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Review

Durability of Fabric-Reinforced Cementitious Matrix (FRCM) Composites: A Review

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Abstract: Strengthening and rehabilitation of masonry and concrete structures by means of externally bonded fabric-reinforced cementitious matrix (FRCM) (also referred to as textile reinforced mortar (TRM)) composites was proposed as an alternative to the use of fiber-reinforced polymer (FRP) composites due to their good mechanical properties and compatibility with the substrate. However, quite limited studies are available in the literature regarding the long-term behavior of FRCM composites with respect to different environmental conditions. This paper presents a thorough review of the available researches on the long-term behavior of FRCM composites. Namely, (i) test set-ups employed to study the FRCM durability, (ii) conditioning environments adopted, and (iii) long-term performance of FRCM and its component materials (mortar and fiber textile) subjected to direct tensile and bond tests, are presented and discussed. Based on the available results, some open issues that need to be covered in future studies are pointed out.

Keywords: fabric-reinforced cementitious matrix (FRCM); textile reinforced concrete (TRC); textile reinforced mortar (TRM); inorganic-matrix; open-mesh textile; long-term behavior

1. Introduction

The use of fiber-reinforced polymer (FRP) composites to strengthen and retrofit existing masonry and reinforced concrete (RC) structures was proven to be an effective solution due to the FRP good mechanical properties, resistance to corrosion, and ease of application [1–4]. However, some concerns raised regarding the poor sustainability and compatibility with the substrate of organic resins used in FRPs [5–8]. In addition, organic resins produce toxic fumes when exposed to fire and lose their mechanical properties at temperature close to their glass transition temperature, which for resins commonly adopted in FRPs ranges between 45 °C and 82 °C [9–11].

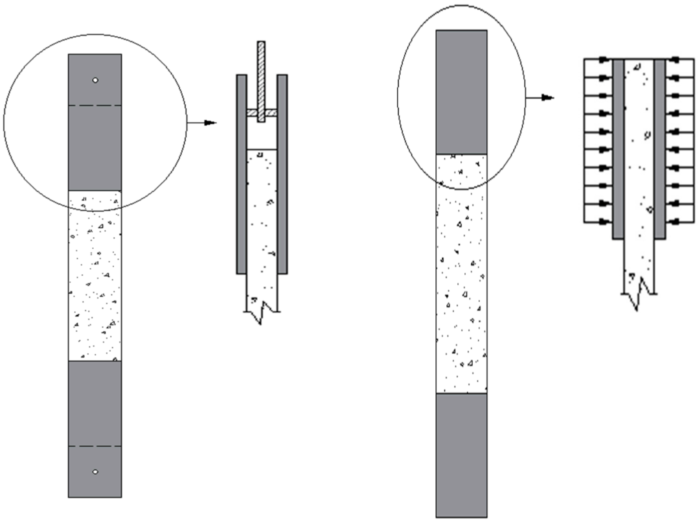
Fabric-reinforced cementitious matrix (FRCM) composites, which are also referred to as textile reinforced mortar (TRM) composites, were proposed as an alternative to FRP composites to overcome the drawbacks associated with the organic binders. FRCM are comprised of high strength fiber open-mesh textiles embedded within inorganic matrices. The textile can be made with different types of fiber, such as carbon, alkali-resistant (AR) glass, polyparaphenylene benzobisoxazole (PBO), or basalt. When steel fibers organized in steel cords are adopted, the inorganic-matrix composite is referred to as steel reinforced grout (SRG) [12]. The textile layout (dimension and shape of single yarns, yarn spacing, and direction) can be varied to modify the textile-matrix stress-transfer mechanism and customize the composite behavior [10,13]. In addition, textile yarns can be coated with organic resin to improve their bond with the matrix, FRCM ease of handling and installing, and to protect the fiber filaments. Various types of inorganic matrix can be found in the literature, such as cement-based and lime-based mortars and geopolymers, sometimes modified with fly ash, polymers, silica fume, and short fibers to increase the adhesion to the textile and substrate [7,14–18]. FRCM composites are generally employed as externally bonded reinforcement (EBR) for masonry [19] and RC members [20]. Inorganic-matrix composites comprising high-strength fiber textiles embedded within high-performance cement-based matrices were also used to construct high-strength panels often employed for new structural elements. These types of composite, referred to as textile reinforced concrete (TRC), have peculiar properties that make them generally different from FRCM composites [21,22].

Although an increasing number of experimental and analytical studies are available regarding the mechanical behavior of FRCM and TRC composites, limited work has been done to investigate their durability. Since they are externally bonded, FRCM can be exposed to various environmental conditionings, such as wet–dry (WD) and freeze–thaw (FT) cycles, high-alkalinity environments, and salt attack, which may affect their performance. The same holds for TRC composites when high-strength panels are used for outdoor applications. In this study, the available literature is reviewed to gain an insight on the state of research regarding mainly the long-term behavior of FRCM composites. In particular, (i) testing methods adopted to study the FRCM long-term behavior; (ii) accelerated ageing and conditioning environments considered to simulate the outdoor environments; and (iii) possible degradation of FRCM components (matrix and textile), FRCM coupons, and FRCM-substrate interface are analyzed and discussed. Based on this discussion, aspects that need to be further investigated are pointed out. When available, results of TRC composites are also analyzed to discuss their long-term behavior with respect to that of FRCM composites.

2. Test Methods

Recently, US acceptance criteria AC 434 (2018) [23] and Italian Initial Type Testing procedures CSLLPP (2019) [24] proposed standard tests to evaluate the durability of FRCM composites. However, the available research does not comply with these recent procedures. In fact, different methods were adopted to investigate the FRCM long-term behavior. The changes in the mechanical properties of FRCM and TRC exposed to a control environment, approximately 23 °C and 60% relative humidity (RH), with respect to those of corresponding composites aged in different conditions (discussed in Section 3) were studied adopting various test procedures, such as uniaxial tensile, three-point bending, pull-out, and direct-shear tests [21,25–28]. Among them, uniaxial tensile tests were often used in the literature to evaluate the long-term behavior of the matrix, bare (non-impregnated) textile, and composite coupon. Two main tensile test set-ups, which differ for the specimen gripping method, were proposed for the mechanical characterization of FRCM coupons. (i) In the clevis-grip test [23] (Figure 1a), metal plates are bonded to the end of the specimens and then connected to the testing machine through a clevis joint. In general, FRCM coupons subjected to clevis-grip tests fail due to cracking of the matrix and subsequent debonding of the fibers at the matrix–fiber interface. The slope of the cracked phase of the axial stress-axial strain curve obtained is referred to as the tensile modulus of elasticity of the cracked composite and is employed in designing the strengthening intervention using the tested FRCM composite [23]. (ii) In the clamping-grip test [24] (Figure 1b), the ends of the FRCM coupon are clamped applying sufficient pressure to avoid slippage of the fiber within the matrix [29]. Therefore, after cracking of the matrix, the axial stress is sustained mainly by the textile and the specimen fails due to subsequent rupture of the fiber filaments [28,29]. These two set-ups generally provide completely different results that cannot be easily compared. However, provided that the stress-transfer mechanism between matrix and fibers is properly investigated, the axial stress-axial strain curves obtained by clevis- and clamping-grip tests can be compared, deriving also information on the matrix crack spacing and opening [30].

In addition to the uniaxial tensile test, other test methods were adopted to investigate the durability of the FRCM coupons such as three- and four-point bending tests [21,28,31]. However, these tests do not provide direct information about the effect of conditioning on the matrix–fiber bond behavior since several parameters, such as the matrix tensile and compressive strength, affect the specimen behavior. Therefore, they were mainly used to evaluate the durability of mortar (without textile) [32–35] or they were coupled with uniaxial tensile and pull-out tests to gain further information combining the results obtained [21,28].



(a) (b)

Figure 1. Sketch of (**a**) clevis-grip and (**b**) clamping-grip uniaxial tensile test set-ups.

Regarding pull-out tests, different methods and procedures were proposed depending on the purpose of each study. For instance, Butler et al. [27] and Yin et al. [21] used two different pull-out set-ups to investigate the bond between matrix and fiber. The bond behavior of FRCM composites was also studied using single- and double-lap direct-shear tests, which allow for the study of the interaction between the composite and substrate [33,36].

3. Conditioning Environments

The best way to evaluate the long-term behavior of materials is to expose them to the actual environment. However, this procedure requires several years and would hinder the use of the material until its conclusion. In addition, the differences in the weathering conditions from one place to another and the variability of the exposures make this procedure difficult to be standardized. Indeed, non-repeatability of the data and excessive duration of actual environmental exposures led to the development of accelerated laboratory tests. Accelerated ageing was adopted in an attempt to mimic actual environments and to predict the long-term behavior of the material [37].

Currently, the US Acceptance Criteria AC 434 (2018) [23] and Italian Initial Type Testing CSLLPP (2019) [24] are the only guidelines available regarding test methods for FRCM composites. These guidelines recommend test methods to evaluate the durability of the FRCM including freeze–thaw cycles, ageing in high-moisture condition (hygrothermal environment), concentrated solutions (chloride and sulfate solutions and alkaline environments), and even exposition to fuel (not covered in this paper). Since these guidelines are quite recent, different test methods were adopted in the past by some researchers [14,22,26,36,38] and the results obtained could not be easily compared due to the differences in ageing temperature, number of cycles, and solution type. In this section, the results found in the literature are discusses and critically compared in an attempt to gain general indications on the long-term performance of FRCM and TRM composites.

