious Matrix (FRCM); glass fibers; environmental exposure; durability

1. Introduction

Fabric-Reinforced Cementitious Matrix (FRCM), also known in the international literature as Textile-Reinforced Mortar (TRM), represents a new class of composite materials that has gained considerable interest in recent years as a promising technique to upgrade, strengthen and rehabilitate concrete or masonry structures. This system is constituted by a structural reinforcement fabric, consisting of an open grid of perpendicularly connected multifilament yarns, which is applied on concrete or masonry structural elements through an inorganic-based matrix [1].

FRCMs are considered a valid alternative to Fiber-Reinforced Polymers (FRPs), since the use of an inorganic matrix in place of organic resins allows one to overcome the typical drawbacks of FRPs, such as the decrease in mechanical properties and strengthening ability at high temperatures [2–4], poor fire resistance [5], low vapor permeability, and inapplicability on wet surfaces or at low temperatures. Multifilament yarns (usually made of alkali-resistant glass, carbon, basalt or PBO fibers) can be dry or impregnated with polymeric coatings in order to reduce the slippage between the single filaments, to improve the bond with the inorganic matrix and to increase the long-term performance of the fabric [6,7]. Despite the term 'cementitious', the FRCM matrix may be a lime-based mortar when the FRCM system is designed to be applied on historic masonry substrates, or a mixture of lime and cement when designed for different substrates. Furthermore, the matrix can be polymer-modified by adding organic compounds (dry polymers), limited to 5% or 10% by weight of the inorganic binder (lime or cement), according to the ACI 549.4R-13 [1] or the Italian guideline issued by Consiglio Superiore dei Lavori Pubblici [8], respectively.

Although the mechanical characterization and the effectiveness of FRCMs as externally bonded reinforcement systems have been deeply investigated [2,7,9–13], their ability to withstand the exposure to service environments is relatively unknown at present. A recent review published by Al-Lami et al. highlights a grate lack of studies conducted on the topic, reporting a great difficulty in the comparison of results due to differences in the materials used, tests performed and conditioning protocols adopted [14]. Of course, the use of fibers and textiles for structural applications is not a new concept. Experimental studies on glass and basalt fibers, which may be subjected to corrosion in alkaline environments (typical of cementitious matrix), have been carried out by several researchers [15–17]. Detailed analyses of degradation processes that may occur in Glass Fiber-Reinforced Concrete (GFRC) have been conducted [18], along with accelerating aging of fibers in artificial environments [19]. The durability of FRPs has also been largely investigated and several studies on the exposure to alkaline and saline environment, elevated temperature, freeze–thaw cycle, high relative humidity (RH) and ultraviolet (UV) radiation have been carried out [20–22].

On the contrary, at present, very few works concerning the resistance of FRCM (or TRM) systems under various environmental exposure conditions have been conducted. Butler et al. studied the correlation between matrix alkalinity and the mechanical performance of TRM made with Alkali-Resistant (AR) glass fibers, reporting an important decrease in tensile strength and strain capacity after accelerated ageing in matrix with a high pH value [23]. Degradation processes are similar to those observed for GFRC (Glass-Fiber-Reinforced Concrete); thus, when FRCMs are reinforced with basalt or glass-fiber fabrics, it is reasonable to consider the alkalinity of the cementitious matrix as an aggressive environment for the reinforcement fabric.

Moreover, the long-term behavior of FRCM systems also concerns all the degradation mechanisms typical of cementitious materials. For example, alkali aggregate reaction, sulphate attack and freeze–thaw cycles represent chemical-physical conditions that may promote the formation of expansive compounds usually responsible for crumbling or spalling of cementitious materials [24]. The decay of mechanical properties due to freeze–thaw cycles and salt attack is more noticeable in matrices with high porosity and low strength, as reported by some authors [25–29]. Thus, in the case of FRCM systems made of lime-based matrices, the effects of artificial exposure could be more compromising than in the case of cementitious matrices. On the other hand, the pH of lime-based matrices is lower compared to cementitious ones, and therefore the environment may be less aggressive for the internal reinforcement made of glass or basalt fibers. Furthermore, environmental conditions may also influence the bond behavior of the composite when applied to different substrates [30–32].

In a work conducted by Nobili on lime-based FRCM systems reinforced with glass fabrics, tested before and after exposure to alkaline and saline environments, it is reported that the flexural strength of the mortars is reduced for more than 50% and that tensile strength of the FRCM composite is between 10% and 15% lower than that of reference specimens [33]. Another work by Nobili and Signorini investigated on the effect of curing time and environmental exposure on the mechanical properties of FRCM with impregnated carbon fabric and pozzolan-based mortar [34]. Seawater and alkaline environments caused a significant reduction in the FRCM tensile strength. Franzoni et al. investigated the mechanical behavior of brick masonry specimens reinforced with FRCM, made of hydraulic lime-based mortar and steel strips, subjected to salt crystallization cycles [31]. The study reports that, even if the matrix presents a marked salt accumulation after artificial aging, no significant decrease in the mechanical properties is observed. Previous studies conducted by Donnini on the mechanical behavior of lime-based FRCM systems reinforced with glass fabrics, after immersion in tap water and saline solution, showed a decay of the peak load in single-shear bond tests of about 29% for specimens immersed in saline solution and of 20% when subjected to wet–dry cycles [32].

Recent guidelines, such as ACI 549.4R-13 [1], AC434 [35] and the Italian guideline issued by "Consiglio Superiore dei Lavori Pubblici" [8], provide durability tests to evaluate the residual mechanical properties of FRCM systems after being subjected to different environmental exposures. These tests include aging in water vapor, immersion in saltwater and alkaline solution at 22 °C up to 3000 h, freezing–thawing cycles, fuel resistance, and thermal tests. These guidelines provide for mechanical tests on FRCM coupons, constituted by the coupling of fabric reinforcement and inorganic matrix. However, beside the importance of investigating the effect of different aging protocols, a deep understanding of the factors affecting the durability of FRCM composite systems should also consider the behavior of each of its components subjected to environmental stresses.

