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Influencing Parameters for the Failure Mechanism of Carbon-FRCM (Fibre Reinforced Cementitious Matrix Systems)

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Abstract. Nowadays, FRCM (Fibre Reinforced Cementitious Matrix) systems are highly attractive for the building materials market; thus, their optimization and development cover an essential role. This work points out the chemical and physical parameters influencing the carbon-FRCM mechanical behaviour. Three different FRCMs composed of commercially available carbon fabric and different inorganic matrices are involved. Matrices are specifically developed to enhance the adhesion with the fabric and differ in organic additive used. Moreover, different fabric geometry (twisted and untwisted) and fibre coatings are considered: micro-silica, fine silica aggregate and medium-size silica aggregate. A new shear test setup is designed to obtain an inexpensive characterization method and employs traditional mechanical tests. Morphological and compositional analyses were performed on the surface fractures. On equal reinforcement typology, significant improvements in shear strength are promoted by organic additives and fabric coatings. Also, pull-out test displays that the twisted bundle promoted the fibre-to-matrix adhesion and remarkably modified the sample failure mechanism compared to the untwisted one. Finally, the FRCM mechanical performance is primarily influenced by mechanical adhesion contribution that might be increased by adopting simple geometrical choices or fabric surface treatments.

Introduction

The demand for reinforcing systems for existing structures has increased trough year due to the ageing of the buildings and the raising of safety standards requested [1]. In this context, Fibre Reinforced Cementitious Matrix (FRCM) composite materials for structures reinforcement is a more and more common choice owing to their property versatility [2].

Depending on the substrate and final application requirements, the optimization of the phases, namely cementitious matrix and fibre reinforcement, and of their interaction is required. For these reasons, the development of new matrices [3] and new methods to increase the compatibility between the fibres and the matrix play a considerable role in the R&D sector. Apart from the composition of the cementitious matrix and of fibres, the mechanical performances of FRCM systems and the failure modes might be influenced by several parameters as, for instance, the grain size of mortar, the presence of organic additives in mix [3, 4], the fabric typology, the bundle geometry [5], coatings etc. Indeed, all these parameters might affect the chemical and mechanical adhesion between the cementitious matrix and the fibre reinforcement, thus providing a different FRCM behaviour during mechanical loading.

This work investigates the influence of the above-mentioned parameters on FRCM mechanical behaviour and attempts to highlight feasible optimization solutions toward adhesion enhancement between fibre reinforcement and cementitious matrix.

Materials and Methods

Cementitious Matrices. Three matrices for structural purpose and belonging to the R4 resistance class (R_{ck} equal or greater than 45 MPa) were selected. Moreover, a fine particle size was sought to obtain a higher matrix penetration level into the carbon bundle, thus the best adhesion between the matrix and the carbon fabric. So, 20wt% of 0-3mm silica aggregate, 25wt% of 0-5mm silica aggregate and 10wt% of 0-150µm carbonate filler were considered.

For each matrix formulation, a 35wt% of Ordinary Portland cement was prescribed to reach the desired threshold value of compressive strength of 45 MPa. Compared with the traditional mortar, this content also limits the water content and provides good mortar workability. An expansive additive by 1.5wt% was also implied to reduce hydraulic shrinkage, whereas the remaining content was reserved for other fillers and rheological regulators.

The influence of organic additive in adhesion enhancement between fabric and matrix is eventually investigated. So, the three matrices involved differed in organic additive in mix: without organic additive (M1 mortar), 1wt% of Polyvinyl Acetate (PVAc) and 1wt% of acrylic binder (M2 mortar), 2wt% of Vinyl Acetate Ethylene (M3 mortar). On equal workability conditions, the addition of organic additive also reduces water content: 20wt%, 19wt% and 19.5wt% for M1, M2, M3, respectively.