3.1. Freeze–Thaw Cycles

Four methods were employed in the literature to evaluate the durability of FRCM composites subjected to freeze–thaw cycles. All the methods recommended performing thawing in water or in a humid environment to increase the degree of saturation of the materials, which can play a fundamental role in the durability of the material. In general, if the material saturation is lower than a certain threshold, the material is considered resistant to frost, i.e., dry materials should not be affected by frost [22].

ASTM C666 [39] recommended a low temperature range of (4 to −18 °C) with a short cycle length of 2–5 h. EN 12467 [38] adopted freezing at −20 °C for 1–2 h and thawing at 20 °C for 1–2 h. Pekmezci et al. [14] performed 6 h of freezing at −25 °C followed by 2 h of thawing in water at 20 °C. Finally, AC 434 (2018) [23,28] and CSLLPP (2019) [24] utilized a wide temperature range and a long cycle period (4 h at −18 °C and 12 h at approximately 38 °C).

The combination of cycle duration and number of cycles affects the material response. Available studies reported that high number of cycles (more than 100 cycles) is required to develop small deteriorations in TRC composites [22,26]. Accordingly, the methods proposed by ASTM C666 [39] and EN 12467 [38], which adopt short cycle lengths allowing for performing a high number of cycles within a short time frame, can be suitable candidates to evaluate the long-term behavior of FRCM. However, it is important to mention that the main purpose of these methods is to determine the resistance of the material to the repeated cycles of freezing and thawing. They can be used to compare between different FRCM composites, but they are not intended to provide a quantitative measure of the material service life [22,39].

3.2. Hygrothermal Environment

The simplest and most utilized method to investigate the durability of FRCM composites is accelerated ageing in water, which consists in the immersion of the specimens in hot water for a certain period. However, AC 434 (2018) [23] and Italian Initial Type Testing CSLLPP (2019) [24] recommend ageing in 100% RH at approximately 38 °C for 1000 and 3000 h. Donnini et al. [33] considered the recommendations provided by ASTM D7705 [40] to evaluate the resistance of FRP bars exposed to alkaline environments and immersed the FRCM in water heated at 60 °C. EN 12467 [38], was also used to investigate the effect of moisture on inorganic-matrix composites. EN 12467 requires water immersion at 60 °C for 56 days to evaluate the durability of fiber–cement flat sheets [38]. Moreover, EN 12467 specifies heat rain (HR) tests in which the specimen is heated to 60 °C for 3 h using radiant heat and then cooled down to room temperature using water spray for 3 h. De Munck et al. [26] considered this method to study the durability of a TRC composite comprising a glass textile and a cement-based matrix. However, in order to reduce the cycle period, the heating time was reduced to 1 h and the cooling time to 30 min. In addition, the water spray was replaced by immersion in water at 15 °C. Finally, Ceroni et al. [35] investigated the effects of water immersion at various temperatures (23–40 °C) with different exposure periods (5–74 days) on the FRCM-concrete bond behavior. Although Ceroni et al. [35] found that increasing the ageing temperature from 23 to 30 °C did not significantly influence the bond behavior observed, yet this finding should not be extended to higher temperature due to the lack of studies investigating the effect of the ageing temperature on the FRCM long-term behavior.

Studies on FRP composites showed that using high temperature can increase water diffusion and increase the degradation rate [41] of GFRP reinforcing bars. These observations allowed for defining accelerated testing procedures that require ageing temperature up to 60 °C and a conditioning period of approximately 60 days [6,37,42]. Since in FRCM composites the organic fraction is usually quite limited if not absent, exposure to a relatively high temperature (close to the glass transition temperature of the resin used in FRP) does not represent an issue. Therefore, an ageing temperature of 60 °C could be considered adequate for FRCM accelerated testing. It should be noted, however, that the maximum exposure temperature specified by AC 434 (2018) [23] and CSLLPP (2019) [24] is approximately 38 °C. Short-term high-temperature tests shall be carried out according to CSLLPP (2019), and the exposure temperature shall be decided by the manufacturer [24]. The limited data available in the literature did not allow to identify a clear effect of accelerating tests in water of FRCM composites. Therefore, further and detailed investigations should be performed.

Another method employed to evaluate the effect of moisture on the durability of FRCM is the exposure to a series of wet–dry cycles. According to EN 12467 [38], 50 cycles of immersion in water at ambient temperature (more than 5 °C) for 18 h followed by drying in ventilated oven at 60 °C and 20% RH for 6 h are needed to investigate the behavior of fiber-cement flat sheets. Franzoni et al. [36] found that 8 h are enough to saturate masonry specimens with externally bonded SRG strips via capillary absorption and exposure to 60 °C in a ventilated oven is enough to dry them. However, since the purpose of the study was investigating salt crystallization within the interfaces, two days of wetting and two days of drying at 60 °C were utilized to ensure adequate salt accumulation. In another study, Franzoni et al. [43] utilized 3 days of drying. Donnini et al. [33] utilized two days of wetting and two days of drying in a ventilated oven at 60 °C. Yin et al. [21] wetted the FRCM specimens for 12 h at room temperature and dried them again at room temperature for 12 h. Other methods for performing wet–dry cycles can be found in the literature regarding FRP composites (see e.g., [44]).

It should be noted that there is no specific standard to perform wet–dry cycles on FRCM composites. Lab tests should be performed to determine the time required to fully saturate and dry the specimens for a given exposure temperature to correctly conduct these types of test.

3.3. Concentrated Solutions

Sulfate and chloride attack are one of the common weathering environments that can affect the long-term behavior of inorganic materials.

AC 434 (2018) [23] and CSLLPP (2019) [24] require uniaxial tensile tests of FRCM coupons continuously immersed in a saline solution reproducing the seawater conditions. In order to mimic the effect of marine environment (chloride attack) that generally triggers this damage, researchers immersed FRCM specimens in seawater or in aqueous solutions containing 3.5 wt. % (i.e., percentage by weight) of sodium chloride (NaCl) to reproduce a common seawater salinity [23,28,33,34]. Exposure periods of 1000–3000 h were adopted in most cases. Donnini et al. [33] subjected FRCM-brick joints to a series of wet–dry cycles in saline solution containing 3.5 wt. % of NaCl, exposing them to 60 °C to accelerate the process rate. Yin et al. [21] utilized saline solution with 5 wt. % of NaCl companied with a series of wet–dry or freeze–thaw cycles.

Standards have adopted different procedures to investigate the resistance of porous materials, such as stone and bricks, to the sulfate attack. EN 12370 [45] suggests total immersion in solution containing 14 wt. % of sodium sulfate followed by oven drying at 105 °C. Rilem MS-A.1 [46] suggests using 10 wt. % of sodium sulfate and 10 wt. % of sodium chloride These conditions were considered too aggressive by Franzoni et al. [43], which adopted a solution containing 2 wt. % of NaCl and 8 wt. % of sodium sulfate decahydrate ($Na_2SO_4{\cdot}10H_2O$) to avoid FRCM failure before the end of the cycles. During the ageing procedure, FRCM-masonry joints were laid down and immersed up to 20 mm (measured from the lower face), so that the solution was not in contact with the FRCM strip. Subsequently, they were dried in a ventilated oven at 60 °C for 3 days. This procedure was repeated to obtain six cycles [43]. The results indicated that salt accumulation on the FRCM matrix was comparable to that found in old masonry buildings subjected to rising damp and marine aerosol spray for centuries. Indeed, in addition to the chloride and sulfate attack, durability of FRCM used to strengthen masonry structures may be also influenced by salt carried by rising damp. Salt accumulation and crystallization within the matrix-fabric and matrix-substrate interfaces can significantly affect the bond at these interfaces.

FRCM durability can be also influenced by alkaline environments, which can have a significant effect on glass fibers embedded within the inorganic matrix [41]. The effect of exposure to alkaline environments was investigated by immersing FRCM coupons in alkaline solutions made of various components for a period ranging between 1000 and 3000 h. Arboleda et al. [28] used a solution with pH > 12 containing calcium hydroxide ($Ca(OH_2)$), sodium hydroxide (NaOH), and potassium hydroxide (KOH). Nobili [34] utilized a solution with pH = 10 made with sodium bicarbonate. Instead of immersing FRCM specimens in alkaline solutions, Butler et al. [47] used three types of mortars with different level of alkalinity to evaluate their influence on the embedded glass fabric textile. The studies that investigated the durability of FRCM in alkaline environments clearly showed that the results depend on the alkalinity level, exposure temperature, and exposure period. Therefore, a shared standard procedure including also wet–dry cycles is needed to allow the comparison of the results obtained.

4. Durability of Composite

The durability of FRCM composites depends on the long-term behavior of their components (matrix and fiber textile) and of the interfaces between them. The durability of each component and of the matrix–fiber and composite–substrate interfaces is discussed in the following sections based on the studies available in the literature. Results are presented in term of retained (or residual) strength ratio, which is defined as the ratio σ_f/σ_{fu} between the strength σ_f of the conditioned specimens (i.e., exposed to the conditioning environment) and the strength σ_{fu} of the unconditioned specimens.

4.1. Durability of Composite Matrix

The inorganic matrix employed in FRCM composites is generally cement-based or lime-based, although other types can be found in the literature (see e.g., [14,19–21]). This section focuses on the durability of cement-based and lime-based mortars. In the figures presented in this section, the blue color indicates cement-based mortars, whereas the orange color indicates lime-based mortars. Details of the tests included in the figures below are provided in Table A1.

Exposing FRCM matrices to freeze–thaw cycles, alkaline and sulfate attack may influence its durability. For example, the water present within the matrix voids may freeze when exposed to low temperatures, increasing its volume by 9% [22]. Consequently, it may induce damage and cracks if the internal stresses exceed the matrix tensile strength. However, researches available regarding freeze–thaw of FRCM composites did not generally report the specimen moisture content.