In this study the effects of different environmental exposures on the mechanical properties of an FRCM system constituted by a bidirectional fabric, made of Alkali-Resistant (AR) glass fibers coupled with a cement-based matrix have been investigated. Experimental tests have been conducted on the individual materials (AR glass yarns, FRCM matrix) and on FRCM coupons, in order to assess the structural efficiency of the whole composite system subjected to detrimental environmental actions (immersion in saltwater and alkaline solutions, freeze–thaw cycles).

Ion chromatography analysis has been performed to evaluate the penetration of alkaline and saline ions within the inorganic matrix. Optical macroscope observations were also conducted to evaluate the effects of environmental exposures on the glass yarns' cross-sections.

2. Materials and Methods

2.1. Materials

The FRCM system investigated in this study is constituted by a cementitious matrix reinforced with a bidirectional glass fabric (see Figure 1). The FRCM matrix comprises a mix of cement, hydrated lime, calcium carbonate with two different particle size distribution (up to 400 μm and 600 μm) and vinyl acetate/vinyl ester of versatic acid/ethylene polymers. Table 1 gives the composition of the FRCM matrix.

The bidirectional fabric is made of multifilament Alkali-Resistant (AR) glass fiber yarns pre-impregnated with SBS (styrene-butadiene-styrene). The unit area net weight of the glass fabric is 182 g/m^2 and the spacing between yarns is about 27 mm. The cross-sectional area of a single glass yarn, as reported by the manufacturer, is equal to 0.789 mm^2.

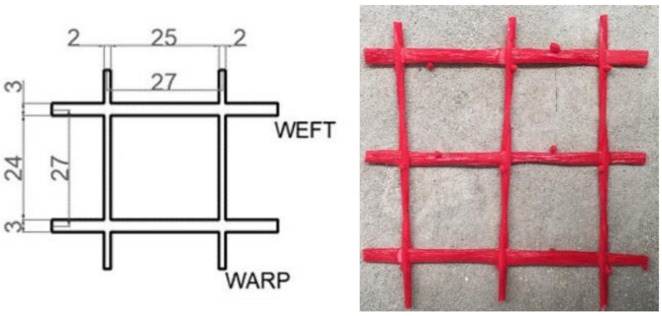

Figure 1. Glass fabric used in experiments.

Table 1. Fabric-Reinforced Cementitious Matrix (FRCM) matrix composition (mixture proportions by weight).

CEM II/B-LL 42.5 R	Calcium Carbonate 400 μm	Calcium Carbonate 600 μm	Hydrated Lime	Dry Polymer	Water
1	2.86	0.82	0.44	0.08	1.04

2.2. Preparation of FRCM Coupons for Tensile Test

Mechanical properties of FRCM were evaluated through tensile tests on prismatic coupons with dimensions of about 400 × 70 × 12 mm^3, according to AC434 [35]. Specimens were manufactured using a manual impregnation technique by placing the glass fabric between two matrix layers 6 mm thick. The fabric was placed to have the 3 weft yarns parallel to the longitudinal axis of the specimen. Unconditioned FRCM specimens (FRCM_Ref) were tested after 70 days of curing under laboratory conditions (20 °C, 70% RH). Specimens subjected to artificial aging were cured for 28 days at the same laboratory conditions before starting the environmental conditioning and then dried in oven at 40 °C for 24 h before testing.

2.3. Environmental Exposure Tests

Table 2 describes the artificial environments considered in this study. FRCM matrix samples and FRCM coupons were cured at laboratory conditions (20 °C, 70% RH) up to 28 days before starting the environmental conditioning (1000 h). By doing so, the total curing time for all specimens was about 70 days. Therefore, also reference specimens (both FRCM matrix samples and FRCM coupons) were tested after 70 days of curing at laboratory conditions. Exposure to alkaline and saline environments was conducted by completely immersing the specimens in the two solutions (see Figure 2a).

Table 2. Test environments.

Environment	Temp.	RH	Solution	Time of Exposure
None	20 °C	70%	-	-
Saline (S_40)	40 °C	100%	2.45% NaCl + 0.41% Na_2SO_4	1000 h
Alkaline (A_40)	40 °C	100%	4% NaOH	1000 h
Freeze–thaw (FT)	−18 °C/ +40 °C	40%/ 100%	-	960 h (40 cycles)

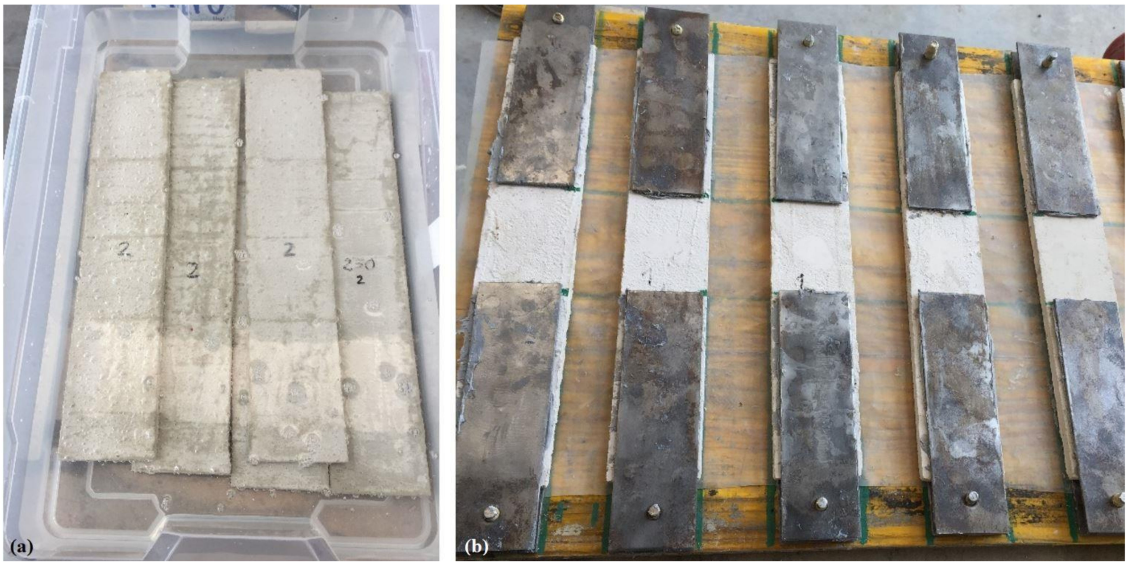

Figure 2. (**a**) Specimens immersed in saline solution and (**b**) the application of metal tabs on FRCM coupons.