Fabrics and surface treatments. Two different carbon fabrics were selected depending on commercial availability. A unidirectional full fabric (Fig. 1a, named F1) was selected to solely investigate the chemical affinity between the carbon fabric and the matrix. Indeed, the mechanical interlocking between phases was supposed to be avoided due to no spacing between fabric bundles. A bidirectional fabric (Fig. 1b, named F2) characterized by spaced bundles was selected to additionally investigate the contribution of the mechanical interlocking between the matrix and the fabric. The weight of F1 fabric was 300g/m^2, whereas F2 displayed 182g/m^2 and 42 g/m^2 in the principal and secondary direction, respectively.

Furthermore, three different coatings were roller-applied on F1 fabric to promote both chemical and mechanical adhesion with the matrix. All the coatings were prepared by mixing 20wt% water, 50wt% Vinyl Acetate ethylene (VAE) and 30wt% different grained-size inorganic fillers. The fillers involved were: micro-silica (0.8-30µm, C1 sample), fine-silica sand (0-0.3mm, C2 sample), medium size-silica sand (0-0.5mm, C3 sample).

Finally, two different bundle geometries were considered (see Fig. 2) to possibly highlight a different pure mechanical adhesion with the inorganic cementitious matrix (M1 mortar). The same commercially available bundle (Fig.2a) was manually twisted (Fig.2b) to increase its waviness, thus, to increase the number of anchoring sites.

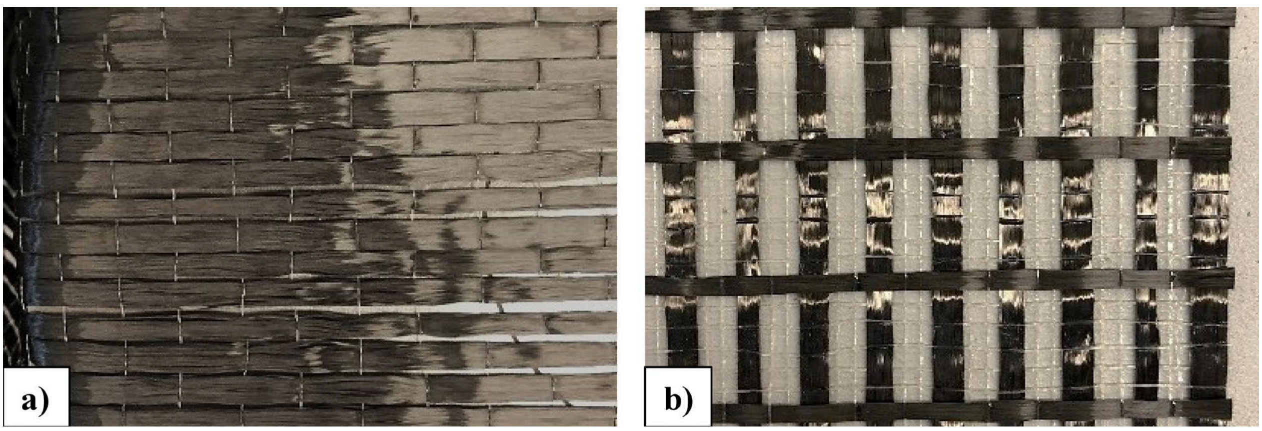

Fig. 1 – Commercially available fabrics: a) F1, unidirectional full fabric, b) F2, bidirectional fabric