Figure 2 presents the effect of the freeze–thaw cycles on the retained cracking (tensile) strength of different FRCM matrices, which was determined by uniaxial tensile test on FRCM [14,28] and TRC [22,26] coupons. The details of freeze–thaw cycles utilized in each study are indicated in the legend of Figure 2. All specimens subjected to less than 100 cycles showed an improvement of the matrix cracking strength. However, a large scatter of the results was observed [22]. Moreover, Colombo et al. [19] reported a continuous increase in the matrix tensile strength from 50 to 100 cycles, whereas De Munck et al. [26] observed a reduction for 100 cycles. The difference in the obtained results is mainly attributed to the different performance of the adopted matrices. Colombo et al. [22] considered a high-strength cementitious matrix (average cubic compressive strength and flexural strength equal to 97.5 MPa and 13.6 MPa, respectively [22]), whereas De Munck et al. [26] used a cement-based matrix with average cubic compressive strength and flexural strength of 29.6 MPa and 5.0 MPa, respectively [26]. Studies reported that concrete with a high strength is less susceptible to freeze–thaw cycles due to its low permeability [48,49], which can explain the better performance of the matrix with the highest compressive and tensile strength. In addition, the range of temperature and the period of the freeze–thaw cycles adopted by Colombo et al. [22] were shorter and smaller, respectively, than those adopted by De Munck et al. [26]. However, after 100 cycles, Figure 2 shows that the retained matrix cracking strength decreased, which was attributed to the occurrence of microcracks [22,26].

Yin et al. [21] investigated the combined effects of freeze–thaw cycles (−18 °C to 5 °C with 3 h cycle length) and saline environment (5 wt. % NaCl) on the cracking strength of TRC composites using four-point bending test. The obtained results are not shown in Figure 2, where the effect of only freeze–thaw cycles is considered. Yin et al. [21] reported a retained cracking strength after exposing to 50, 70, and 90 cycles equal to 0.98, 0.91, and 0.86, respectively. Similar to the result shown in Figure 2, freeze–thaw cycles did not have a significant effect for small number of cycles. However, the degradation gradually increased with increasing the number of cycles. The degradation developed with 90 cycles was slightly higher than the one reported by De Munck et al. [26] with a similar number of cycles (100 cycles). This result can be attributed to: (i) presence of the sodium chloride that may have increased the degradation process rate and (ii) test method employed (four-point bending test vs. uniaxial tensile test).

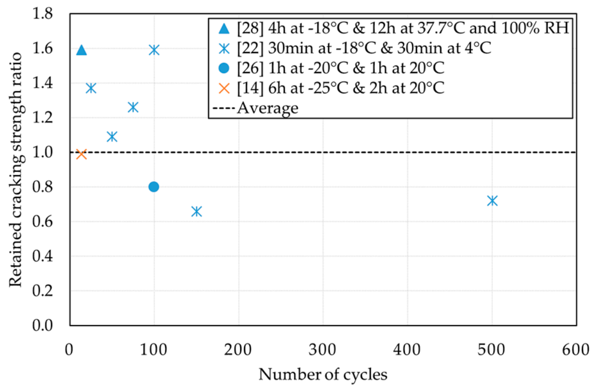


Figure 2. Effect of freeze–thaw cycles on the matrix tensile strength (blue marker = cement-based matrix, orange marker = lime-based matrix).

Chlorides and sulfates can interact with some components of the matrix such as calcium hydroxide ($Ca(OH)_2$) and aluminum oxide (Al_2O_3) leading to a reduction of the matrix durability [28]. Figure 3a presents the effect of continuous immersion in a saline solution (seawater or 3.5 wt. % of NaCl) on the retained strength of the FRCM matrices studied. Nobili et al. [34] and Donnini et al. [33] utilized three-point bending tests of lime-based mortars specimens according to EN 1015 [32]. Arboleda [28] studied the cracking strength of cement-based FRCM coupons using uniaxial tensile tests. The results showed that although Nobili et al. [34] utilized a lower ageing temperature than Donnini et al. [33], the degradation of the mortar was higher (up to 60%, see Figure 3). This controversial result might be attributed to the difference in the porosity and mechanical properties of the mortar investigated by the two researchers. A mortar with high porosity such as natural lime-based mortar could be more influenced by saline environments than hydraulic lime or cementitious mortars [33]. Further studies are required to relate the physical nature of the FRCM matrices with their durability in various environmental conditions. Arboleda [28] reported a remarkable increase in the cracking strength of the cement-based matrix. This result was not significantly affected even when the exposure period was extended to 3000 h.

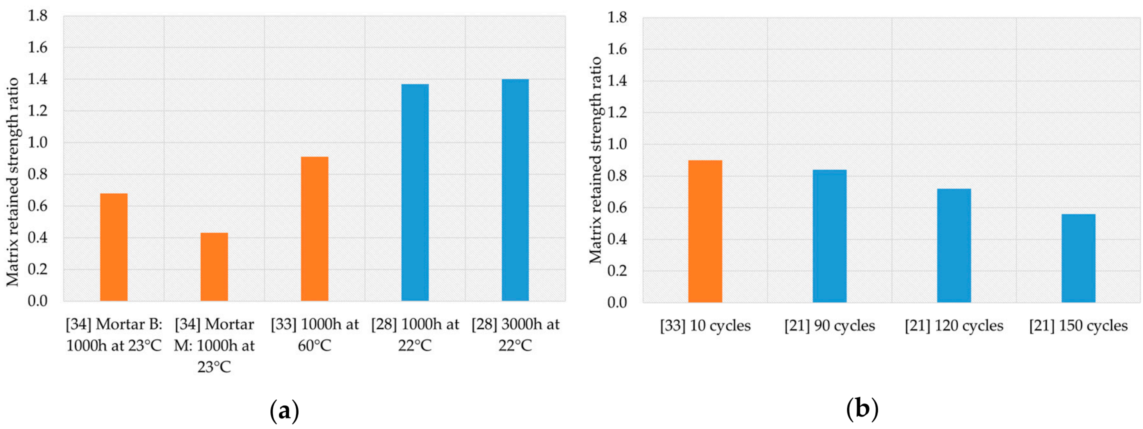


Figure 3. Effect of saline environments on the matrix tensile strength: (**a**) continuous immersion and (**b**) wet–dry cycles (blue bin = cement-based matrix and orange bin = lime-based matrix).

Figure 3b shows the effect of wet–dry cycles in saline solutions on the retained strength of the matrices. Regarding the cementitious matrix, Yin et al. [21] performed 12 h of wetting in a saline solution (5 wt. % of NaCl) followed by 12 h of drying at room temperature on TRC coupons with cement-based matrix, which were subsequently tested using a four-point bending test set-up. The results showed that the matrix flexural strength progressively decreased with increasing the number of cycles. Regarding the lime mortar, Donnini [33] reported similar residual flexural strengths for specimens subjected to continuous immersion and wet–dry cycles, showing a percentage reduction of approximately 10%.

Alkali-aggregate chemical reaction, which is the reaction between the potassium and sodium oxide (K_2O and Na_2O) of the cement and the reactive silica (SiO_2) present in some types of aggregate, may affect glass micro-fibers (if present) dispersed within the mortar [28]. The effect of matrix immersion in alkaline solution on the flexural [34] and uniaxial tensile strength [28] is presented in Figure 4. It can be noticed that the retained flexural strength of the lime-based mortar decreased to approximately 55%, whereas the retained tensile strength of the cement-based matrix was not significantly affected (a slight increase, lower than 10%, was observed).

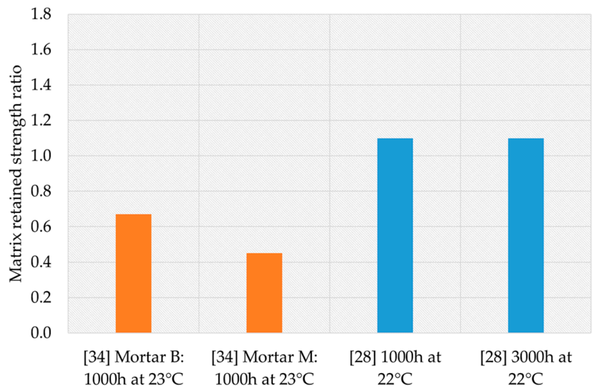


Figure 4. Effect of the alkaline environment on the matrices (blue bin = cement-based matrix and orange bin = lime-based matrix).

Finally, studies on the effect of immersion of the matrix in deionized water, which is a conditioning typically employed for GFRP reinforcing bars [41], showed that this type of exposure can improve the performance of the cement-based mortar if it is followed by an appropriate drying period due to the resumption of the hydration process [33,35].

It should be noted that the mechanical properties of the matrix affect the FRCM behavior when it is still not cracked. The results gathered show that the exposure of the FRCM to some harsh environmental conditions may lead to the formation of microcracks, which in turn affect the cracking strength and stiffness of the composite. In addition, matrix microcracks can promote the penetration of water and external agents into the composite.

4.2. Durability of the Fibers

Textiles used in FRCM can be made of carbon, AR-glass, PBO, aramid fibers, and steel (in the case of SRG). This section is dedicated to the durability of textile. Details of the tests included in the figures below are provided in Table A1. Although carbon fiber showed good durability [50,51], it has a high cost in comparison with other fibers such as AR-glass or basalt. Basalt fiber is often compared to E-glass and AR-glass due to the similarities in the chemical structure [51,52]. Limited results on the durability of PBO fibers employed in the civil engineering field can be found in the literature. AR-glass fiber is commonly used in civil engineering applications due to its availability and low cost. For these reasons, more results are available regarding the durability of AR-glass fiber than of other types of fiber. In the figures presented in this section, the blue color indicates tests at room temperature, whereas the orange color indicates tests at temperature equal to 60 °C.

