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Effect of salt crystallization on the bond behavior of glass FRCM-masonry joints

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ABSTRACT: The use of fabric-reinforced cementitious matrix (FRCM) composites for reinforcement of existing masonry members has attracted an increasing interest in recent years. FRCM composites are particularly suitable for masonry strengthening and retrofitting due to their ease of installation, reversibility, excellent compatibility with the substrate and vapor permeability. Tensile mechanical properties and bond behavior of FRCM composites were extensively studied. However, limited information is available regarding the durability of FRCM and FRCM-strengthened members, which may represent a critical issue for the effectiveness of the strengthening system. Indeed, existing masonry structures suffer from the presence of moisture, which can come from rising damp, condensation, infiltration of rainwater, etc. Water is often responsible for the presence of salt within the element, which represents a major cause of masonry damage. When the salt crystallization takes place at the interface between the FRCM and the substrate, a possible reduction of the FRCM bond capacity can be observed.

In this paper, the effect of salt crystallization on the bond behavior of an FRCM applied onto a masonry substrate is experimentally investigated. The FRCM composite employed comprises a glass open mesh reinforcing textile and a cementitious matrix. FRCM-masonry joints were conditioned in a saline solution to induce salt crystallization in the FRCM, i.e., within the composite strips and at the FRCM-masonry interface. The bond behavior of the FRCM composite before and after the conditioning is investigated with single-lap direct shear tests. The results obtained provide information on the long-term behavior of the glass FRCM composite considered.

1 INTRODUCTION

Fabric-reinforced cementitious matrix (FRCM) composites have gained large popularity in recent years as externally bonded reinforcement (EBR) for masonry (Carozzi and Poggi 2015) and reinforced concrete (RC) structures (Täljsten and Blanksvärd 2007), where they proved to be effective as in-plane (de Felice et al. 2014) and out-of-plane (Papanicolaou et al. 2008) reinforcement for walls and flexural, shear, and torsional reinforcement for RC beams (Bencardino et al. 2018, Triantafillou and Papanicolaou 2006, Alabdulhady et al. 2017). They comprise different high strength fibers arranged in open-mesh textiles embedded within inorganic matrices. FRCMs overcome some of the main drawbacks related to the use of fiber-reinforced polymers (FRP) composites, such as irreversibility of the application and absence of vapor permeability (Ombres 2015, Del Prete et al. 2015). Furthermore, recent studies on FRCM long-term behavior showed that these inorganic matrix composites have better resistance to high temperatures (Ferretti et al. 2022) and to aggressive environments (Franzoni et al. 2019, Al-Lami et al. 2021) than FRPs (Trapko 2013, Tedeschi et al. 2014). However, the inorganic matrix of FRCMs is not able to uniformly impregnate fiber filaments as the organic resin of FRP composites does, due to the dimension of the components of the mortar matrix. In FRPs, an even stress distribution among fiber filaments can be assumed thanks to the use of organic resins and this leads to different resisting mechanism developing in FRP and FRCM when subjected to external loads. FRCM mechanical properties are determined with tensile tests (i.e., clamping- (CSLLPP 2022) or clevis-grip (International Code Council Evaluation Service (ICC-

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ES) 2018) tests) and single- or double-lap direct shear tests (European Organization for Technical Assessment (EOTA) 2018), which allows for assessing the composite tensile strength and the FRCM-substrate interface debonding mechanism, respectively (Focacci et al. 2022). When failure occurs due to debonding, direct shear tests provide information on the bond behavior of the interface where debonding occurs and allow the evaluation of the bond capacity and cohesive material law (CML) of this interface (Bertolli and D'Antino 2022, D'Antino et al. 2020).

Moreover, durability of FRCMs is a fundamental aspect to be considered when dealing with their application on external surfaces of existing structures, where they can be exposed to humidity, rainfall, and to saline and alkaline environments (Al-Lami et al. 2020). Among different detrimental effects of atmospheric processes, salt attack is the most common cause of weathering in masonry structures (Donnini 2019). There are limited studies in the literature focused on the effects of aggressive saline environment on the mechanical behavior of FRCM composites. Long-term tensile behavior of FRCM was evaluated by Arboleda (2014) and the results indicated a slight increase in tensile capacity of FRCM conditioned in saline and alkaline solution and with freeze-thaw cycles. Similarly, Nobili (2016) assessed FRCM durability against alkaline and saline environments through tensile tests on alkali-resistant (AR) glass FRCM coupons. The saline solution employed comprised 3.5 wt% of sodium chloride (NaCl). Even though not as high as that obtained for the alkaline solution, a reduction of the peak stress attained by the specimen conditioned in saline environment was observed. Tensile behavior of FRCM conditioned in saltwater was also investigated by Donnini et al. (2020), in which it is shown that the tensile strength slightly increased after conditioning, due to curing of the mortar matrix.