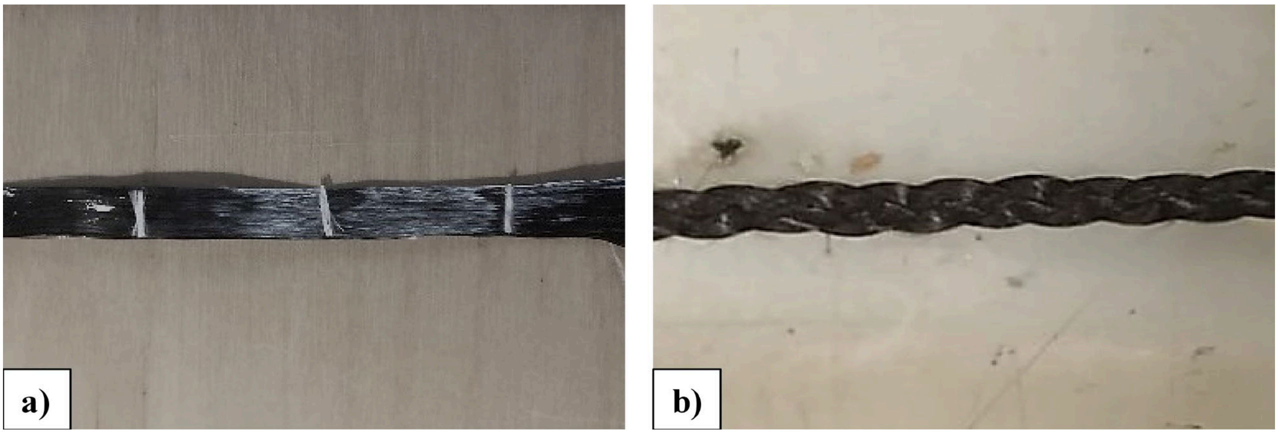

Fig. 2 – Different bundle geometries: a) untwisted, b) manually twisted

Characterization of mortars. Six cubic samples 4x4x4cm for each mortar (M1, M2, M3) were prepared ad cured for compression test. The compressive strength at 24h, 7days and 28days of curing was achieved through a Universal testing machine.

Special care was paid to the shrinkage phenomenon as a direct influencing parameter of mortar early degradation. Hygrometric shrinkage measurements were performed on four samples (2.5x2.5x18cm) for each mortar using a digital comparator with a sliding rod. The measurements were acquired from 24h to 28days. Moreover, the entity of crack formation related to shrinkage was visually detected by comparing mortar plates prepared following the EN 1542 standard.

Characterization of FRCMs. A customized shear test was developed ad hoc to measure the shear strength of FRCM systems (FRCMs) through the Zwick100 testing machine. The test setup included a vertical compressive load up to 100kN that acted as a shear strength on an interlaminar specimen (Fig. 3b). Interlaminar specimens consisted of rectangular FRCM with dimensions of 10x5x0.7cm in which the carbon fabric is embedded in mortar with 3mm distance from the edges. The specimens are cured for 28days and bonded between two concrete supports with epoxy resin (Fig. 3a).

A single lap test was carried out, accordingly to CE standard, to understand the adhesion limit between the composite FRCM system on supports. The specimen was prepared by realizing an FRCM reinforcement by 32x5x0.7 cm on concrete support as reported in Fig.3c.

A pull-out test was conducted on mortar specimens in which two different bundle typologies were longitudinally embedded, namely untwisted and twisted. Rectangular formworks with 4x4x16cm dimensions were used to cast the cementitious paste as reported in Fig.3d and specimens were cured at room conditions for 28days.