The first environment (S_40) comprises 2.45% weight sodium chloride (NaCl) and 0.41% weight of sodium sulphate (Na_2SO_4) aqueous solution. The amount of salt dissolved in the solution was chosen according to ASTM D1141–98 [36]. The temperature of 40 °C was chosen because it was considered a good compromise between the need to accelerate the aging process and the risk of promoting unrealistic chemical reactions. Moreover, since an SBS-impregnated glass fabric was used, an aging temperature close to the glass transition temperature (T_g) of the polymer was avoided in order to prevent undesired softening of the external coating.

The second environment (A_40) comprises a 4% weight sodium hydroxide (NaOH) aqueous solution that correspond to a pH of 13.

The last type of conditioning consisted of freeze–thaw cycles that comprised a freezing phase of 12 h at −18 °C followed by a 12 h thawing phase conducted in an oven at 40 °C with 100% RH. A total of 40 cycles have been performed. Finally, after artificial conditioning, all specimens have been dried in an oven at 40 °C for 24 h before testing.

2.4. Characterization Tests

2.4.1. FRCM Matrix

The compressive and flexural strengths of the FRCM matrix were evaluated on three prismatic specimens (40 × 40 × 160 mm^3) for each type of environmental conditioning, according to UNI EN 1015-11 [37]. Then, X-ray analysis and Ion Chromatography analysis (IC) were also performed on the FRCM matrix exposed to different environments. Ion Chromatography analysis (IC) allowed to investigate the permeation of ions in the FRCM matrix after environmental exposure. A total of 500 mg of fine-grained samples collected from the core of prismatic specimens was added to a 500 mL volumetric flask and made up to volume with distillated water. The flasks were immersed in an ultrasonic bath at 40 °C for 20 min. The pH of the dispersion obtained was measured with a pH meter Denver Basic and found equal to 11.7 for all three samples. The solution was then filtered with a 0.2 μm pore size membrane filter and analyzed with an Ion Chromatograph Dionex ICS-900 and DX-100.

2.4.2. Glass Yarns

The fabric was characterized with tensile tests performed in displacement-control (0.5 mm/min) on five glass yarns 300 mm long, according to [38]. FRP tabs were bonded with epoxy resin at the ends of each specimen to guarantee a perfect grip. Tensile strain and elastic modulus were evaluated with a macro-extensometer (gauge length equal to 50 mm) positioned at the center of the yarn (see Figure 3).

Figure 3. Tensile test on glass yarn.

The tensile strength $\sigma_{max,y}$ has been obtained as follows:

$$\sigma_{max,y} = F_{max,y}/A_y$$

where $F_{max,y}$ is the maximum axial force and A_y is the cross-sectional area of a single yarn. The ultimate tensile strain $\varepsilon_{u,y}$ is the maximum deformation at failure. The elastic modulus E_y has been calculated as the slope of the stress–strain curve comprised between 0.2 and 0.5 of the tensile strength, according to [38].

2.4.3. FRCM Coupons

A series of direct tensile tests have been carried out on a total of 20 FRCM coupons. According to the instructions of AC434 (Annex A) [35], specimens were tested using a clevis grip system which allows one to transfer the load from the testing machine to the specimens through 4 steel plates (3 mm thick) epoxy glued at the ends of the specimen with a bonded length of 150 mm (Figures 2b and 4a,b). Monotonic tensile tests were performed in displacement control (0.5 mm/min) by using a universal testing machine with a total capacity of 50 kN (Figure 4a). Axial force (F) was recorded by using a loading cell integrated in the testing machine while the axial strain on the free length of the coupon was measured with a 100 mm gauge length macro extensometer (Figure 4a).

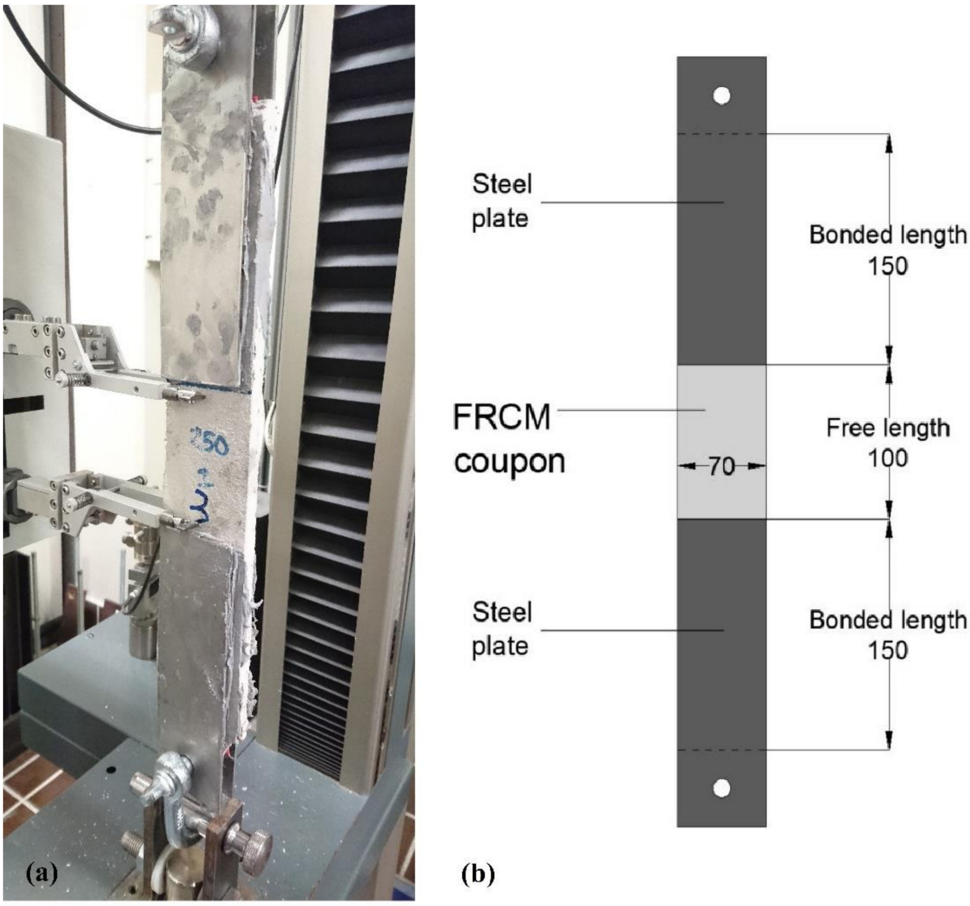

Figure 4. FRCM specimens: (**a**) tensile test setup and (**b**) the geometry of a coupon.