Long-term bond behavior of FRCM was investigated by Franzoni et al. (2017), which carried out direct shear tests on steel reinforced grout (SRG) composites aimed at defining an accelerated conditioning procedure able to reproduce the actual environmental conditions to which FRCM are subjected in real applications. The conditioning consisted in four wet-dry cycles, composed of 2-day wetting phase in a sodium chloride (NaCl, 2 wt%) and sodium sulfate decahydrate ($Na_2SO_410H_2O$, 8 wt%) solution, followed by a 3-day drying phase in a ventilated oven at 60 °C. The duration of wetting and drying phases was selected to allow for water saturation and evaporation, respectively. Moreover, to avoid possible effects due to the presence of water within the specimen (i.e., water saturation effect (Franzoni et al. 2015)) on the bond behavior of the specimens (Franzoni et al. 2018), they were oven dried at 60 °C for 2 days before testing. This accelerated procedure was modified by Franzoni et al. (2018), where six wet-dry cycles were performed on SRG-masonry joints. Then, the same conditioning procedure was performed in Franzoni et al. (2019), where different mortar matrices were adopted to investigate the matrix role on the bond behavior of SRG composites. Results showed a reduction of the peak stress attained in direct shear tests in all the conditioned specimens, with lower strength reduction for specimen with cement-based matrix. In Donnini (2019), the same saline solution of Franzoni et al. (2019) was employed for the conditioning of 12 glass FRCM DS test specimens that were subjected either to 1000 hour immersion in saline solution or to wet-dry cycles. Results showed higher strength reduction for the specimens immersed in the saline solution. The effect of salt crystallization on FRCM-masonry joints was also investigated by Garavaglia et al. (2020) by means of pull-off tests. The conditioning procedure was selected according to (RILEM TC 127-MS 1998), and the specimens were inserted in a dry gravel layer filled with water saturated with a 10 wt% of Na_2SO_4 solution for 11 months. Pull-off test showed strong reduction on the bond strength (ASTM International 2004) of conditioned specimens.

The number of studies available in the literature assessing the long-term bond behavior of FRCM is quite limited. US and Italian acceptance criteria (AC 434-13 2013, CSLLPP 2022) evaluate FRCM durability by means of clamping- or clevis- grip tensile tests on specifically conditioned specimens. For example, (International Code Council Evaluation Service (ICC-ES) 2018) prescribes conditioning procedure for 1000 or 3000 hours in water, saltwater (immersion in a solution at 22 °C), alkaline solution, and freezing and thawing cycles. However, as also evidenced in (Franzoni et al. 2019), a common conditioning procedure for the evaluation of the effect of salt crystallization on the bond behavior of different FRCM composites is not yet defined.

In this paper, the effect of salt crystallization on the bond behavior of FRCM-masonry joints is investigated considering a coated glass FRCM embedded within a cement-based mortar matrix. Four specimens were exposed to three wet-dry cycles in saline solution and then tested using a single-lap direct shear test set-up. The results obtained were compared with those of four corresponding control (i.e., unconditioned) specimens highlighting the detrimental effect of the conditioning procedure on the FRCM bond behavior.

2 MATERIALS AND METHODS

2.1 *Materials*

To evaluate the effect of salt crystallization on the bond behavior of FRCM-masonry joints, an experimental campaign was carried out on eight FRCM composite strips applied to masonry wallettes, tested with a push-pull single-lap direct shear set-up. Four out of eight specimens were subjected to an accelerated conditioning procedure whereas the remaining four were used as control specimens.

The FRCM composite comprised a coated glass open-mesh textile and a cementitious matrix. The textile employed was made with alkali-resistant glass fibers arranged in discrete bundles, each coated with styrene butadiene rubber (SBR). The textile was embedded within a commercial M20 (EN 998-2 2016) cementitious matrix (Sika Italia SpA 2021). The textile cross-sectional area was determined by the calcination method (EN 1172 1999) on eight bundle specimens and was A^{*}=1.05 mm^2 (CoV 0.8%) for a single longitudinal bundle (warp direction) and A_t^{*}=0.99 mm^2 (CoV 0.4%) for a single transversal bundle (weft direction). The equivalent thickness of the textile in longitudinal direction was t_f=0.063 mm. Tensile tests of nine bare textile strips (i.e., not impregnated with the mortar) including 3 longitudinal bundles provided a tensile strength, ultimate strain, and modulus of elasticity of 756 MPa (CoV 6.1%), 1.48% (CoV 15.6%) and 52 GPa (CoV 6.1 %).