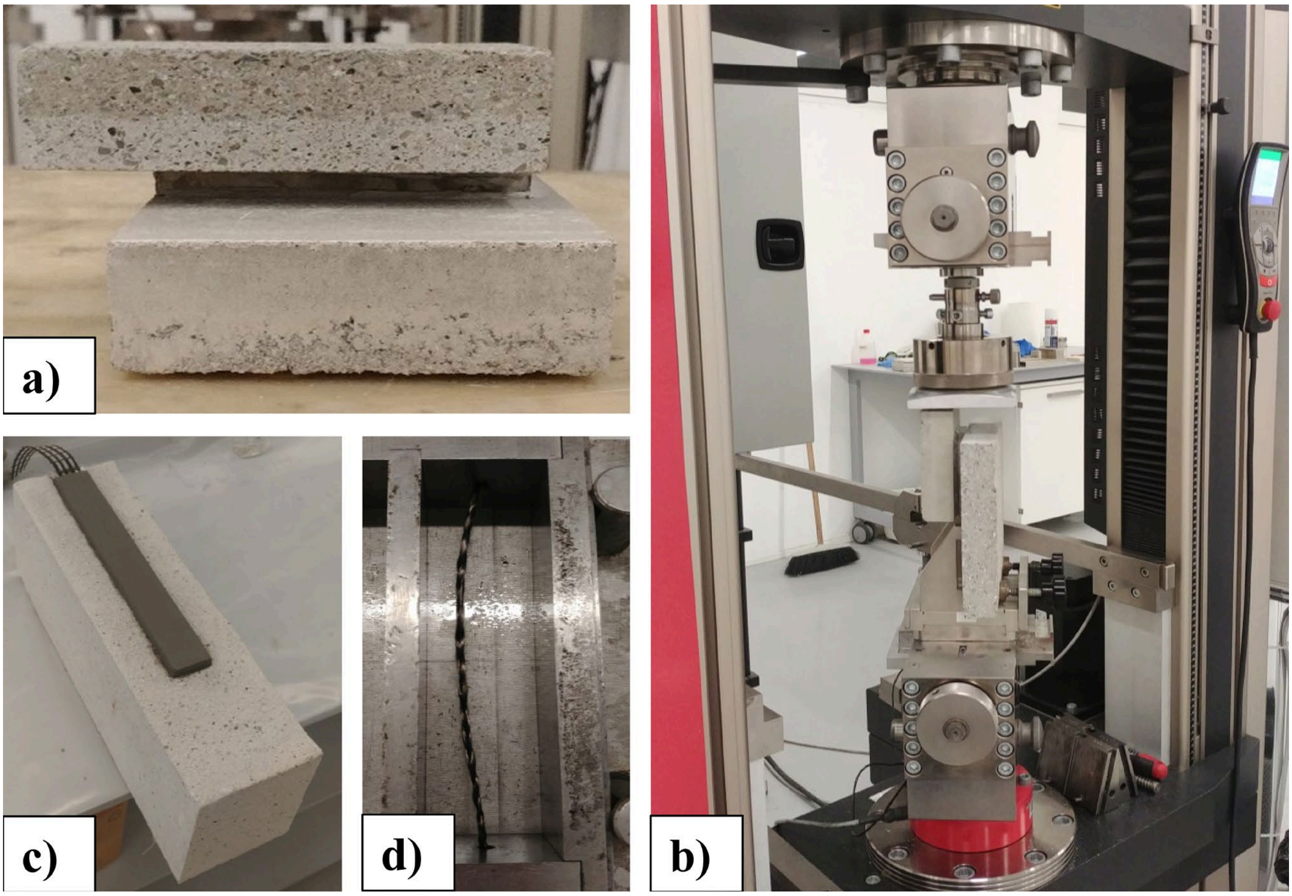

Fig. 3 – Mechanical test specimens and devices: (a) shear test specimens, (b) shear test setup, (c) single lap specimen, (d) formwork for pull-out specimens

Results and Discussion

Mortars. As reported in Fig.4, all the mortars positively satisfied the required compressive strength by 45MPa at 28days. Interestingly, different shrinkage behaviours occurred by varying the mortar composition (see Fig. 5).

Unlike the organic matrices M2 and M3, the inorganic matrix M1 displayed a preliminary expansion phase before shrinkage occurrence (Fig. 5a) that caused a significant cracking formation (Fig. 5b). Conversely, the organic additives empowered the plasticity of the mortar absorbing expansion (Fig.5a) and reducing the crack formation due to shrinkage after 28days (Fig. 5c and Fig.5d). Apart from the enhance in fibre to matrix adhesion to probe, the organic additive appeared to improve the durability of mortars for FRCM systems.

