Durability of Inorganic-Matrix Composites

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Fabric-reinforced cementitious matrix (FRCM) composites, comprising high-strength fiber textiles embedded within inorganic matrices, represent an effective, cost-efficient, and low-invasive solution for strengthening and retrofitting existing masonry and reinforced concrete structures. Among different textiles employed in FRCM composites, polyparaphenylene benzo-bisoxazole (PBO) textiles are adopted due to their high tensile strength and good adhesion with the matrix. Although several experimental, numerical, and analytical works were performed to investigate the mechanical properties of PBO FRCM composites, limited information is available on their long-term behavior, as well as in the case of exposure to aggressive environments.

FRCM TRM PBO composites tensile test durability long-term

1. PBO FRCM

Due to the relevant thickness of inorganic-matrix layers constituting fabric-reinforced cementitious matrix (FRCM) composites, which should be able to guarantee proper stress transfer between the fiber and substrate [1] and protect the embedded textile from the environmental exposure, the durability of polyparaphenylene benzo-bisoxazole (PBO) textiles has not been properly investigated and only a few studies are available to date. Chin et al. [2] investigated the effect of hygrothermal conditioning on the tensile strength of PBO fiber adopted for body armor equipment. The research demonstrated that the combined effect of high temperature (50–60 °C) and relative humidity (37–60% relative humidity, RH) determined a 30% reduction in tensile strength after a 26-week exposure. However, the research showed that when the same fiber was exposed to high temperature in a dry environment (5% RH) a slight reduction in tensile strength was recorded (<4%), which indicated that moisture is a key factor in the degradation of PBO fiber. In [3], the effect of alkaline environments with different chemical compositions and temperatures on the tensile strength of bare PBO textile employed in FRCM systems was investigated. The results showed that the alkalinity of lime mortar environments did not affect the PBO fiber strength even after 180 days. Tensile strength reductions of approximately 20% were observed after 90- and 180-day treatments in highly alkaline environments, namely those provided by the ETAG 029/A protocol [4] and Portland cement conditions, respectively. Higher concentrations of alkaline ions determined a 34% fiber strength reduction after a 30-day exposure. Increasing the temperature up to 45 °C accelerated the diffusion of alkaline ions in the specimens, determining 31% and 51% textile strength reductions after 60 days in lime and Portland cement environments, respectively. Ombres et al. [5] investigated the effect of high temperature on the physical and mechanical properties of a bare PBO textile for FRCM applications. Results showed that high temperatures determined a change in textile color and a significant reduction in weight (18% and 43% at 100 and 200 °C, respectively). However, the temperature did not affect the failure load of textile specimens.

FRCM composites including PBO fibers typically employ a cement-based high-performance embedding matrix due to the mechanical compatibility with the fiber. The effect of hygrothermal conditionings on the tensile and compressive strength of a short-fiber-reinforced cement-based matrix was experimentally investigated in [6] by means of compressive and bending tests. Mortar specimens were cured for 28 days in air (23 °C, 50% RH) or in water (23 °C) and then were subjected to different hygrothermal conditionings, including alternations of days of immersion and drying. Specimens showed a substantial increase in their compressive strength (34–54%) when the curing period in water was followed by an air-drying period. This was due to the fact that curing in air does not allow the specimen to reach the optimal moisturizing level of the grout. Conversely, the increase in flexural strength of specimens cured in water and then dried in air was not as significant as that observed for the compressive strength. Al-Lami et al. [7] investigated the effect of freeze–thaw cycles and saline environments on the tensile strength of cement-based matrices using results available in the literature [8][9]. These results showed that exposure to a high number of freeze–thaw cycles may reduce the matrix tensile strength due to the micro-cracks formation promoted by the volume increase of interstitial water during the freezing phase. However, this effect was not significant for a low number of cycles (<100) and was affected by the aggregate size and by the concrete strength grade, in light of the low permeability of high-strength mixtures that guarantees a low vulnerability to freeze–thaw cycles. Similarly, interstitial salt crystallization and its chemical interaction with matrix components such as calcium hydroxide and aluminum oxide determined a reduction in cement-based matrix tensile strength and durability. Results analyzed in [7] showed that this effect is enhanced by wet–dry cycles in saline environments. Finally, Ombres et al. [5] demonstrated that high temperatures affected both the compressive and flexural strength of the cement-based mortar, which decreased by 9% and 22%, respectively, at 200 °C.