To the authors' best knowledge, specific results of the freeze–thaw cycles long-term behavior of fiber textiles employed in FRCM composites are not available in the literature. Similarly, no results were found regarding the effect of sulfate exposures.

The retained tensile strength of AR-glass fiber textiles subjected to various combined immersion in deionized water and temperature (hygrothermal environments) observed by different research groups is shown in Figure 5. Portal et al. [51] reported no difference in the tensile capacity after 10 days of conditioning at 20 °C. However, Hristozov et al. [53] reported a 15% reduction after 21 days of ageing. When the ageing temperature was raised to 60 °C, both Portal et al. [51] and Hristozov et al. [53] noticed a clear reduction in the strength, even larger than 60%. Nonetheless, Donnini [33] did not see a significant change of the textile tensile capacity at the same temperature (i.e., 60 °C). This conflict in the obtained results may be attributed to the difference in the coating materials of the fibers used by each research group. The fiber used by Portal et al. [51] and Hristozov et al. [53] was coated by 20% of styrene–butadiene resin (SBR) and vinylester, respectively, whereas the fiber used by Donnini [33] was coated by polyvinyl alcohol (PVA). In addition to the effect of coating, the difference in the textile layout and number of fiber filaments in each yarn may also have influenced the results.

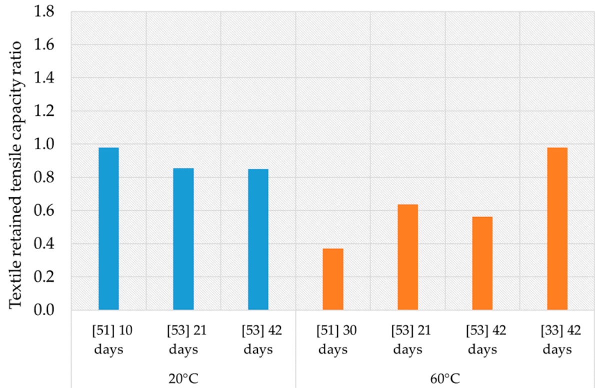


Figure 5. Retained tensile capacity ratio of AR-glass exposed to hygrothermal environments (blue bin = room temperature and orange bin = temperature equal to 60 °C).

Figure 6 presents the retained tensile capacity ratio of AR-glass fibers immersed in seawater (3.5 wt. % of NaCl) for 1000 h (~42 days). At the room temperature, (ranging between 20 °C and 23 °C), Nobili et al. [34] and Hristozov et al. [53] reported a small degradation of the tensile capacity. However, the degradation increased up to 40% when the conditioning temperature was raised to 60 °C.

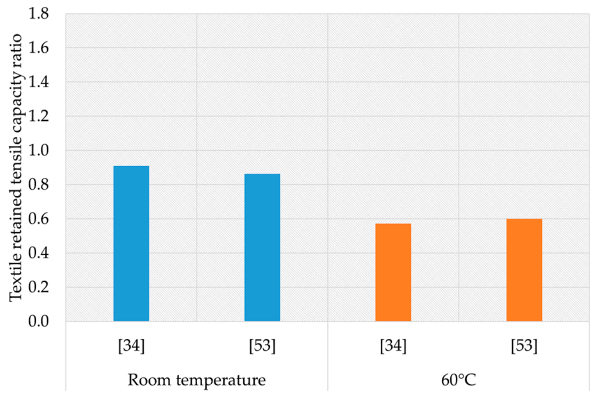


Figure 6. Retained tensile capacity ratio of AR-glass immersed in seawater (blue bin = room temperature and orange bin = temperature equal to 60 °C).

The effect of the alkaline solution on the tensile capacity of AR-glass textiles is presented in Figure 7. At room temperature, different levels of degradation were reported (minimum textile retained tensile capacity ratio lower than 40%) depending on the alkalinity of the solution, exposure period, and fiber coating materials [34,51,53]. Besides, the degradation level increased with increasing the alkalinity and the exposure period. When the conditioning temperature was raised to 60 °C, the degradation level was increased especially in the case of Portal et al. [51], where the material completely failed (dissolved) before performing the tensile test (these results are not shown in Figure 7 for this reason). Butler et al. [27,47] studied the durability of the AR-glass embedded in three different types of cementitious matrix with different level of alkalinity. Coupons were then not immerged in an alkaline solution as in the previous studies (for this reason, these results are not included in Figure 7). Results indicated continuous reduction in the tensile strength of the coupons with increasing the ageing period. Furthermore, the FRCM coupons made with high alkalinity matrix developed a brittle failure, as explained in Section 4.3.

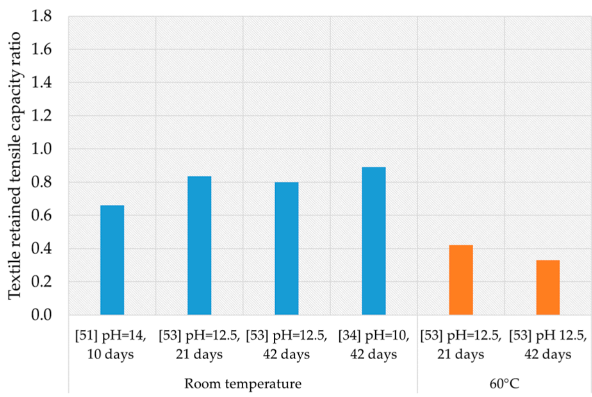


Figure 7. Retained tensile capacity ratio of AR-glass exposed to alkaline environments (blue bin = room temperature and orange bin = temperature equal to 60 °C).

It should be noted that the accelerated ageing environments considered to study the durability of glass fibers represent extremely harsh conditions that are never present in real applications. Therefore, detailed investigations on the effect of these harsh conditionings on the fiber coatings, which protect the fiber from external attacks, should be carried out to correctly understand the results obtained.

Regarding the durability of steel cords employed in SRG composites, unlike the numerous studies on the corrosion of galvanized steel rebar in concrete [54–56], there is limited research addressing the corrosion of steel cords embedded within inorganic-matrix [43]. The performance of steel fibers can be highly dependent on the environment and duration of the exposure. For instance, long exposure periods to an environment containing chloride ions can cause strong steel corrosion. Franzoni et al. [36] investigated the performance of steel SRG-masonry joints under wet–dry cycles exposed to a saline solution containing 8% weight ratio of $Na_2SO_4 \cdot 10H_2O$. In this study, steel fiber did not show significant changes. However, in another study by the same authors [43], steel fibers were corroded when 2 wt. % of NaCl was added to the same solution and the number of cycles was increased from 4 to 6.

The limited number of results available in the literature indicate that further studies are needed to gain a deeper understanding of the long-term behavior of steel cords under various environments.

4.3. Durability of the Matrix–Fiber Interface Capacity

The effectiveness of externally bonded reinforcements depends on the stress-transfer between its components and between the reinforcements and the substrate. When a single layer of fiber is employed, externally bonded FRCM composites have two main interfaces, i.e., the matrix–fiber interface and the matrix-substrate or composite–substrate interface [57]. Although the long-term bond behavior of the various interfaces of an inorganic-matrix composite should be studied with bond tests, some studies available in the literature derived information on the effect of various environmental factors on the matrix–fiber interface from uniaxial tensile tests of composite coupons [22,28,34]. In particular, the degradation of the matrix–fiber interface was assessed by direct observation using scanning electron microscopy (SEM) [26] or evaluated by studying the differences in the load response of control and conditioned specimens that can be explained by the matrix–fiber bond behavior.

In this section, the effect of various environments on the matrix–fiber bond behavior, either directly studied with bond tests or derived by uniaxial tensile test results, is discussed, whereas the durability of the composite–substrate interface is discussed in Section 4.4. Details of the tests included in the figures below are provided in Table A1.

Figure 8 presents the effect of freeze–thaw cycles on the ultimate strength of FRCM coupons comprising different types of textile. The range of cycles adopted by each research group was discussed in Section 3.1. Colombo et al. [22] investigated the effect of freeze–thaw cycles on uncracked specimens and on specimens cracked by applying a uniaxial tensile load 20% higher than the cracking load. It can be noticed that the retained ultimate strength of the uncracked specimens progressively decreases with increasing the number of cycles until it reaches 0.8 at the end of 500 cycles. However, cracked specimens showed fluctuating results and a clear trend could not be identified. Arboleda [28] reported a slight increment (approximately 10%) in the ultimate strength of PBO-FRCM coupons, whereas the ultimate strength of carbon-FRCM coupons did not change significantly. Pekmezci et al. [14] reported a slight reduction (approximately 16%) in the case of a biaxial fabric. De Munck et al. [26] reported a small reduction (approximately 16%) in the ultimate strength of TRC coupons with AR-glass fibers after 100 cycles. Anyhow, freeze–thaw cycles had a slight effect on the coupon ultimate strength, being the variation always lower than 20%.

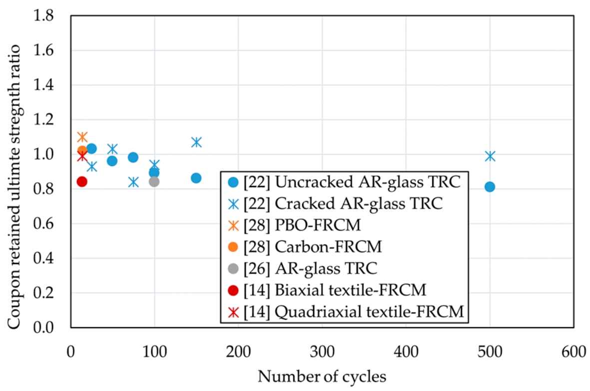


Figure 8. Effect of freeze–thaw cycles on the retained ultimate strength ratio of composite coupons.