Each masonry wallette was made of seven solid clay UNI bricks and six 10 mm-thick mortar joints. The masonry wallettes total height was 480 mm, and their width and depth 240 and 110 mm, respectively. The bricks had nominal dimensions 240×110×60 mm and compressive strength ranging from 15 to 25 MPa, according to information provided by the manufacturer (Danesi srl 2020). The mortar used for the joint was a commercial pre-mixed mortar (Fassa Bortolo srl 2020, EN 998-2 2016). The FRCM strips were applied to the 240 mm-wide side of the wallettes with the loaded end placed 30 mm below the upper edge of the masonry wall. The strips had bonded width b_f=50 mm and bonded length L=300 mm (CSLLPP 2022). The specimens were cast with the following procedure:

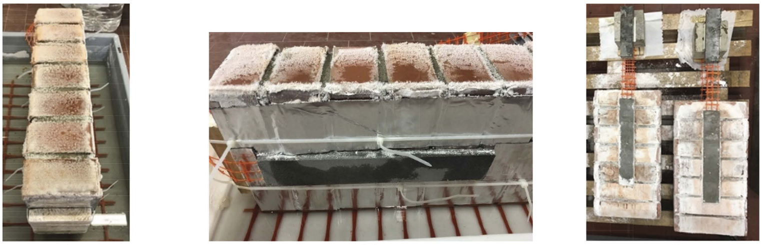
- A first 5 mm-thick layer of mortar was applied to the surface of the wallette using a mold to accurately control the strip geometry.
- The open-mesh textile, which comprised n=3 bundles longitudinal bundles, was gently pressed onto the first mortar to assure proper impregnation. A portion of the textile with length 270 mm was left bare beyond the loaded end.
- A second 5 mm-thick layer of mortar was applied as finishing layer. Thus, the total thickness of the FRCM strip was 10 mm.

2.2 *Accelerated conditioning procedure*

After being left to cure for at least 28 days, four FRCM-masonry joints were subjected to an accelerated weathering procedure. The conditioning comprised three wet-dry cycles in which the specimens were first immersed in a saline solution for 48 hours and then dried in a controlled environment characterized by a 23 ± 2 °C temperature and a 50 ± 10 % relative humidity for 72 hours. As reported by (Franzoni et al. 2017), at least 8h immersion is necessary to obtain a complete saturation of masonry walls by capillarity adsorption. However, the amount of time required depends on the type of brick and mortar employed and 48 hours were selected in this work for the wetting phase. During the 72 hours drying phase, specimens were stored at room conditions and water evaporated from the masonry substrate, promoting salt crystallization. Dry conditions of the specimens were essential to guarantee the absorption of saline solution during the following cycle.

During the wetting phase, the specimens were partially immersed in a 20 mm-head Na_2SO_4 (10 wt%) solution for 48 hours, to allow capillary absorption of the saline solution. In each cycle, during the first 24 hours the specimen was immersed in the solution on one 480×110 mm side and then was turned and immersed on the opposite side for the remaining 24 hours (Figure 1a). During immersion, the masonry wallettes were placed on a composite grid to promote a homogeneous solution absorption. Duct tape was applied to every side of the masonry wall (except for the two alternatively immersed in the solution), including the side where the composite strip was applied, to induce salt crystallization through the FRCM strip. The level of the solution was kept constant through the cycles. At the end of the conditioning procedure, a considerable amount of salt crystallized in the free (i.e., not covered by the duct tape) surfaces of the masonry wallettes. Salt crystallization was also observed in the FRCM strip, with most of the crystallized salt located on the strip sides and in correspondence of the mortar joints (Figure 1b). At the end of the conditioning cycles, the duct tape around the wallettes was removed and the specimens were left to cure for additional 48 hours before testing (Figure 1c).

The conditioning applied in this work was an accelerated procedure (see (Franzoni et al. 2018)) aimed at inducing a realistic damage in a relatively short period of time without changing the masonry deterioration process. The end of the conditioning procedure was determined by visual inspection when a remarkable amount of efflorescence was obtained on the wall free surfaces.



a) b) c)

Figure 1. A) Specimen immersed in salt solution during the second wet-dry cycle. b, c) Specimens 48 hours after the end of the conditioning procedure.