The durability of both PBO fiber and cement-based matrix affects the long-term behavior of PBO FRCM composites. As previously mentioned, the external matrix layer provides protection to the textile against aggressive environments. However, premature cracking of the matrix due to shrinkage or to long-term reduction in its tensile properties may induce direct environmental exposure of the textile, which can cause fiber deterioration over time. Furthermore, exposure to aggressive environments can affect the stress-transfer mechanism between matrix and fiber, reducing the FRCM composite mechanical properties. Indeed, salt crystallization and water freezing–thawing cycles at the contact interface between textile yarns and matrix may affect the bond between the two phases, leading to potential modification of the FRCM mechanical behavior and failure mode. The currently available studies on the long-term behavior of PBO FRCM composites are based on the comparison between results of tensile tests on conditioned (control) and unconditioned composite rectangular coupons, whereas studies that consider long-term bond tests are limited [8][10]. Results obtained by Arboleda et al. [11] showed that the ultimate stress σ_u of PBO FRCM specimens subjected to clevis-grip tensile tests was not reduced after 1000 and 3000 h of exposure to hygrothermal, saline, and alkaline environments, twenty freeze–thaw cycles, and 4 h immersion in fuel. Conversely, conditioning protocols that accounted for immersion in aqueous solutions led to a substantial increase in the composite tensile strength, attributed to the aforementioned matrix hydration and curing, which improved the bond between the fiber yarn and surrounding matrix. The clevis-grip tensile test set-up is particularly interesting for the research of the long-term behavior of inorganic-matrix composites. Indeed, clevis-grip tensile tests allow for investigating the matrix–fiber interaction [12]. Differently, the tensile strength of conditioned specimens subjected to clamping-grip tests depends mainly on the effect of the aggressive environment on the fiber mechanical properties, since fiber rupture is the expected failure mode. The excellent long-term behavior of PBO FRCM was confirmed in [13], where 1000 h treatments were considered in saline, alkaline, hydrochloride acid, and distilled water solutions. For all the conditioning protocols, the composite exhibited a full maintenance of its control tensile strength, with some increases in the case of distilled water and acid conditionings. This suggests that when adequate preparation is provided, uncracked matrix provides adequate protection to fibers. However, the strength degradation of the composite can be significant if conditioning is performed after matrix cracking. Carozzi et al. [14] experimentally observed that when PBO FRCM specimens were pre-cracked before being subjected to freeze–thaw cycles, the corresponding ultimate stress was 36% lower than that of control specimens and 20% lower than equally conditioned non-pre-cracked specimens. In contrast with other findings, the results presented in [5] show that temperature can dramatically reduce the tensile strength of PBO FRCM composites, with 48% and 62% reductions at 100 and 200 °C, respectively. However, it should be noted that the results of control specimens are not consistent with other studies on the same material.

The composite bond capacity with the substrate is a fundamental parameter in design practice [15] and exposure to an aggressive environment could affect it over time. The environmental temperature seems not to affect the bond capacity of PBO FRCM–concrete joints subjected to a direct shear test, as demonstrated in the experimental campaign conducted by Al-Jaber et al. [16], which considered three different testing temperatures (21, 50, and −18 °C) and high-temperature cycles (27 to 50 °C hysteresis) combined with freeze–thaw cycles. Specimens exhibited average variations in their bond capacity in the range −10% to + 19%. In [6], beam tests of PBO FRCM–concrete joints were performed on specimens conditioned in water. The results confirmed that matrix hydration in water followed by air curing improved the quality of matrix adhesion with substrate, resulting in an average of 7% bond capacity increase. Al-Lami et al. [10] investigated the effect of wet–dry cycles on the bond behavior of PBO FRCM–masonry joints subjected to direct shear tests, determining a scarce influence of the treatment on the composite bond capacity (7% reduction) after 50 cycles, which can be partially attributed to the overexposure to the wet environment of bare textile portions of the specimen.

2. Glass FRCM

Glass fiber has been increasingly used in FRCM applications due to the relatively low cost of the raw material and to the mechanical compatibility with masonry elements. However, the durability of glass fiber is significantly affected by exposure to the alkaline ions present in alkali environments. Recently, the application of a chemical zirconium treatment (alkali-resistant, AR glass) and the use of thin rubber external coating (coated glass fiber) on the fiber were proven to be effective in increasing the durability of glass fiber in alkaline environments. The long-term behavior of AR styrene butadiene rubber (SBR)-coated glass FRCM was investigated by the authors in [17] by tensile testing of rectangular coupons including one layer of a coated AR glass textile, subjected to hygrothermal, saline, alkaline, freeze–thaw cycles, and dry-heat treatments. The results showed a slight decrease in the specimen tensile strength only for saline and freeze–thaw cycles (maximum decrease equal to 12% for specimens subjected to freeze–thaw cycles). As observed for other composites, the matrix cracking stress increased after conditioning, except for specimens immersed in alkaline solutions for 1000 h, due to the continuous matrix curing. In general, the average slope E_3, i.e., the slope of the fully cracked stage of the stress–strain response obtained by the clamping-grip test, was not affected by the exposures. E_3 showed a limited decrease only for specimens subjected to the alkaline environment and freeze–thaw cycles, which was attributed to the degradation of the textile and SBR coating, respectively. Finally, the dry-heat conditioning did not induce any degradation in the tensile properties of the specimens.