Yin et al. [21] utilized a pull-out test to investigate the combined effect of freeze–thaw cycles (−18 °C to 5 °C with 3 h cycle duration) and saline environments (5 wt. % of NaCl) on the matrix–fiber bond capacity. The results obtained in [21] are not listed in Figure 8 since the authors considered the effect of saline solution and used a different test set-up. Similarly, Yin et al. [21] reported not significant effect of the ageing condition.

The effect of saline environments on the matrix–fiber bond behavior was investigated by immersing FRCM coupons in saline solutions (seawater or 3.5 wt. % of NaCl) and observing the variation of the ultimate strength obtained, which was attributed to the degradation of the matrix–fiber interface [28,34]. Figure 9 shows the retained ultimate strength ratio obtained by FRCM coupons immersed in saline solutions for different periods. Arboleda [28] reported an increase of the retained ultimate strength for FRCM including PBO and carbon fibers with cement-based matrix. This increment (larger than 40%) was attributed to the continuous hydration of the mortar, which may improve the matrix–fiber bond behavior leading to high ultimate strengths. Nobili et al. [34] observed a slight reduction (less than 20%) of the retained ultimate strength for FRCM including glass fibers and lime-based matrix.

It should be noted that a significant scatter was observed among the results, which indicate the need to perform a large number of tests to obtain reliable results.

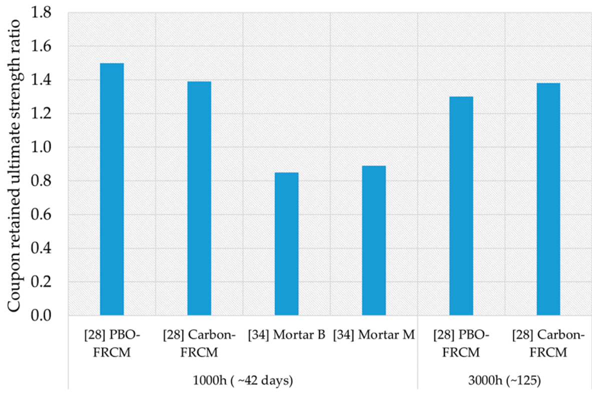


Figure 9. Effect of immersion in saline solutions on the retained ultimate strength ratio of fabric-reinforced cementitious matrix (FRCM) coupons.

Yin et al. [21] investigated the effects of wetting in a saline solution (5 wt. % of NaCl) and drying at room temperature on the bond behavior between a cementitious matrix and a hybrid glass-carbon textile, using a pull-out set-up. Since also the effect of drying was considered, these test results are not reported in Figure 9. However, no significant difference in the maximum pull-out load was observed after 90 and 120 cycles. Nevertheless, a certain degradation was observed after 150 cycles due to the crystallization of the salt that affected the matrix–fiber interface.

The effect of moisture and wet–dry cycles on the bond capacity can be controversial. For not entirely hydrated matrix, they can be beneficial due to the continuation of the hydration process [35,36]. However, it should be noted that the continuation of the hydration process can cause a densification of the matrix next to the multi-filament yarn with the penetration of hydration products within the voids among the filaments, which may lead to a reduction of the matrix–fiber bond properties [26]. More studies are needed to identify the dominant effect among these two competing factors.

For completely hydrated matrix, moisture and wet–dry cycles may not directly affect the bond behavior. However, by damaging the fibers (e.g., corrosion of steel cords or swelling of glass fibers [33,43]) and the matrix due to the expansion of water within the pores, they can lead to a decrease of the matrix–fiber bond properties [35,43].

The stress-transfer between the fiber and matrix can be also influenced by the alkalinity of the matrix, as discussed in Section 4.2. Butler et al. [27,47] utilized pull-out tests and uniaxial tensile tests to investigate the effect of the matrix alkalinity on the bond between cement-based matrices and AR-glass fibers. Specimens were aged in a humid chamber at 40 °C and 99% RH. One year of this condition was assumed to be equal to 50 years of exposure to the middle European climate. Three cementitious matrices with different level of alkalinity and hydration kinetics were employed. The low alkalinity matrix (M1) had a pH of 12.4 at the mixing time, which gradually reduced to 11.8 after 1 year. The pH of the high alkalinity matrix (M3) was 12.7. For the medium alkalinity matrix (M2), the pH value was between M1 and M3. The results of unconditioned specimens showed that the maximum pull-out force of specimens made with high alkalinity matrix (M3) was higher than the others due to the fast hydration process and homogeneous structure of calcium silicate hydrate (CSH) phase close to the fiber. However, an opposite trend was observed after ageing. Figure 10a shows the behavior of the maximum pull-out force ratio, which progressively decreased with proceeding the ageing period. The reduction was higher for specimens with matrix M2 than with matrix M1. Results of specimens with matrix M3 are not shown in Figure 10a because they failed at the formation of the first crack, without slippage of the fibers within the matrix.

The retained ultimate strength ratio of corresponding FRCM coupons subjected to uniaxial tensile test is shown in Figure 10b. The behavior observed is consistent with that of pull-out tests, with the exception that the ultimate strength of the coupons made with matrix M1 increased after 30 days of ageing due to the continuation of the matrix hydration process.

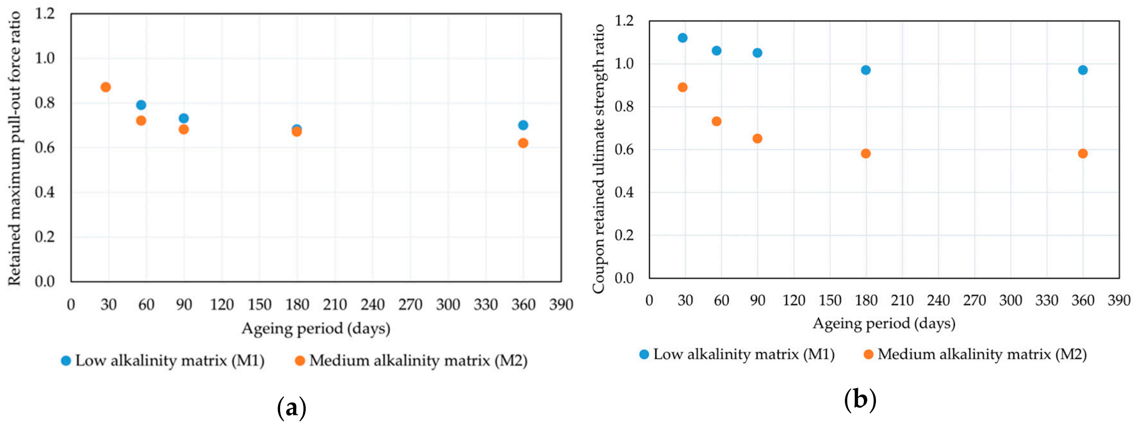


Figure 10. Effect of the matrix alkalinity on the (**a**) maximum pull-out force and (**b**) ultimate tensile strength of the FRCM coupons tested by Butler et al. [27,47].

4.4. Durability of the Composite–Substrate Bond Capacity

Being employed as externally bonded reinforcements, FRCM can debond at the composite–substrate interface. However, limited number of studies dedicated to investigating the durability of the composite–substrate bond are available in the literature. They are summarized in this section and details of the tests included in the figures below are provided in Table A1.

Sulfate attack can reduce the adhesion between the composite and substrate degrading the composite–substrate interface [33,36]. Salt crystallization within the interface can also reduce the bond capacity and shift the failure from the matrix-fabric interface to the composite–substrate interface [33,43]. Figure 11 shows the effect of sulfate and chloride attack on the load-carrying capacity of FRCM-masonry joints subjected to direct-shear tests. Donnini et al. [33] exposed FRCM–masonry joints with an AR-glass textile and a lime-based matrix to 10 wet–dry cycles in saline solution of sodium chloride (3.5 wt. % of NaCl) at 60 °C. After conditioning, the specimens failed at the composite–substrate interface and the load-carrying capacity was reduced. Franzoni et al. [36] studied an SRG composite made of a lime-based matrix and steel cords externally bonded to masonry blocks. They found that four wet–dry cycles in a saline solution containing 8 wt. % of sodium sulfate decahydrate ($Na_2SO_4{\cdot}10H_2O$) followed by drying at 60 °C did not have a significant effect on the load-carrying capacity. In addition, all the specimens developed interlaminar failure characterized by fiber slippage from the internal layer of matrix, which remained bonded to the substrate. However, when 2 wt. % of sodium chloride (NaCl) was added to the same solution and the number of cycles increased to 6, the load-carrying capacity decreased.

The results analyzed showed that the reduction in the bond capacity and shifting of the failure mode to the composite–substrate interface require a high salt accumulation and crystallization within the interface, which may depend on the porosity of the matrix and on the radius of the pores. For instance, a matrix with pores radius bigger than the radius of substrate pores will allow the solution to pass through it. Consequently, the effect of sulfate and saline attack on the interface may not be as significant as its effect on the fibers and matrix [36]. However, this hypothesis needs to be confirmed by using matrices with different porosity and pore sizes.