The FRCM tensile strength ($\sigma_{u,f}$) was calculated according to [35] as follows:

$$\sigma_{u,f} = F_{max}/3A_y$$

where F_{max} is the maximum axial force and $3A_y$ is the cross-section of the fabric in the load direction (consisting of 3 yarns). The modulus of elasticity in the cracked phase ($E_{u,f}$) has been calculated as the slope of the stress–strain curve in the region between 0.60 and 0.90 $\sigma_{u,f}$, according to [35].

3. Results and Discussion

3.1. FRCM Matrix

The mechanical properties of the FRCM matrix after environmental exposure are reported in Table 3 in terms of average compressive strength $\sigma_{c,m}$ and average flexural strength $\sigma_{f,m}$ (Coefficient of Variation in round brackets, %).

Table 3. Mechanical properties of the FRCM matrix after environmental exposure.

Specimen	Compressive Strength $\sigma_{c,m}$ (MPa)	Compressive Strength Variation	Flexural Strength $\sigma_{f,m}$ (MPa)	Flexural Strength Variation
Matrix_Ref (28 days)	17.95 (4.35%)	-	5.66 (5.61%)	-
Matrix_Ref (70 days)	23.10 (4.20%)	-	9.80 (3.96%)	-
Matrix_S_40	24.99 (3.83%)	+8.2%	12.08 (8.58%)	+23.3%
Matrix_A_40	25.37 (3.27%)	+9.8%	11.98 (9.63%)	+22.2%
Matrix_FT	21.83 (3.93%)	−5.5%	8.88 (7.04%)	−9.4%

The compressive and flexural strengths of specimens subjected to different environmental exposures have been compared with those of the matrix cured under laboratory conditions (20 °C, 70% RH) for up to 70 days (Matrix_Ref (70 days)).

First, it can be observed that the average values of compressive and flexural strength obtained for the reference samples at 70 days are significantly higher than those of the matrix tested after 28 days of curing (see Table 3), proving that the curing process was not completed in the first 28 days.

Moreover, the compressive and flexural strength of prismatic specimens immersed in alkaline and saline solution are higher than those obtained for the same samples cured at standard condition. Probably, the curing of specimens at 100% RH and 40 °C may have promoted an additional curing of the matrix immersed in aqueous solutions. On the contrary, samples subjected to freeze–thaw cycles showed a lower compressive and flexural strength with respect to reference specimens. However, no cracks or visible damage were observed on specimens after conditioning, thus suggesting that the different temperature and humidity (−18 °C, 40% RH for freeze condition) may have influenced the curing process.

Different results can be found in the literature for cementitious matrices exposed to saline environments [25,39–41]. Usually, failure may occur due to sulphate attack, which causes a sequence of chemical reactions responsible for degradation phenomena. As shown in Equations (1) and (2), sulphate ions react with both portlandite and calcium silicate hydrate, promoting the decalcification of the matrix.

$$Ca(OH)_2 + SO_4^{2-} + 2H_2O \rightarrow CaSO_4{\cdot}2H_2O + 2OH^- \quad (1)$$

$$Ca{\cdot}2SiO_2{\cdot}3H_2O + SO_4^{2-} + H_2O \rightarrow CaSO_4{\cdot}2H_2O + 2SiO_2{\cdot}H_2O \quad (2)$$

Moreover, gypsum formed in those reactions can further react with tricalcium silicate, leading to the formation of ettringite (Equation (3)). These processes are reported to involve expansion phenomena and therefore to cause the crumbling and spalling of the mortar [24].

$$3CaO{\cdot}Al_2O_3 + 3CaSO_4{\cdot}2H_2O + 26H_2O \rightarrow 3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O \quad (3)$$

Although the formation of gypsum and ettringite in the presence of sulphate-rich environments has been reported by many works [39–41], the conditions that promote these reactions are still not well understood [42]. A study conducted by Lanas et al. on the durability of aerial and hydraulic lime-based mortar revealed a different behavior of the two matrices to SO_2 exposure: the formation of gypsum in aerial mortars caused a strength decrease. Conversely, in hydraulic mortars, a strength increment was observed [25]. In addition, the protocol employed can also influence the obtained results. Different investigations on test methods for the determination of sulphate attack underline a wide divergence of results depending on the experimental set up. Large-scale studies conducted by the US Bureau of Reclamation on the exposure of concrete to sulphate estimated that one year of accelerated test consisting of wet–dry cycles corresponds to eight years of immersion in sulphate solution [43]. Although the mechanical tests on Matrix_S_40 suggest that no degradation has occurred, X-ray analyses were conducted to investigate the possible formation of gypsum and ettringite.

The results of the X-ray analyses confirm that the FRCM matrix was not affected by saline environment exposure, since neither gypsum nor ettringite formed within the matrix (see Figure 5).

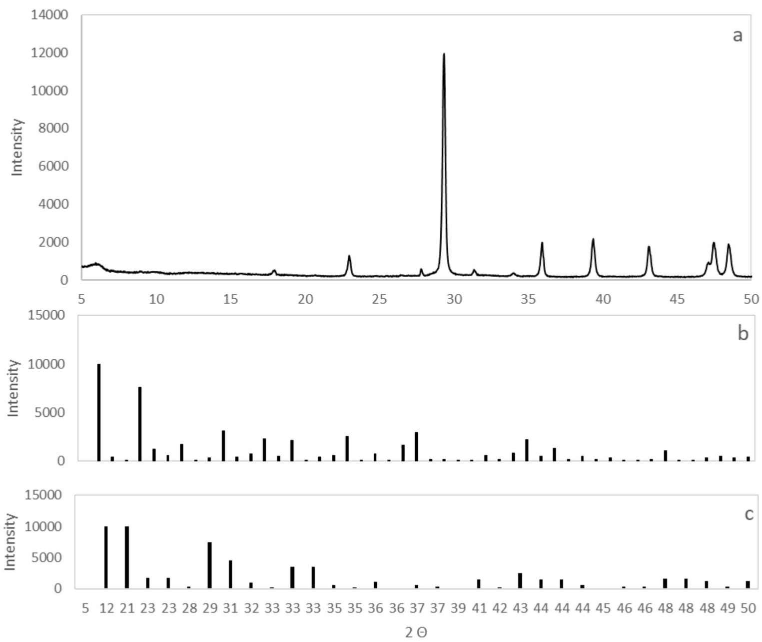

Figure 5. X-ray diffractogram of (**a**) S_40 sample compared with (**b**) a ettringite diffractogram and (**c**) a gypsum diffractogram from the database.