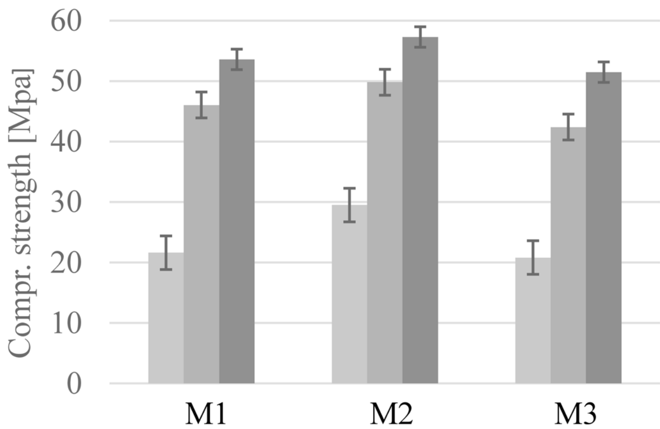

Fig. 4 – Development of the compressive strength of mortars at 24h (light grey), 7 days (grey), 28 days (dark grey)

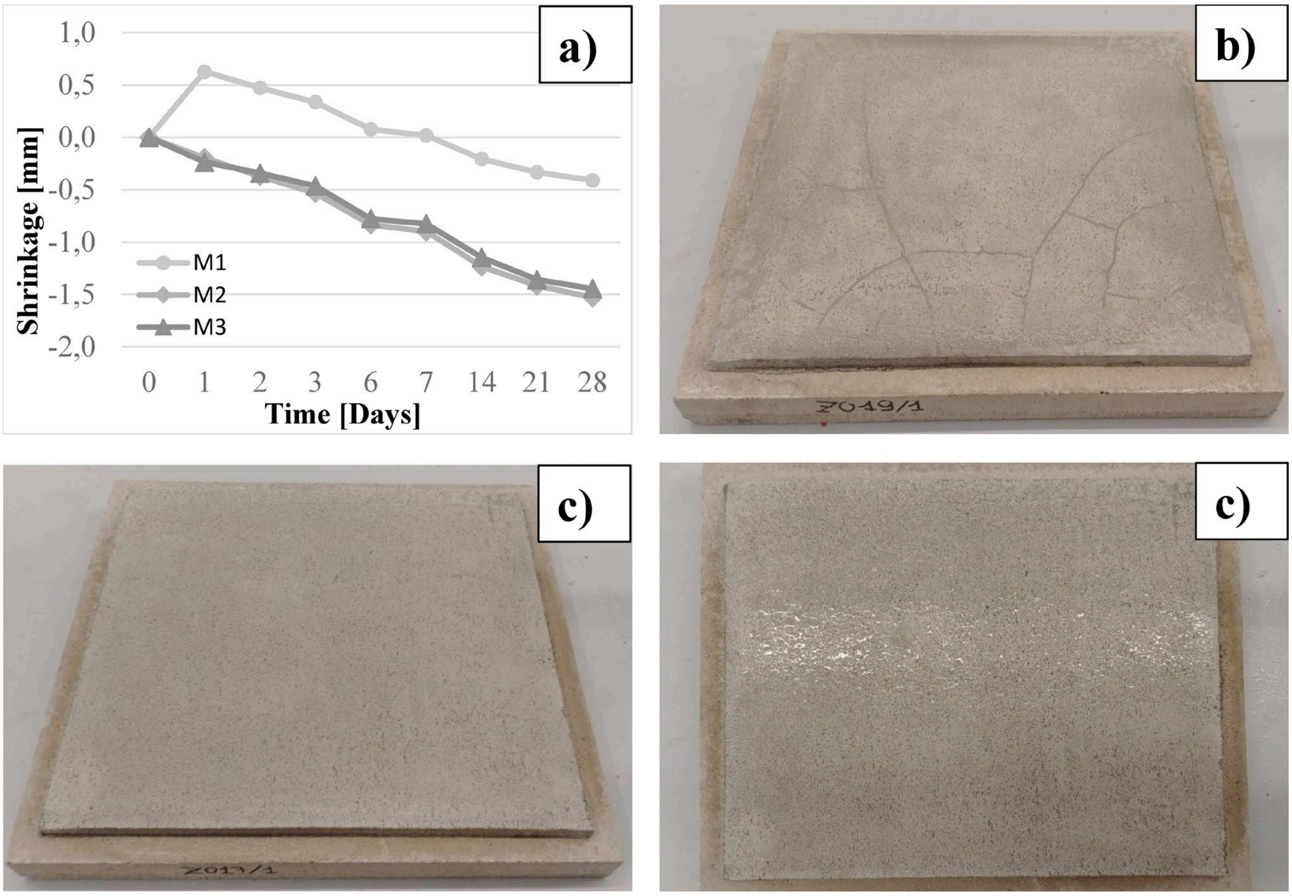

Fig. 5 – Hygrometric shrinkage of mortars as a function of time (a) and crack formation after 28days for M1 (b), M2 (c), M3 (d) mortars