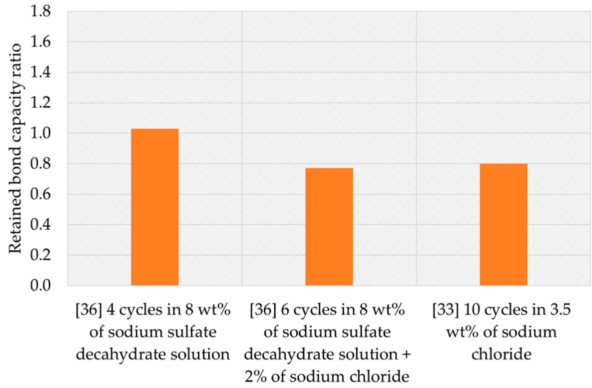


Figure 11. Effect of sulfate and chloride attack on the load-carrying capacity of steel reinforced grout (SRG)–masonry [36] and FRCM–masonry [33] joints.

5. Conclusions

Inorganic-matrix composites have been increasingly used for strengthening and repairing existing masonry and concrete structures. However, limited studies are available regarding their long-term behavior. This paper presented a review of the available state of research on the durability of FRCM, SRG, and TRC composites. Various testing procedures and ageing conditions were used to investigate the durability of inorganic-matrix composites. Results indicated that their durability strongly depends on the matrix and fiber employed. Furthermore, the literature review showed that the following aspects still need to be investigated:

1. Various conditioning environments were utilized in the literature to simulate the effect of outdoor exposure. Some of them were proposed by researchers and some others taken from standards for different materials. Therefore, the results could not be easily compared. In order to standardize specific conditioning environments for durability tests of FRCM, a thorough comparison among these conditioning environments is needed.
2. Studies reported contradictory results regarding the durability of FRCM lime-based matrices exposed to saline environments. The difference among the results was attributed to the variation in the porosity and pore radius. Further studies are required to correlate the physical properties of the matrix with its durability against various environments.
3. Limited studies are available regarding the corrosion of steel cords embedded within inorganic matrices. Studies of the performance of steel cords in corrosive environments are required to gain information on the durability of SRG composites.
4. The effect of wet–dry cycles on the durability of inorganic-matrix composites including glass fiber textiles can be influenced by the contrasting effects of hydration and densification. Therefore, more studies are needed to better understand the dominant effect.
5. The durability of the bond between matrix and fiber and composite and substrate was not thoroughly investigated yet. Studies on the effect of freeze–thaw and wet–dry cycles, alkaline environments, sulfate attack, and other exposures are needed to gain a clear and reliable understanding of the long-term behavior of externally bonded inorganic-matrix composites.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Effects of the ageing environments on the matrix, fabric, coupon, and composite–substrate retained capacity.

Reference	Materials	Exposure Conditions	Tests	Average Retained Matrix Cracking Strength	Average Retained Tensile Strength of Fiber	Average Retained Ultimate Tensile Strength of Coupons
[28]	• PBO–FRCM with cement-based matrix • Carbon–FRCM with cement-based matrix.	1. Hygrothermal: 100% RH at 37.7 °C for 1000 and 3000 h 2. FT: 20 cycles with 4 h at −18 °C and 12 h at 37.7 °C and 100% RH 3. Saline: (seawater) 4. Immersion in alkaline solution [$Ca(OH)_2$, KOH, NaOH] with pH > 12	• Visual inspection of the coupon surfaces with 5× magnification lenses • Uniaxial tensile test on FRCM coupons	• Hygrothermal: at 1000 h and 3000 h, retained strength was 1.56 and 1.34, respectively. • FT: retained strength was 1.59 • Saline: at 1000 h and 3000 h, the retained strength was 1.37 and 1.4, respectively. • Alkaline: retained strength was 1.10 for both 1000 h and 3000 h	• NA	• FT: retained ultimate tensile strength of the FRCM made of PBO fiber was 1.10 • Saline: retained ultimate tensile strength of the PBO FRCM after 1000 h of exposure was 1.50. However, this value became 1.30 when the exposure period increased to 3000 h • The retained ultimate tensile strength of the carbon-FRCM was increased by 13% after hygrothermal and alkaline conditionings.
[22]	• TRC with AR-glass fiber textile and cement-based matrix	• FT (ASTM C666 2015) (25–500 cycle): 30 min at +4, 30 min at −18 with cooling/heating rate of 11 °C/h	• Uniaxial tensile test on the TRC coupons	• FT: The retained strength at 25, 50, 75, 100, 150, and 500 cycles was 1.37, 1.09, 1.26, 1.59, 0.66, and 0.72, respectively	• NA	• Retained ultimate tensile strength of the coupons exposed to 25, 50, 75, 100, 150, and 500 cycle was 1.03, 0.96, 0.98, 0.89, 0.86, and 0.81, respectively.
[21]	• TRC coupons made of cement-based matrix and hybrid fabric (warp carbon bundles and weft E-glass bundles) impregnated with epoxy resin.	• Combined effect of FT (−18 °C to 5 °C with 3 h cycle length) and saline environment (5 wt. % NaCl)	• Four-point bending and pull-out tests	• Retained first cracking strength after exposing to 50, 70, and 90 cycles was equal 0.98, 0.91, and 0.86, respectively	• NA	• Retained ultimate pull-out strength after exposing to 50, 70, and 90 cycles was 1.00, 0.98 and 0.99, respectively

Table A1. *Cont.*

Reference	Materials	Exposure Conditions	Tests	Average Retained Matrix Cracking Strength	Average Retained Tensile Strength of Fiber	Average Retained Ultimate Tensile Strength of Coupons
[35]	• Fiber reinforced cement-based mortar with 4% polymeric content • PBO–FRCM with cement-based matrix	1. WI at the 23 °C for 5–28 days (this condition used to evaluate flexural and compressive performance of the mortar only) 2. WI at 23 °C for 5, 9, 40, and 74 days 3. WI at 30 °C for 9 and 74 days 4. WI at 40 °C for 4 days 5. Hygrothermal at 30 °C for 9 days	• Matrix bending and compressive tests • Three-point bending test on small concrete beams strengthened with FRCM. Tests were done in an environment-controlled room	• 1st condition: 0.67 (flexural) and 0.74 (compressive) for 28 days	• NA	• 2nd condition: 0.57, 0.77, 0.96, and 1.12 respectively. • 3rd condition: 0.6 and 1.01 • 4th condition: 0.73 • 5th condition: 0.72
[26]	• TRC with AR-glass fiber and cement-based matrix	• FT: 100 cycle with temperature range of −20 to 20 °C (EN 12467 2004) • 50 cycles heat-rain (HR): heating to 60 °C within 15 min and maintained for 45 min, then cooled with water immersion at 15 °C • Combined effect of the two previous conditions with 100 FT cycles followed by 50 HT cycles	• Uniaxial tensile test on TRM coupons • Measure of crack width and crack spacing via DIC	• Average retained cracking strength for the specimens exposed to FT was 0.81 • Average retained cracking strength for specimens exposed to HR was 0.7 • Average retained cracking strength for the specimens exposed to combined effect of FT and HR was 0.6	• NA	• Retained ultimate tensile strength of specimens exposed to FT was 0.84 • Retained ultimate tensile strength of specimens exposed to HR was 0.58 • Retained ultimate tensile strength of specimens exposed to combined effect of FT and HR was 0.73

Table A1. *Cont.*

Reference	Materials	Exposure Conditions	Tests	Average Retained Matrix Cracking Strength	Average Retained Tensile Strength of Fiber	Average Retained Ultimate Tensile Strength of Coupons
[33]	• FRCM with AR glass and lime-based mortar, also bonded to masonry substrate	1. WI: tap water at 60 °C for 1000 h 2. Immersion in saline solution (3.5% NaCl) at 60 °C for 1000 h 3. WD 10 cycles (960 h): 2 days immersion in saline solution (3.5% NaCl) at 60 °C and 2 days drying at 60 °C	• Flexural tests on mortar specimens • Compressive tests on mortar specimens • Uniaxial tensile test on single fiber yarn • Single-lap shear test on FRCM bonded to a masonry substrate	• WI: Small Increment in the retained flexural and compressive strength (1.03 and 1.06, respectively) • The retained flexural and compressive strength after continuous immersion in saline solution were 0.91 and 1.08, respectively. • WD cycles in saline solution: slight decrease in the flexural and compressive strength of (0.9 and 0.95, respectively)	• Saline: average retained tensile strength of the specimens exposed to continuous immersion and WD cycles in saline solutions decreased to 0.6 and 0.36, respectively. • WI: retained tensile strength was not affected (0.98)	• WI: average ultimate retained strength was 0.89 • Saline: average ultimate retained strength was 0.71 • WD: average ultimate retained strength was 0.8
[53]	• Unidirectional glass fabric impregnated in vinylester resin	1. WI in distilled water at 20, 50 and 60 °C for 500, 1000, 2000, and 3000 h. 2. Saline (3.5 wt.% of NaCl) at 20, 50, and 60 °C for 500, 1000, 2000, and 3000 h 3. Alkaline (pH = 12.5) at the same temperature and exposure periods of the previous conditions	• Uniaxial tensile test (ASTM D638 2004)	• NA	• WI: retained tensile strength at 20 °C decreased to 0.85 at 500 h and 1000 h. Retained tensile strength at 60 °C decreased to 0.64 at 500 h and to 0.56 at 1000 h. • Saline: retained tensile strength was decreased from 0.86 to 0.57 when the exposure temperature increased from 20 °C to 60 °C	• NA