Regarding the effect of an alkali environment, it should be outlined that high pH values are not usually considered to be potentially harmful for cementitious matrices. To the authors' best knowledge, the only degradation process promoted by alkaline environments is the so-called "Alkali-Silica Reaction" (ASR). This reaction is promoted by alkali hydroxides, such NaOH and KOH, that react with thermodynamically unstable silica, forming an alkali-silica gel that absorbs water inducing the expansion and cracking of the concrete [24,44]. Aggregates that have been found to give ASR are: opal, tridymite, cristobalite, volcanic glass, chart, cryptocrystalline (or microcrystalline) quartz and strained quartz [44]. Since no one of those aggregate was present in the cementitious matrix, the FRCM matrix of this study has not been damaged by exposure to an alkaline environment.

Ion chromatography analyses were also performed for FRCM matrix samples (as described in Section 2.4.1), and the results are reported in Table 4. It can be observed that the percentage of chlorine and sodium ions is much higher for the specimens immersed in saline solution, thus demonstrating the ability of ions to penetrate inside the FRCM matrix. However, the same is not true for sulphate ions, probably because of the much lower concentration of Na_2SO_4 in the aging solution. It was also observed that sodium concentration in A_40 specimens was lower than those of S_40 samples, even though the molar concentration of Na^+ was higher in the alkaline than in the saline solution. Since studies on the permeability of ions in concrete matrix are usually conducted to evaluate the exposure to saline solution, no studies are available on the migration of sodium from NaOH solution in cementitious matrices.

Moreover, while many studies report on the diffusivity of chlorine ions in concrete, experimental studies are usually less concern with the mobility of sodium in inorganic matrices.

Table 4. Ion chromatography analysis on matrix samples.

Specimen	Sodium Na+ (%)	Calcium Ca++ (%)	Chloride Cl^- (%)	Sulphate SO_4^- (%)
Matrix_Ref	0.04	4.44	0.01	0.10
Matrix_S_40	0.12	4.51	0.24	0.10
Matrix_A_40	0.03	4.02	0.01	0.11

However, theoretical studies conducted on the diffusion of mixture of ions in concrete, report that the ionic species present in the solution may affect the mass flow of anions and cations [45,46]. Moreover, experimental studies that document the effect of counter-ions and pH of the exposure solution on chloride binding in concrete matrix are also available [47]. Based on these investigations, it seems reasonable to believe that the different penetration of Na^+ ions in S_40 and A_40 samples was due to the high concentration of OH^- in the alkaline solutions. However, further studies are certainly needed to better investigate this phenomenon.

Regarding the degradation process of cementitious materials subjected to freeze–thaw cycles, this is usually related to the tensile strength of the matrix and its microstructure [24]. Lanas et al. compared the resistance of hydraulic and aerial lime to freeze–thaw cycle and observed that the first, which possess higher compressive strength and lower porosity, was less affected by environmental exposure, even though both matrices were severely damaged [25]. A first visual inspection of the specimens tested in this study did not reveal any evident damage. It can be concluded that FRCM matrices were not damaged by freeze–thaw cycles, and that the lower mechanical performances observed were a consequence of the compromised curing process due to the low temperature and relative humidity.

3.2. Glass Yarns

After exposure of glass yarns to the conditioning protocols described in Section 2.3, a visual inspection has been carried out and pictures of the glass fabric surface are reported in Figure 6. The formation of salt crystals on the yarns' surface was clearly observed in specimen S_40 (Figure 6b) while those immersed in alkaline solution showed a darker surface due to some reaction between alkaline ions and SBS polymer.

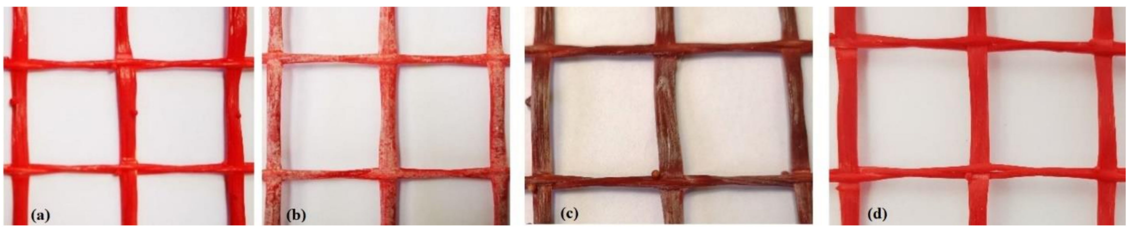

Figure 6. Glass fabrics after environmental exposure: (**a**) Ref, (**b**) S_40, (**c**) A_40, (**d**) freeze–thaw (FT).

Then, tensile tests have been performed on 5 samples for each environmental exposure and average values are reported in Table 5 (Cofficient of Variation in round brackets, %). Tensile test setup has been previously described in Section 2.4.2. Stress–strain curves are reported in Figure 7. All the specimens showed a linear elastic deformation up to failure, which always involved the fibers in the central part of the yarn.

Table 5. Mechanical properties of the glass yarns before and after environmental exposure.