FRCMs

Shear Test. Compared to the inorganic matrix M1, the organic ones M2 and M3 improved the FRCMs strength during shear test (see Table 1 and Table 2). The maximum improvement was more significant for FRCMs reinforced with F1 fabric (+51%) than F2 fabric (+38%). However, F2 fabric provided stronger mechanical performance to FRCMs thanks to the mechanical interlocking between spaced bundles and mortar. Apart from the fabric typology, a contribution to the phases' adhesion was interestingly provided by considering organic additives in cementitious matrices.

For all the FRCMs under investigation, a failure occurrence at the interface between fabric and matrix was observed. However, FRCM samples with organic matrix M3 differed from the other in displaying a significant presence of mortar particles adhered to the carbon fibres (Fig.6). Thus, confirming the better shear strength results of Table 1 and Table 2, the M3 matrix promoted a better chemical adhesion between the phases.

On equal mortar and fabric typology, the grain size of the fillers embedded in surface coatings also appeared as an influencing parameter for the shear strength of FRCMs. As reported in Table 3, increasing the dimensions of the fillers also increases the shear strength, suggesting an additional mechanical adhesion between fibres and matrix promoted by the modified surface morphology of coated fabrics. This evidence was further confirmed by considering that the failure of FRCM with coated fabrics occurred with the fabric failure itself (Fig.7b) instead of in the interphase zone (Fig.7a).

Table 1 – Shear test results for FRCMs with F1 fabric

	M1_F1	**M2_F1**	**M3_F1**
F_{max} [N]	6770 ± 1589	9168 ± 1718	10234 ± 2593
τ [MPa]	0,9 ± 0,2	1,3 ± 0,2	1,4 ± 0,4

Table 2 – Shear test results for FRCMs with F2 fabric

	M1_F2	M2_F2	M3_F2
F_{max} [N]	9812 ± 1812	13545 ± 2116	12121 ± 2916
τ [MPa]	2,4 ± 0,4	3,3 ± 0,5	2,94 ± 0,7

Table 3 – Shear test results for FRCMs with F1 fabric coated with different treatments: C1 micro silica, fine silica aggregate (C2), medium-size silica aggregate (C3)

	C1_M1_F1	C2_M1_F1	C3_M1_F1
F_{max} [N]	9099 ± 1531	9432 ± 2027	12247 ± 676
τ [MPa]	2,2 ± 0,4	2,3 ± 0,5	3,0 ± 0,2