Table A1. *Cont.*

Reference	Materials	Exposure Conditions	Tests	Average Retained Matrix Cracking Strength	Average Retained Tensile Strength of Fiber	Average Retained Ultimate Tensile Strength of Coupons
					• Alkaline: retained tensile strength at 20 °C decreased to 0.84 at 500 h and to 0.80 at 1000 h. Retained tensile strength at 60 °C decreased to 0.42 at 500 h and to 0.33 at 1000 h.	
[34]	• AR-glass FRCM coupon with matrix B (rich in hydrated lime and pozzolan) • AR-glass FRCM coupon with mortar M (air-hardening lime, pozzolan and marble sand)	1. Immersion in alkaline solution (sodium bicarbonate, pH = 10) for 1000 h 2. Immersion in saline solution (3.5% sodium chloride) for 1000 h	• Three-point bending tests • Uniaxial tensile test on the fiber textile • Uniaxial tensile test on FRCM coupons	• Alkaline: retained strength decreased for mortar B and M to 0.67 and 0.45, respectively. • Saline: retained strength decreased to 0.68 and 0.43 for mortar B and M, respectively.	• Alkaline: retained strength was 0.89 • Saline: retained strength was 0.91	• Alkaline: retained ultimate strength of the coupons with matrix B and M is 0.89 and 0.90, respectively • Saline: retained ultimate strength of the coupons with matrix B and M is 0.85 and 0.89, respectively.
[51]	• AR-glass fiber • Basalt fiber • Carbon fiber	1. Immersion in alkaline solution (0.8% of NaOH and 2.24% of KOH) pH = 14 for 5–30 days at 60 °C (ISO 10406-1) 2. WI in deionized water at 60 °C for 30 days 3. Immersion in the alkaline solution 1. for 10 days at 20 °C 4. WI in deionized water for 10 days at 20 °C	• Uniaxial tensile test on single yarns • Visual inspection	• NA	• WI: retained strength decreased from 0.98 to 0.39 when the temperature increased from 10 °C to 60 °C and the exposure period increased from 10 to 60 days • The retained strength of the AR-glass after exposing to alkaline environment 1. for10 days in the lab temperature was 0.66	• NA

Table A1. *Cont.*

Reference	Materials	Exposure Conditions	Tests	Average Retained Matrix Cracking Strength	Average Retained Tensile Strength of Fiber	Average Retained Ultimate Tensile Strength of Coupons
[47]	• AR-glass fiber • Three types of matrices (M1, M2, M3) with different level of alkalinity	1. Ageing period: 28-360 days 2. M1 mortar: low alkalinity reduced from pH = 12.4 at mixing to pH = 11.8 after 1 year. 3. M3 mortar: high alkalinity, pH = 12.7 4. M2 mortar: medium level of alkalinity ranging between M1 and M3	• Uniaxial tensile tests on FRCM coupons reinforced with 5 layers of textile • Pull-out tests	• NA	• Retained tensile strength of FRCM coupons with matrix M1, M2, and M3 after 360 days was 0.97, 0.62 and no retained load-carrying capacity, respectively	• Retained maximum pull-out forces for matrix M1 at period of 28, 56, 90, 180, and 360 days are 0.87, 0.72, 0.68, 0.67 and 0.62, respectively • Retained maximum pull-out forces for matrix M2 at the same periods are 0.87, 0.72, 0.68, 0.67, and 0.62, respectively
[14]	• FRCM coupons with lime-based mortar and biaxial glass fabric and • FRCM coupons with lime-based mortar and quadriaxial hybrid fabric	1. FT: 14 cycles of 2 h in water at 20 °C and 6 h at −25 °C	• Uniaxial tensile tests on mortar and FRCM coupons	• Retained tensile strength of the mortar was 0.63 • Retained cracking strength of the FRCM coupons was 0.99 after exposure	• NA	• Retained ultimate strength for coupons with biaxial glass fabric was 0.84 • Retained ultimate strength of coupons with hybrid fabric was 0.99

Table A1. *Cont.*

Reference	Materials	Exposure Conditions	Tests	Average Retained Matrix Cracking Strength	Average Retained Tensile Strength of Fiber	Average Retained Ultimate Tensile Strength of Coupons
[36,43]	• SGR composite with lime-based matrix and steel cords bonded to masonry substrate	1. WD: 4 cycles of 2 days of partially immersion in a saline solution (8 wt. % of $Na_2SO_4 \cdot 10H_2O$) and 2 days drying in ventilated oven at 60 °C 2. WD: 4 cycles of 2 days immersion in deionized water and 2 days drying in ventilated oven at 60 °C 3. WD: 6 cycles of 2 days partially immersed in saline solution (2 wt. % of NaCl and 8 wt. % of $Na_2SO_4 \cdot 10H_2O$) at 20 °C and 3 days drying with ventilated oven at 60 °C 4. WD: 6 cycles equal to the previous condition 3 except for the deionized water used for drying instead of the saline solution	• Single-lap shear tests	• NA	• NA	• 1st condition: 1.03 • 2nd condition: 0.98 • 3rd condition: 0.73 • 4th condition: 0.78

Note: FT: freeze–thaw; HR: heat rain; WD: wet–dry; WI: water immersion.

References

1. Abid, S.R.; Al-lami, K. Critical review of strength and durability of concrete beams externally bonded with FRP. *Cogent Eng.* **2018**, *5*, 1525015. [CrossRef]
2. Breveglieri, M.; Aprile, A.; Barros, J.A.O. Shear strengthening of reinforced concrete beams strengthened using embedded through section steel bars. *Eng. Struct.* **2014**, *81*, 76–87. [CrossRef]
3. Karbhari, V.M.; Chin, J.W.; Hunston, D.; Benmokrane, B.; Juska, T.; Morgan, R.; Lesko, J.J.; Sorathia, U.; Reynaud, D. Durability Gap Analysis for Fiber-Reinforced Polymer Composites in Civil Infrastructure. *J. Compos. Constr.* **2003**, *7*, 238–247. [CrossRef]
4. Larson, K.H.; Peterman, R.J.; Rasheed, H.A. Strength-Fatigue Behavior of Fiber Reinforced Polymer Strengthened Prestressed Concrete T-Beams. *J. Compos. Constr.* **2005**, *9*, 313–326. [CrossRef]
5. Micelli, F.; Mazzotta, R.; Leone, M.; Aiello, M.A. Review Study on the Durability of FRP-Confined Concrete. *J. Compos. Constr.* **2015**, *19*, 04014056. [CrossRef]
6. Sen, R. Developments in the durability of FRP-concrete bond. *Constr. Build. Mater.* **2015**, *78*, 112–125. [CrossRef]
7. Kouris, L.A.S.; Triantafillou, T.C. State-of-the-art on strengthening of masonry structures with textile reinforced mortar (TRM). *Constr. Build. Mater.* **2018**, *188*, 1221–1233. [CrossRef]
8. Grace, N.F.; Grace, M. Effect of repeated loading and long term humidity exposure on flexural response of CFRP strengthened concrete beams. In *Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005)*; Chen, J.F., Teng, J.G., Eds.; International Institute for FRP in Construction: Hong Kong, China, 2005; pp. 539–546.
9. ACI Committee 440. *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures*; American Society of Civil Engineers: Farminton Hills, MI, USA, 2008; ISBN 9780870312854.
10. Firmo, J.P.; Correia, J.R.; Pitta, D.; Tiago, C.; Arruda, M.R.T. Experimental characterization of the bond between externally bonded reinforcement (EBR) CFRP strips and concrete at elevated temperatures. *Cem. Concr. Compos.* **2015**, *60*, 44–54. [CrossRef]
11. Ferrier, E.; Rabinovitch, O.; Michel, L. Mechanical behavior of concrete-resin/adhesive-FRP structural assemblies under low and high temperatures. *Constr. Build. Mater.* **2015**, *127*, 1017–1028. [CrossRef]
12. De Santis, S.; Ceroni, F.; de Felice, G.; Fagone, M.; Ghiassi, B.; Kwiecień, A.; Lignola, G.P.; Morganti, M.; Santandrea, M.; Valluzzi, M.R.; et al. Round Robin Test on tensile and bond behaviour of Steel Reinforced Grout systems. *Compos. Part B* **2017**, *127*, 100–120. [CrossRef]
13. D'Antino, T.; Carloni, C.; Sneed, L.H.; Pellegrino, C. Matrix–fiber bond behavior in PBO FRCM composites: A fracture mechanics approach. *Eng. Fract. Mech.* **2014**, *117*, 94–111. [CrossRef]
14. Pekmezci, B.Y.; Arabaci, E.; Ustundag, C. Freeze–thaw Durability of Lime Based FRCM Systems for Strengthening Historical Masonry. *Key Eng. Mater.* **2019**, *817*, 174–181. [CrossRef]
15. Donnini, J.; Corinaldesi, V.; Nanni, A. FRCM mechanical properties using carbon fabrics with different coating treatments. In *ACI Special Publication*; American Concrete Institute: Farmington Hills, MI, USA, 2015; pp. 8.1–8.12.
16. Bencardino, F.; Condello, A.; Ashour, A.F. Single-lap shear bond tests on Steel Reinforced Geopolymeric Matrix-concrete joints. *Compos. Part B Eng.* **2017**, *110*, 62–67. [CrossRef]
17. Bencardino, F.; Condello, A. Eco-friendly external strengthening system for existing reinforced concrete beams. *Compos. Part B Eng.* **2016**, *93*, 163–173. [CrossRef]
18. Bencardino, F.; Condello, A. Structural behaviour of RC beams externally strengthened in flexure with SRG and SRP systems. *Int. J. Struct. Eng.* **2014**, *5*, 346–368. [CrossRef]
19. D'Antino, T.; Carozzi, F.G.; Colombi, P.; Poggi, C. Out-of-plane maximum resisting bending moment of masonry walls strengthened with FRCM composites. *Compos. Struct.* **2018**, *202*, 881–896. [CrossRef]
20. Koutas, L.N.; Tetta, Z.; Bournas, D.A.; Triantafillou, T.C. Strengthening of Concrete Structures with Textile Reinforced Mortars: State-of-the-Art Review. *J. Compos. Constr.* **2019**, *23*, 03118001. [CrossRef]
21. Yin, S.; Jing, L.; Yin, M.; Wang, B. Mechanical properties of textile reinforced concrete under chloride wet–dry and freeze–thaw cycle environments. *Cem. Concr. Compos.* **2019**, *96*, 118–127. [CrossRef]
22. Colombo, I.G.; Colombo, M.; Di Prisco, M. Tensile behavior of textile reinforced concrete subjected to freezing-thawing cycles in un-cracked and cracked regimes. *Cem. Concr. Res.* **2015**, *73*, 169–183. [CrossRef]