Specimen	Tensile Strength $\sigma_{max,y}$ (MPa)	Tensile Strength Variation	Elastic Modulus E_y (GPa)	Ultimate Strain $\varepsilon_{u,y}$ (%)
Yarn_Ref	1236 (10.3%)	-	67.58 (5.04%)	1.7 (12.32%)
Yarn_S_40	1133 (7.2%)	−8.35%	67.87 (13.44%)	1.4 (9.73%)
Yarn_A_40	924 (10.4%)	−25.22%	69.37 (10.16%)	1.1 (5.75%)
Yarn_FT	1131 (5.26%)	−8.50%	66.21 (8.15%)	1.7 (7.41%)

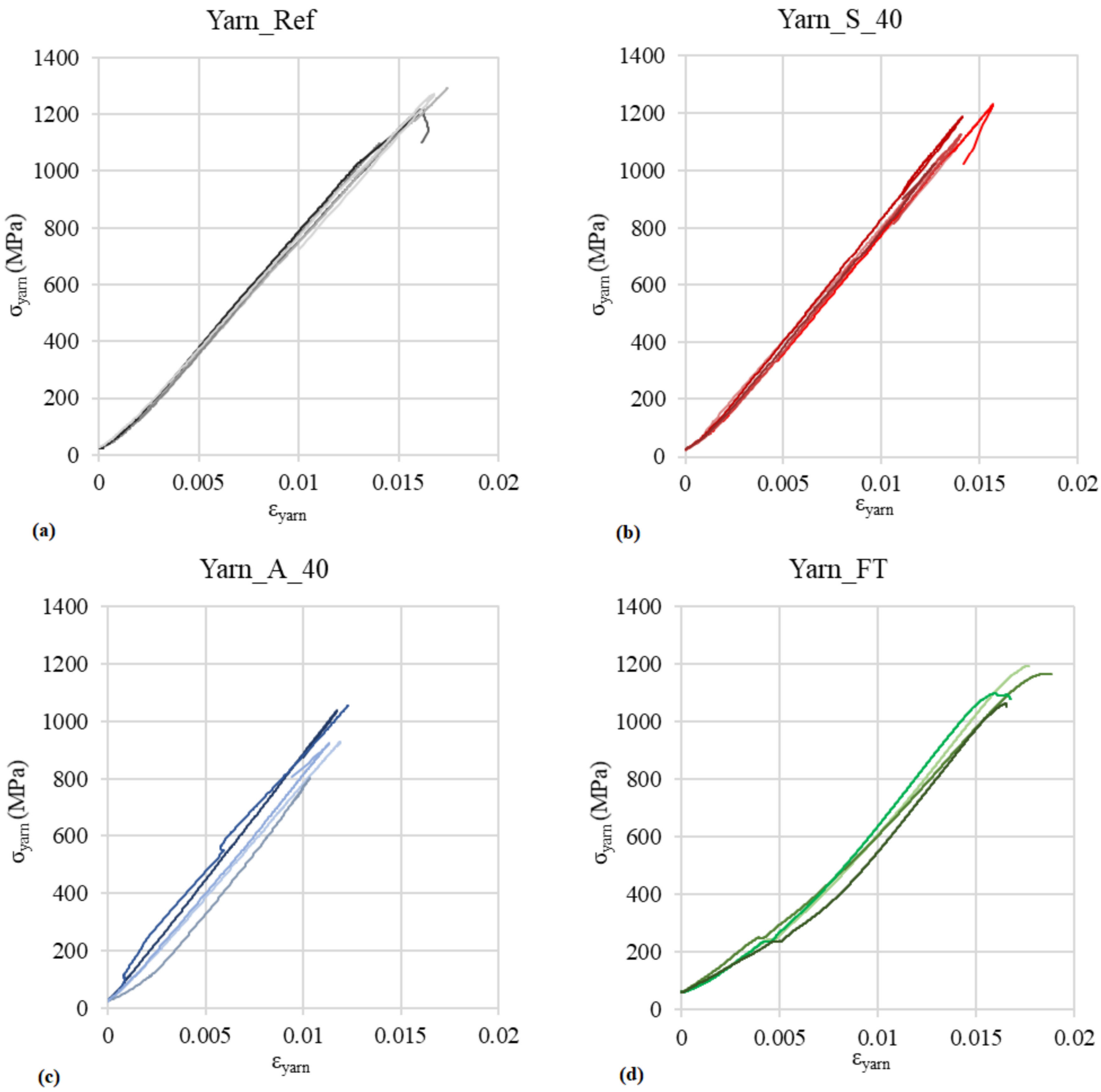

Figure 7. Tensile tests on glass yarns after different environmental exposures showing the stress–strain curves of specimens: (**a**) Ref, (**b**) S_40, (**c**) A_40, (**d**) FT.

A decrease of the ultimate tensile strength $\sigma_{max,y}$ of about 8% and 25% was observed for AR glass yarns exposed to saline (Yarn_S_40) and alkaline (Yarn_A_40) environments, respectively. The ultimate tensile strain $\varepsilon_{u,y}$ was also reduced, while the elastic modulus E_y remained almost unchanged. Glass yarns exposed to freeze–thaw cycles (FT) showed a reduction in tensile strength of about 8%.

These results are comparable with those of other studies from the literature on AR glass yarns exposed to saline and alkaline environments. Nobili reports that the exposure of AR glass yarn to saline environments leads to a reduction in tensile strength of about 11% [33]. An experimental study by Micelli and Aiello [48] on AR glass yarns exposed to alkaline environments (45 °C for 60 days) showed a reduction in tensile strength of between 15% and 25%. The application of organic coatings on AR fibers is usually reported to have a protective effect against alkaline corrosion. However, studies conducted by Scheffler et al. on coated AR glass fibers revealed that film formation and coating distribution play an important role in glass fibers protection, since the inhomogeneous distribution of the coating exposes glass filaments to alkaline attack [17].

In this study, pre-impregnation of AR glass yarns with an SBS polymer coating seemed not to be able to avoid degradation phenomena due to environmental exposures. This is probably due to the incomplete impregnation of the individual glass filaments (Figure 8a), and the poor temperature stability of the SBS polymer. In fact, when immersed in saline or alkaline solutions at 40 °C, a significant swelling of the yarns cross-section was observed (see Figure 8b,c). This phenomenon reduces the mechanical properties of the yarn due to a non-homogeneous distribution of stresses between single filaments and facilitated the penetration of saline and alkaline solutions within the yarn cross-section. The experimental results show that, although the yarns were constituted by AR glass filaments, the alkaline environment was found to be the most detrimental.