3. Carbon FRCM

Carbon FRCM composites represent a promising alternative to PBO FRCM for the strengthening and retrofitting of RC elements due to the textile high elastic modulus and tensile strength. The effect of alkaline environments on a bare carbon textile for FRCM was investigated in [3]. Results showed a full retention of mechanical strength under the attack of several combinations of different types of alkaline ion. This trend was confirmed by the experimental results presented in [11], where rectangular FRCM coupons comprising a carbon textile embedded within a cement-based matrix were subjected to clevis-grip tensile tests. For all the conditionings, the carbon FRCM exhibited and increase in its ultimate stress σ_u and slope of the fully cracked stage, which was attributed to a continuous curing of mortar due to the immersion in aqueous solutions. In contrast, carbon FRCM specimens comprising pozzolanic matrix, subjected to a clamping-grip tensile test, presented in [18], showed significant reductions in ultimate tensile stress (40% and 33%) when subjected to alkaline and saline environments, respectively. A partial performance loss (11%) was also observed in the slope of the stress–strain curve E_3 after both treatments. The effect of saline and alkaline conditionings was more pronounced if the curing time of specimens was reduced to 28 days (instead of 60) before the treatment began. For the same carbon FRCM composite, a full retention of ultimate tensile stress (113%) and elastic modulus (100%) was observed after 20 freeze–thaw cycles. In addition, the results presented in [18] shed light on the effect of environmental conditionings on the composite ultimate strain ε_u (i.e., strain associated with the ultimate stress σ_u) and matrix cracking strength σ_{T1}. For alkaline and saline conditioning, the ultimate strain was significantly reduced as a consequence of the aforementioned reduction in ultimate tensile stress. Conversely, the ε_u retained value increased after freeze–thaw cycles (113%), coherently with the increase in σ_u. The retained matrix cracking strength, σ_{T1}, was equal to 48–50% and 68–76% for 28- and 60-day cured specimens, respectively, under both saline and alkaline environments. However, it increased to 116% after the freeze–thaw cycles. The differences in the long-term behavior observed in [11][18] can be attributed to the different matrices adopted in the two composites analyzed (in the first case a cement-based matrix was employed, while a pozzolanic matrix was used in the second case) and to the different test set-ups employed (i.e., clevis-grip test in [11] and clamping-grip test in [18]). Further results are needed to clarify the effect of aggressive exposures on carbon FRCM composites.

4. Steel-Reinforced Grout (SRG)

Steel-reinforced grout systems are recently developed inorganic-matrix composites characterized by the use of continuous high-strength steel fibers as reinforcement. In SRG, steel fibers are arranged in parallel cords, realized with the wire twisting technique and held together with a polyester mesh to form a stable grid. For durability purposes, steel cords can be coated with brass or zinc to increase their corrosion resistance. Micelli et al. [3] investigated the effect of alkaline environments on the bare (i.e., not impregnated with the matrix) steel textile employed in SRG composites. The results showed a fully retained tensile strength after 30, 90, and 180 days under four different levels of alkalinity and temperature. The bare steel fiber resistance to alkaline conditioning was confirmed from the results presented in [19] on a brass-coated steel textile. In contrast, reductions in the textile tensile strength were recorded after acid conditioning (4%) and outdoor aging (20–27%). Signorini and Nobili [13] investigated the effect of different conditioning protocols on the ultimate tensile performances of two distinct SRG systems, namely a brass-coated SRG and a zinc-coated SRG, by performing clamping-grip tensile tests on rectangular coupons. The conditionings included 1000 h immersions in salt water, alkaline solution, hydrochloric acid, and distilled water. Results showed that zinc-coated SRG is more sensitive to aggressive environments than the brass-coated SRG. Indeed, the former exhibited performance reductions after all the conditionings, which were equal to 14–34% in strength and 30–60% in ultimate strain. The latter showed a 24–26% reduction in both ultimate stress and strain only in the case of hydrochloric acid conditioning, whereas performance increases were recorded after the other exposures.

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