23. International Code Council Evaluation Service (ICC-ES). *Masonry and Concrete Strengthening Using Fabric-Reinforced Cementitious Matrix (FRCM) and Steel Reinforced Grout (SRG) Composite Systems AC434*; International Code Council Evaluation Service: Whittier, CA, USA, 2018.
24. CSLLPP—Servizio Tecnico Centrale. *Linee Guida per la Identificazione, la Qualificazione ed il Controllo di Accettazione di Compositi Fibrorinforzati a Matrice Inorganica (FRCM) da Utilizzarsi per il Consolidamento Strutturale di Costruzioni Esistenti*; CSLLPP: Rome, Italy, 2019.
25. Carozzi, F.G.; Bellini, A.; D'Antino, T.; de Felice, G.; Focacci, F.; Hojdys, Ł.; Laghi, L.; Lanoye, E.; Micelli, F.; Panizza, M.; et al. Experimental investigation of tensile and bond properties of Carbon-FRCM composites for strengthening masonry elements. *Compos. Part B Eng.* **2017**, *128*, 100–119. [CrossRef]
26. De Munck, M.; El Kadi, M.; Tsangouri, E.; Vervloet, J.; Verbruggen, S.; Wastiels, J.; Tysmans, T.; Remy, O. Influence of environmental loading on the tensile and cracking behaviour of textile reinforced cementitious composites. *Constr. Build. Mater.* **2018**, *181*, 325–334. [CrossRef]
27. Butler, M.; Mechtcherine, V.; Hempel, S. Experimental investigations on the durability of fibre-matrix interfaces in textile-reinforced concrete. *Cem. Concr. Compos.* **2009**, *31*, 221–231. [CrossRef]
28. Arboleda, D. Fabric Reinforced Cementitious Matrix (FRCM) Composites for Infrastructure Strengthening and Rehabilitation: Characterization Methods. Ph.D. Thesis, University of Miami, Coral Gables, FL, USA, 2014.
29. Carozzi, F.G.; Poggi, C. Mechanical properties and debonding strength of Fabric Reinforced Cementitious Matrix (FRCM) systems for masonry strengthening. *Compos. Part B* **2015**, *70*, 215–230. [CrossRef]
30. Focacci, F.; D'Antino, T.; Carloni, C. Analytical modelling of the tensile response of PBO-FRCM composites. In Proceedings of the twenty-fourth Italian Association of Theoretical and Applied Mechanics Convention (AIMETA 2019), Rome, Italy, 15–19 September 2019.
31. ASTM International. *Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials. ASTM D2344/D2344M-13*; ASTM International: West Conshohocken, PA, USA, 2013.
32. *EN 1015-11 BSI Standards Publication Methods of Test for Mortar for Masonry*; CEN: Bruxelles, Belgium, 2019.
33. Donnini, J. Durability of glass FRCM systems: Effects of different environments on mechanical properties. *Compos. Part B Eng.* **2019**, *174*, 107047. [CrossRef]
34. Nobili, A. Durability assessment of impregnated Glass Fabric Reinforced Cementitious Matrix (GFRCM) composites in the alkaline and saline environments. *Constr. Build. Mater.* **2016**, *105*, 465–471. [CrossRef]
35. Ceroni, F.; Bonati, A.; Galimberti, V.; Occhiuzzi, A. Effects of environmental conditioning on the bond behavior of FRP and FRCM systems applied to concrete elements. *J. Eng. Mech.* **2018**, *144*, 1–15. [CrossRef]
36. Franzoni, E.; Gentilini, C.; Santandrea, M.; Zanotto, S.; Carloni, C. Durability of steel FRCM-masonry joints: Effect of water and salt crystallization. *Mater. Struct. Mater. Constr.* **2017**, *50*, 201. [CrossRef]
37. Cabral-fonseca, S.; Correia, J.R.; Custódio, J.; Silva, H.M.; Machado, A.M.; Sousa, J. Durability of FRP—Concrete bonded joints in structural rehabilitation: A review. *Int. J. Adhes. Adhes.* **2018**, *83*, 153–167. [CrossRef]
38. BS EN 12467, E.S. Fibre-cement flat sheets—Product specification and test methods. *Shock* **2004**, *2009*, 1–8.
39. ASTM International. *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. ASTM C666/C666M*; ASTM International: West Conshohocken, PA, USA, 2015.
40. ASTM International. *Standard Test Method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars Used in Concrete Construction. ASTM D7705/D7705M*; ASTM International: West Conshohocken, PA, USA, 2019.
41. D'Antino, T.; Pisani, M.A.; Poggi, C. Effect of the environment on the performance of GFRP reinforcing bars. *Compos. Part B* **2018**, *141*, 123–136. [CrossRef]
42. Micelli, F.; Nanni, A. Durability of FRP rods for concrete structures. *Constr. Build. Mater.* **2004**, *18*, 491–503. [CrossRef]
43. Franzoni, E.; Gentilini, C.; Santandrea, M.; Carloni, C. Effects of rising damp and salt crystallization cycles in FRCM-masonry interfacial debonding: Towards an accelerated laboratory test method. *Constr. Build. Mater.* **2018**, *175*, 225–238. [CrossRef]
44. Kabir, M.I.; Shrestha, R.; Samali, B.; Ikramul, M.; Shrestha, R.; Samali, B. Effects of applied environmental conditions on the pull-out strengths of CFRP-concrete bond. *Constr. Build. Mater.* **2016**, *114*, 817–830. [CrossRef]
45. *EN 12370:1999 Natural Stone Test Methods: Resistance to Salt Crystallization*; CEN: Bruxelles, Belgium, 1999.

46. RILEM TC 127-MS MS-A.1. Determination of the resistance of wallettes against sulphates and chlorides. *Mat. Struct.* **1998**, *31*, 2–9. [CrossRef]
47. Butler, M.; Mechtcherine, V.; Hempel, S. Durability of textile reinforced concrete made with AR glass fibre: Effect of the matrix composition. *Mater. Struct. Mater. Constr.* **2010**, *43*, 1351–1368. [CrossRef]
48. Sun, W.; Zhang, Y.M.; Yan, H.D.; Mu, R. Damage and damage resistance of high strength concrete under the action of load and freeze–thaw cycles. *Cem. Concr. Res.* **1999**, *29*, 1519–1523. [CrossRef]
49. Lomboy, G.; Wang, K. Effects of strength, permeability, and air void parameters on freezing-thawing resistance of concrete with and without air entrainment. *J. ASTM Int.* **2009**, *6*, 1–14.
50. Benzarti, K.; Chataigner, S.; Quiertant, M.; Marty, C.; Aubagnac, C. Accelerated aging behaviour of the adhesive bond between concrete specimens and CFRP overlays. *Constr. Build. Mater.* **2011**, *25*, 523–538. [CrossRef]
51. Portal, W.N.; Flansbjer, M.; Johannesson, P.; Malaga, K.; Lundgren, K. Tensile behaviour of textile reinforcement under accelerated aging conditions. *J. Build. Eng.* **2016**, *5*, 57–66. [CrossRef]
52. Scheffler, C.; Förster, T.; Mäder, E.; Heinrich, G.; Hempel, S.; Mechtcherine, V. Aging of alkali-resistant glass and basalt fibers in alkaline solutions: Evaluation of the failure stress by Weibull distribution function. *J. Non Cryst. Solids* **2009**, *355*, 2588–2595. [CrossRef]
53. Hristozov, D.; Wroblewski, L.; Sadeghian, P. Long-term tensile properties of natural fibre-reinforced polymer composites: Comparison of flax and glass fibres. *Compos. Part B Eng.* **2016**, *95*, 82–95. [CrossRef]
54. Roventi, G.; Bellezze, T.; Giuliani, G.; Conti, C. Corrosion resistance of galvanized steel reinforcements in carbonated concrete: Effect of wet–dry cycles in tap water and in chloride solution on the passivating layer. *Cem. Concr. Res.* **2014**, *65*, 76–84. [CrossRef]
55. Fayala, I.; Dhouibi, L.; Nóvoa, X.R.; Ben Ouezdou, M. Effect of inhibitors on the corrosion of galvanized steel and on mortar properties. *Cem. Concr. Compos.* **2013**, *35*, 181–189. [CrossRef]
56. Yadav, A.P.; Nishikata, A.; Tsuru, T. Degradation mechanism of galvanized steel in wet–dry cyclic environment containing chloride ions. *Corros. Sci.* **2004**, *46*, 361–376. [CrossRef]
57. Carloni, C.; D'Antino, T.; Sneed, L.H.; Pellegrino, C. Three-Dimensional Numerical Modeling of Single-Lap Direct Shear Tests of FRCM-Concrete Joints Using a Cohesive Damaged Contact Approach. *J. Compos. Constr.* **2018**, *22*, 04017048. [CrossRef]