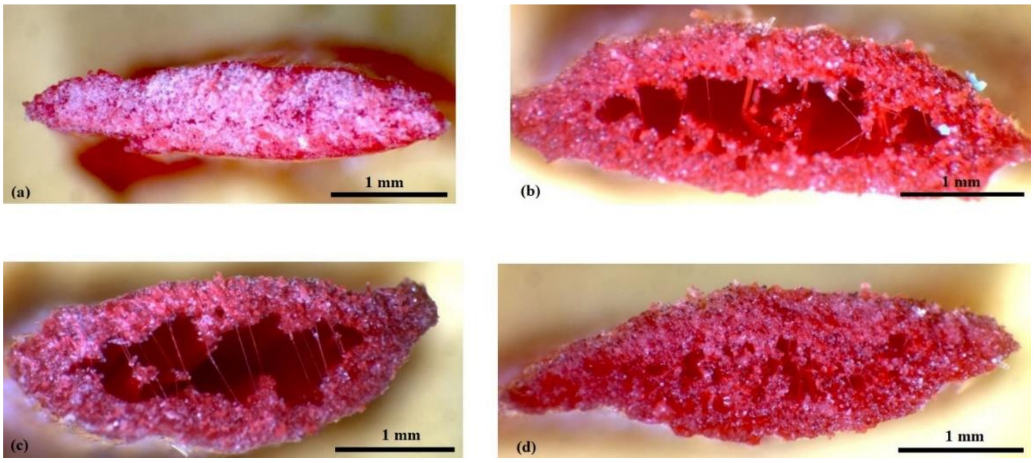

Figure 8. Macroscope observations of the glass yarns' cross-sections after different environmental exposures: (**a**) Ref, (**b**) S_40, (**c**) A_40, (**d**) FT.

3.3. FRCM Coupons

The experimental results of tensile tests on FRCM coupons, evaluated as the average of five specimens for each type of exposure, are reported in Table 6 in terms of maximum force (F_{max}), tensile strength ($\sigma_{u,f}$), ultimate tensile strain ($\varepsilon_{u,f}$) and elastic modulus in the cracked phase ($E_{u,f}$).

Table 6. Results of tensile tests on FRCM coupons according to AC434.

Specimen	F_{max} (N)	$\sigma_{u,f}$ (MPa)	$\sigma_{u,f}$ Variation	$\varepsilon_{u,f}$ (mm/mm)	$E_{u,f}$ (GPa)
FRCM_Ref	2213 (6.8%)	935 (6.8%)	-	0.033 (10.1%)	38.2 (10.2%)
FRCM _S_40	2333 (5.2%)	986 (5.2%)	+5.5%	0.031 (19.3%)	33.0 (10.4%)
FRCM _A_40	2234 (12.6%)	944 (12.6%)	+1.0%	0.029 (18.1%)	36.6 (16.9%)
FRCM _FT	2142 (8.4%)	905 (8.4%)	−3.2%	0.027 (11.2%)	33.1 (13.4%)

Stress–strain curves for all tested FRCM coupons are shown in Figure 9. All tested specimens showed the typical tensile behavior of FRCM coupons tested by using a clevis grip anchoring system [7,49]. The drop of the tensile stress after the formation of the first crack in the matrix is probably due to the low amount of fabric reinforcement area, which is insufficient to absorb the energy released at cracking, as also observed in other studies [50]. Once the matrix has cracked, the FRCM coupons continue to take load, with the formation of further horizontal cracks in the matrix. Failure was always due to breakage of one or more glass yarns within the inorganic matrix, regardless of the type of artificial conditioning (Figure 10a–d).