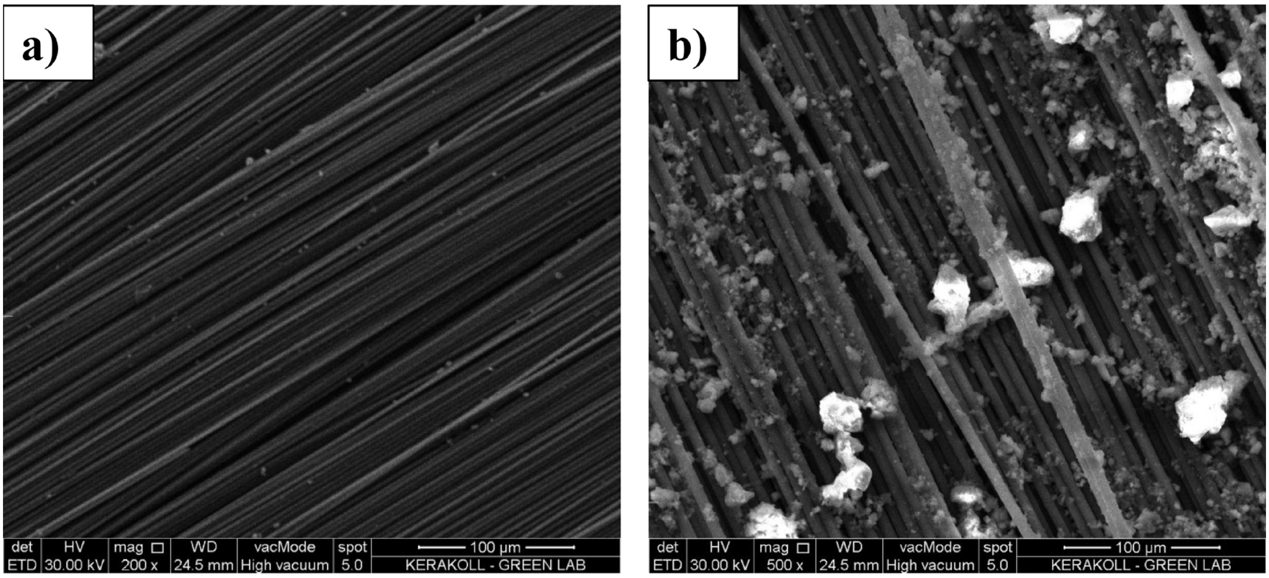

Fig. 6 – SEM micrographs of FRCM fracture surfaces after shear test failure: mortar M1 (a) and mortar M3 (b)

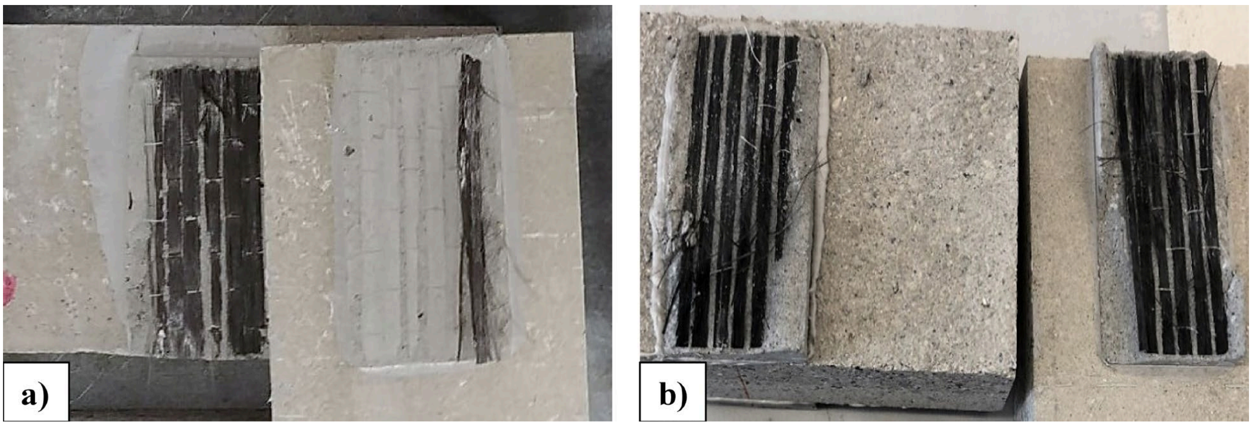

Fig. 7 –Different failure mode for FRCMs reinforced by uncoated fabric (a) and coated fabric (b)

Single Lap. Despite the different matrices involved, similar strength values were observed through a single lap test (Fig.8). However, better results reproducibility was displayed by FRCMs with M3 matrix. The same failure mode occurred for all the samples, consisting of slippage of the fibre inside the matrix.