2.3 *Direct shear tests*

After the conditioning procedure, single-lap direct shear tests were performed on control and conditioned specimens to study the debonding mechanism of the glass FRCM composite. Experimental tests were carried out in displacement control at a rate of 0.0034 mm/s using a servo-hydraulic testing machine. GFRP tabs (with dimensions 50×80 mm) were epoxy bonded at the end of the bare textile beyond the loaded end to promote uniform stress distribution among the bundles and allow for clamping by the testing machine. During the test, fibers were pulled whereas the masonry wallette was restrained with a steel frame (Figure 2a, b).

Two linear variable displacement transducers (LVDTs) with measurement range of 200 mm were employed to measure the relative displacement, i.e., slip, between the masonry wallette and the textile. They were attached to the masonry surface at the loaded end and reacted off of an aluminum L-shaped plate fixed to the bare fibers immediately outside the FRCM strip. The average of the measurements of the two LVDTs ($LVDTa$ and $LVDTb$) was named global slip g in this paper. During the test, the applied load, P, and the stroke of the testing machine, δ, were recorded with a frequency of 5 Hz. The stress in the textile, σ, was obtained as the ratio between the load recorded by the testing machine, i.e., the applied load P, and the textile cross-sectional area in warp direction, $A_f=t_f b_f=n\ A^*=3.15\ \text{mm}^2$.

3 RESULTS AND DISCUSSION

Specimens were named DS_X_Y_C_S_N, where DS = direct shear (type of test), X = bonded length [mm], Y = bonded width [mm], C = clay brick masonry (type of support), S (if present) =

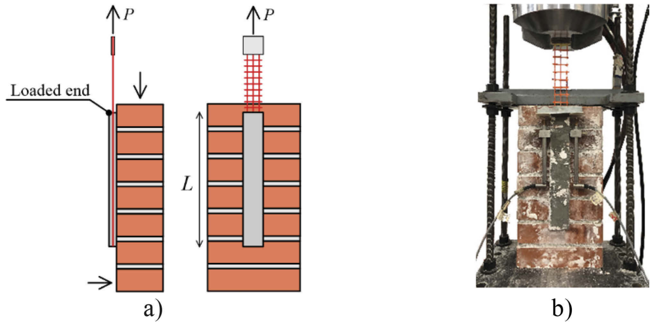


Figure 2. Single-lap direct shear test set-up: a) sketch and b) specimen DS_300_50_C_S_1 before testing.

indicates the salt conditioned specimens, and N = specimen number. The applied stress σ – global slip g curves for the FRCM-masonry joints studied are reported in Figure 3a, b for control and conditioned specimens, respectively. All specimens failed due to rupture of the fibers at the loaded end, either inside the FRCM strip or immediately outside it. Failure occurred first in one bundle and then in the remaining, which indicated the non-uniform stress distribution among the different bundles in the FRCM strip (see Figure 4a, b). However, fibers within each bundle failed approximately at the same time (i.e., no telescopic behavior (Hegger et al. 2006) was observed) due to the presence of the SBR coating that promoted the uniform distribution of stresses among fibers within the bundle.

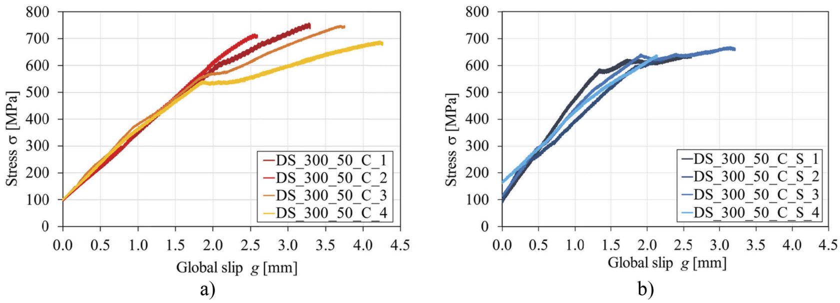


Figure 3. Applied stress σ – global slip g curves for a) control and b) conditioned specimens.