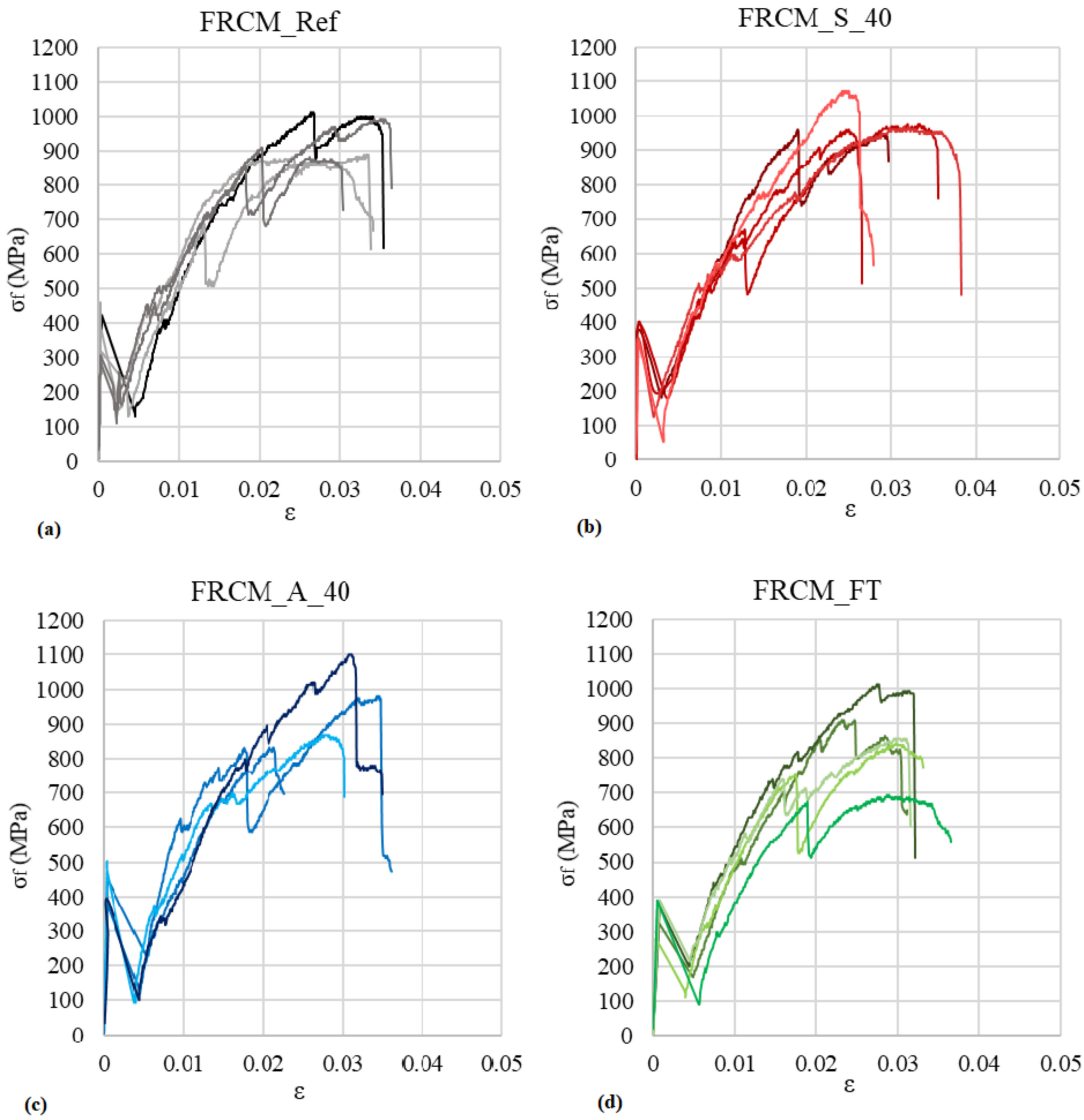

Figure 9. Tensile tests on FRCM coupons after exposure showing the stress–strain curves of specimens: (**a**) FRCM_Ref, (**b**) FRCM_S_40, (**c**) FRCM_A_40, (**d**) FRCM_FT.

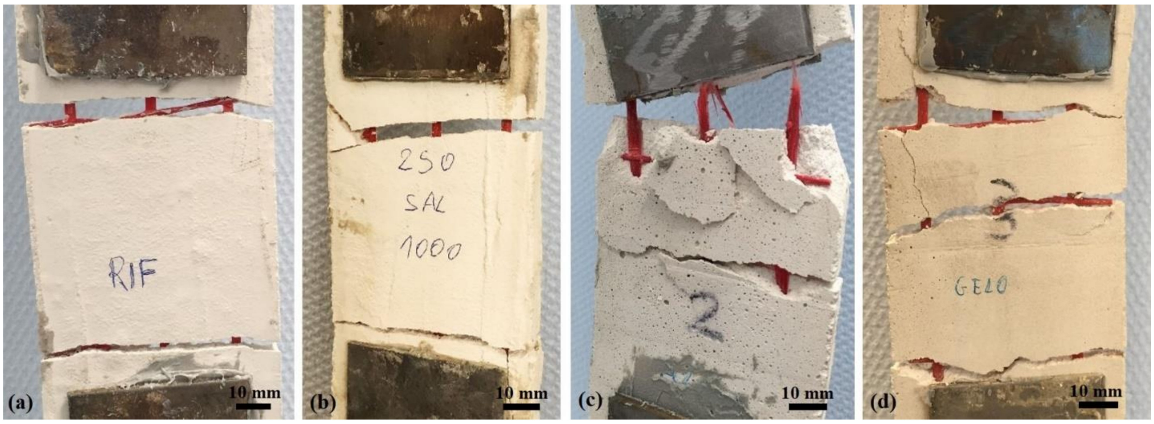

Figure 10. Tensile tests on FRCM coupons: failure mode observed (**a**) FRCM_Ref, (**b**) FRCM_S_40, (**c**) FRCM_A_40, (**d**) FRCM_FT.

FRCM specimens exposed to artificial environmental exposures did not show significant differences among the average values of mechanical properties. FRCM subjected to freeze–thaw cycles showed a reduction in tensile strength of about 3% and in the elastic modulus of about 13%. However, the slight differences observed must be considered within the variability of the results, which, for this type of test, due to the difficulty of sample preparation and to the material heterogeneity, is always quite high. Therefore, it can be observed that the reduction in tensile strength observed in glass yarns exposed to the same environmental conditions (especially in the case of alkaline environments) does not reflect on the mechanical properties of FRCM composites. This is probably due to the protective action of the inorganic matrix, which, although of limited thickness (about 6 mm), does not allow aggressive agents to penetrate within the specimen. Thus, the matrix thickness is a parameter that strongly influences the response of conditioned FRCM coupons. Further studies are certainly needed in order to try to correlate the ability of the matrix to withstand exposure in aggressive environments with the thickness of the FRCM system and with the porosity and mechanical properties of the matrix itself.

4. Conclusions

In this study, the effects of different environmental exposures on the mechanical properties of an FRCM system constituted by a cement-based matrix and an SBS-coated glass fabric have been investigated. Compressive and flexural tests on matrix samples, tensile tests on glass yarns and FRCM coupons (according to AC434) were performed after subjecting all specimens to the same artificial exposures, which include immersion in saline solution, alkaline solution and freeze–thaw cycles. The obtained results can be synthesized as follows:

- The mechanical properties of the FRCM matrix are barely influenced by the different environmental exposures: a slight decrease in compressive and flexural strength was only observed for specimens subjected to freeze–thaw cycles, probably because of the compromised curing process due to the low temperature and relative humidity;
- SBS-coated glass yarns showed greater sensitivity to various environmental exposures, with a reduction in tensile strength of about 25% when immersed in alkaline solution at 40 °C and approximately 8% when immersed in saline solution or subjected to freeze–thaw cycles;
- Macroscope observations of the yarns' cross-section showed that the immersion of AR glass yarns in saline and alkaline solutions at 40 °C causes the formation of voids and swelling at the center of the yarn, which are probably responsible for the reduction in mechanical properties;
- FRCM composite specimens showed a greater resistance to environmental exposures, compared to the glass yarns, thanks to the presence of the inorganic matrix, which, although of limited thickness (about 6 mm per side), was able to guarantee an adequate protection of the internal reinforcement;

- FRCM coupons always failed due to tensile breakage of the internal glass yarns, regardless of the type of environmental conditioning.

Further studies are necessary in order to develop a set of standardized tests to evaluate the long-term behavior of FRCM systems subjected to detrimental environmental actions, which, in addition to the type of matrix and fibrous reinforcement used as constituents, also take into account the support on which the system will be applied.

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