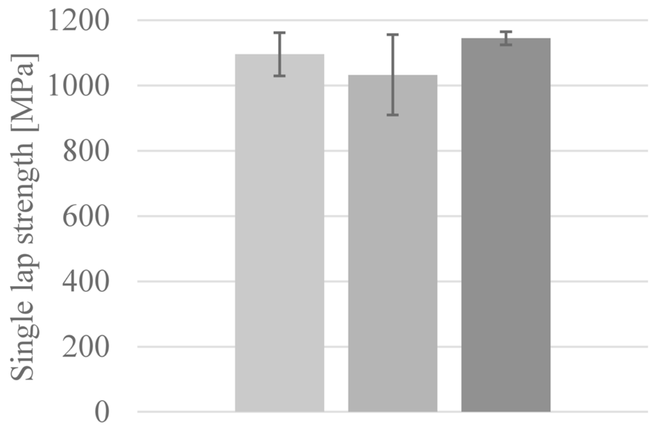

Fig.8 – Single lap strength for M1mortar (light grey), M2 mortar (grey), M3 mortar (dark grey)

Pull-Out. Different pull-out loads (Fig.9) and, more significantly, different failure modes occurred by considering different bundle geometry. The untwisted bundle displayed a lower resistance to pull-out loading and failed with bundle slippage through the matrix due to a lack of adhesion. On the other hand, the twisted bundle exhibited better performances and a carbon fibre failure.

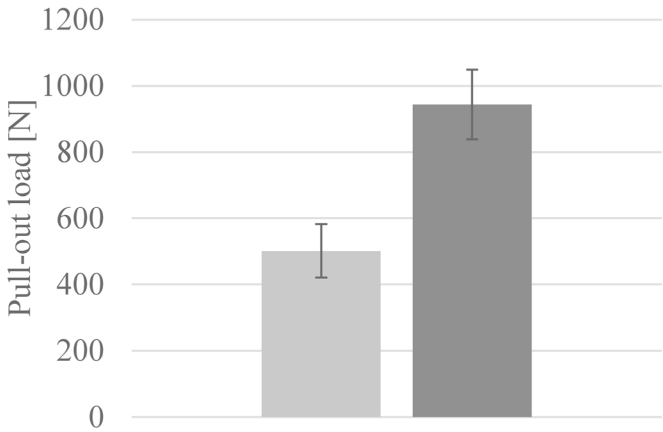

Fig. 9 –Pull-out load for ordinary bundle (light grey) and twisted bundle (dark grey)

Conclusions

The compatibility and adhesion between carbon fibre and cementitious matrix is a key issue toward the optimization of carbon-FRCM systems. In this contest, this work returns important evidence about the most important parameters influencing the mechanical behaviour of FRCM.

First, the addition of Vinyl Ethylene Acetate in the cementitious matrix (M3) reduces the mortar early degradation risk thanks to a significant reduction in hydraulic shrinkage phenomenon and crack formation. Moreover, the organic additive enhances the chemical adhesion with the carbon fabric, which is demonstrated by a higher shear strength and the presence of mortar grains adhered to the fabric after failure. It is also observed that, in comparison with the other matrices, M3 mortar allows to reduce the standard deviation of single lap measurements, so it provides more reliable results.

Unidirectional full fabric displays lower shear strength than bidirectional spaced fabric due to the deletion of interlocking mechanical adhesion between mortar and bundles. Nevertheless, it highlights the contribution of the chemical adhesion promoted by organic additives in the mix and fabric surface treatments.

Surface treatment composed of EVA polymer and different fillers appears more efficient with increasing filler grain size. Indeed, the deposition of 0-0.5mm silica aggregate significantly improves the shear strength of FRCMs due to their additional providing of anchoring sites and mechanical adhesion between fibres and matrix.

According to this, the pull-out test of the single bundle shows that the manually twisted bundles strongly exceed the pull-out strength of an untwisted bundle. Significantly, this increased roughness leads to the failure of the carbon fibre without any telescopic behaviour.

In conclusion, the most important influencing parameters for FRCM behaviour are pointed out to optimize the properties of composite reinforcing systems. Chemical adhesion can be promoted by the mix addition of organic additives that also increases the durability and reproducibility of results. Whereas the greatest contribution to FRCM performance is attributable to the mechanical adhesion phenomenon that mainly depends on fabric's geometrical data and proper surface treatments.

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