The main parameters obtained by direct shear tests on control and conditioned specimens are reported in Table 1. P^* is the peak load, σ^* the corresponding peak stress, and g^* the global slip associated with the peak stress. Average values and coefficient of variations of nominally equal specimens are also reported. The average peak stress of control specimens was σ^*=742 MPa, while that of conditioned specimen was σ^*=645 MPa. Thus, an average reduction of 13.1% was observed for specimens subjected to the conditioning procedure. Moreover, a reduction of 11.8% in the average value of the global slip associated with the peak stress, g^*, was also observed for conditioned specimens.

Figure 4c shows the comparison between the envelope curves of control and conditioned specimens. The conditioning procedure caused a modest decrease in the peak stress attained in direct shear tests and had no influence in the failure modes of the specimens. It is worth noting that a direct evaluation of the effects of the salt crystallization on the bond behavior of the FRCM-masonry joints could not be performed since failure was attained right outside the FRCM strip. Indeed, the only conclusion that could be drawn is that the bond behavior of the joint was not adversely affected enough by the conditioning procedure to induce failure at the matrix-substrate or matrix-fiber interfaces before fiber rupture occurred (due to hierarchy of interface failures (Carloni et al. 2018)). Moreover, visual observation of the crystallized salts suggested a lower porosity of the cementitious matrix employed with respect to the masonry bricks or mortar layers (salt crystallized mostly in correspondence of the mortar joints and on the FRCM strip sides). Thus, salt crystallization could be expected at the FRCM-masonry interface. These aspects will be clarified with the investigations on porosity and salt migration pattern of the different materials involved in the bond behavior.

Table 1. Results of direct shear tests on control and conditioned specimens.

	P^*	σ^*	g^*		P^*	σ^*	g^*
Samples Name	[kN]	[MPa]	[mm]	Samples Name	[kN]	[MPa]	[mm]
DS_300_50_C_1	2.39	759	2.96	DS_300_50_C_S_1	2.03	643	2.66
DS_300_50_C_2	2.26	717	2.09	DS_300_50_C_S_2	1.98	627	2.26
DS_300_50_C_3	2.36	749	3.63	DS_300_50_C_S_3	2.11	670	3.14
DS_300_50_C_4	2.18	691	4.14	DS_300_50_C_S_4	2.01	639	2.12
Avg	2.34	742	2.89	Avg	2.03	645	2.55
CoV [%]	2.4	2.4	21.9	CoV [%]	2.8	2.8	18.0

It is worth noting that a clear conditioning procedure for the evaluation of the effect of salt crystallization on FRCM-masonry joints is not yet defined in the literature. Further experimental results are needed to improve our knowledge on the joint bond behavior of conditioned specimens and to define a shared conditioning procedure.

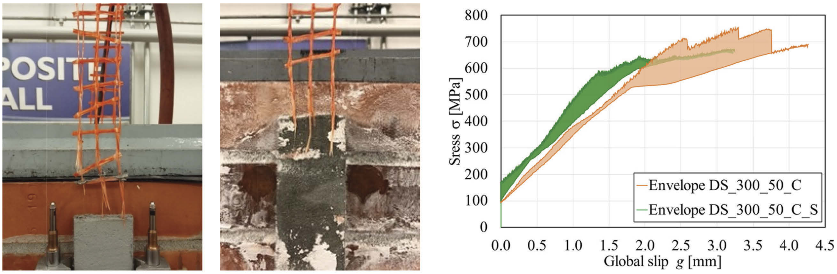


Figure 4. A) Failure modes of representative a) control and b) conditioned specimens; c) comparison between average applied stress σ – global slip *g* curves of control and conditioned specimens.

4 CONCLUSIONS

In this paper, an accelerated conditioning procedure was performed on direct shear test specimens to evaluate the effect of salt crystallization on the bond behavior of glass FRCM-masonry joints. The FRCM comprised a cementitious mortar and a coated glass fiber textile. The results obtained for conditioned specimens were compared with those of corresponding control specimens and allow for drawing the following conclusions:

– the detrimental effect of the conditioning procedure performed resulted in a slightly lower average peak stress attained by conditioned than by control specimens;
– all specimens tested failed due to tensile rupture of the textile either inside the FRCM strip or right outside it;
– physical and chemical investigations on the microstructure of the materials and interfaces will provide additional information on the long-term behavior of the FRCM reinforcement and of FRCM-masonry joints;
– considering the limited number of tests performed and available in the literature, more investigation is needed to clarify the effect of salt crystallization on the behavior of FRCM-

masonry joints. To this aim, a commonly accepted conditioning procedure should be defined for the determination of the salt crystallization resistance of FRCM composites.

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